VALERIA LOSCRÌ

La Dott.ssa Valeria Loscrì ha svolto l'attività di formazione e ricerca con impegno ed ha raggiunto una buona conoscenza delle discipline studiate. Le relazioni prodotte, i seminari tenuti e i colloqui svolti hanno mostrato un'elevata capacità di esposizione e una buona preparazione scientifica.

La tesi della Dott.ssa Loscrì comprende lo studio di diverse tipologie di reti wireless: Mobile Ad hoc NETworks MANETs, Wireless Sensor Networks WSNs e Wireless Mesh Networks WMNs.Il lavoro di tesi è stato incentrato sui livelli Medium Access Control (MAC) e sul livello Rete per le diverse reti wireless. In particolare, per quanto concerne le reti ad hoc il lavoro presenta un innovativo approccio di tipo cross-layer in cui viene sviluppato un Multipath Forward Algorithm (MFA) che consente la gestione dinamica di risorse di banda per il supporto alla QoS di percorsi multipath. I percorsi multipath vengono costruiti garantendo che la proprietà di node-disjointness sia preservata, per migliorare la fault-tolerance nel caso di rottura di un percorso primario. L'ambiente applicativo di un simile approccio è quello di reti che si organizzano on the fly con supporto alla mobilità, in cui è necessario garantire buone performance in termini di dati consegnati ai nodi destinazione senza introdurre un'eccessiva latency. Nell'ambito dei protocolli di routing di tipo multipath, è stata proposta la definizione di una nuova proprietà che i percorsi multipli di una stessa coppia sorgente-destinazione devono soddisfare per migliorare le performance in termini di data delivery e di ritardo, la zone-disjointness property. Attraverso la definizione di questa proprietà si è mostrata la possibilità di costruire percorsi multipli simultanei che interferiscano nel minor modo possibile l'uno con l'altro. Il nuovo protocollo di routing sviluppato, Il Geografic Multipath Protocol (GMP), basato su locazioni geografiche è stato implementato in un simulatore di reti che ha consentito di fare il testing del nuovo protocollo e di confrontarlo con un approccio in cui è considerato un criterio noto in letteratura (node-disjointness property) di selezione dei percorsi. Le simulazioni condotte hanno mostrato l'efficacia del nuovo criterio per la costruzione di percorsi multipli. Nell'ambito delle reti wireless di sensori sono state analizzate delle soluzioni presenti in letteratura per reti di sensori con alta densità atte a monitorare ambienti esterni in cui è ritenuta non conveniente se non impraticabile la ricarica delle batterie dei sensori. E' stata presentata una dettagliata analisi in termini energetici relativa alla costruzione di cluster di reti a due livelli. Infine, stato studiato dettagliatamente lo standard per reti wireless l'IEEE 802.16 e si è fatto specifico riferimento al Coordinated Distributed Scheme (CDS). Infine, sono stati proposti due differenti schemi, alternativi al CDS, per la gestione distribuita degli schedules che non richiedono cambiamenti hardware rispetto allo standard.

Il lavoro di tesi svolto dalla Dott.ssa Loscrì dimostra una buona capacità di analisi delle tematiche affrontate che le ha consentito di pervenire a risultati teorici e sperimentali di significativo interesse tecnico e scientifico. L'organizzazione del lavoro di tesi è di buona qualità e ciò porta alla espressione di un giudizio positivo sulla attività svolta.

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Dottorato di Ricerca in
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XIX ciclo

Tesi di Dottorato

Protocol Architectures for Wireless Networks: issues, perspectives and enhancements

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DEIS

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This thesis is dedicated to my mother
and to the memory of
my father
(1938-1993)

Acknowledgements

First of all I would like to thank my lovely family and my “husband”. I would like to thank Professor Edward Knightly for his support during the time spent at Rice University in ECE group.

Summary

Recently, static multi-hop wireless networks, or “mesh” networks, have attracted research, commercial and standardization interest. Unlike traditional ad-hoc wireless networks that have been motivated by mobile scenarios like the future battlefield, mesh networks have commercial applications such as community wireless access. In such networks, most of the nodes are either stationary or minimally mobile. We are motivated by the all-wireless office scenario. In this application, offices with PCs are cooperatively interconnected by ad-hoc wireless links instead of Ethernet links, and few servers or proxies have wired connectivity to a corporate network or the Internet. This scenario is useful for small or low cost businesses and rapid deployment of short-term office space. Mesh networks are a natural solution for this space as they do not require the installation of any additional network equipment or wires, and potentially offer significant reduction in network administration (no access points or switches to maintain). Wireless mesh networks (WMNs) are an alternative technology for last-mile broadband Internet access. In WMNs, user packets are forwarded to and from an Internet-connected gateway in multi-hop fashion. Despite the recent start-up surge in WMNs, much research remains to be one before WMNs realize their full potential. To meet the needs of wireless broadband access, the IEEE 802.16 protocol for wireless metropolitan networks has been recently standardized. The medium access control (MAC) layer of the IEEE 802.16 has point-to-multipoint (PMP) mode and mesh mode. Previous works on the IEEE 802.16 have focused on the PMP mode. In the mesh mode, all node are organized in an ad hoc fashion and use a pseudo-random function to calculate their transmission time. My thesis is that this harsh environment requires an application-specific protocol architecture, rather than the traditional layered approach, to obtain the best possible performance. When TDMA is used, distributed protocols are needed to generate transmission schedules. An important issue is how to produce a schedule quickly and in a fair fashion. This dissertation supports this claim introducing two fully distributed protocols for generating TDMA schedules. Contention is incorporated into the scheduling protocols for them to work independently of the network size. The schedules can be generated at multiple parts of the network simultaneously. Our main contribution is developing a new distributed scheduler for mesh mode and implementing the distributed scheduler of IEEE 802.16 in a well-known simulator, NS2. Moreover, an analytical model has been introduced to evaluate the delay with an ideal TDMA scheme and an ideal scheme has been developed in a simulator in order to obtain a lower bound in terms of delay. The last topic multipath routing in a mobile wireless network. The main objective of using multipath routing in a mobile wireless network is to use several *good* paths to reach destinations, not just the one *best* path, without imposing excessive control overhead in maintaining such paths. Multipath routing has long been recognized as an important feature in network to adapt to load and increase reliability. In this dissertation we will show ho the using of multipath routing permits better performance in terms of delay and throughput to be obtained.

Keywords:
Wireless Networks, Medium Access Control, CSMA, TDMA, ad hoc networks, wireless sensor networks, wireless mesh networks, 802.11, 802.16, Routing Protocol, Multipath, NS2, performance evaluation.

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Abbreviations

AC	Admission Control
AODV	Ad hoc On demand Distance Vector
AODV-BR	Ad hoc On demand Distance Vector –Backup Routing
AOMDV	Ad Hoc On demand Multipath Distance Vector
BS	Base Station
BER	Bit Error Rate
BWA	Broadband Wireless Access
CA	Coverage Area
CAC	Connection Admission Control
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CDS	Coordinated Distributed Scheme
DAMA	Demand Assignment Multiple Access
DL	Downlink
DL-MAP	Downlink MAP
DSS	Distributed Scheduling Scheme
E-TDMA	Evolutionary-TDMA
ETSI	European Telecommunications Standards Institute
FCA	Free Capacity Assignment
FCFS	First Come First Served
FCH	Frame Control Header
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FPRP	Five Phase Reservation Protocol
FTP	File Transfer Protocol
GPS	Global Positioning System
GSM	Global System for Mobile Communication
GT	Guard Time
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISP	Internet Service Provider

ITU	International Telecommunication Union
LAN	Local Area Network
MAC	Medium Access Control
MANET	Mobile Ad hoc NETwork
MBWA	Mobile Broadband Wireless Access
MSH-CSCF	Mesh Centralized Scheduling Configuration
MSH-CSCH	Mesh Centralized Scheduling
MSH-DSCH	Mesh Distributed Scheduling
MSH-NENT	Mesh Network Entry
MSH-NCFG	Mesh Network Configuration
NIC	Network Interface Cards
OFDM	Orthogonal Frequency Division Multiplexing
PDA	Personal Digital Assistant
PDU	Protocol Data Unit
PHY	Physical layer
PMP	Point-to-Multipoint
QoS	Quality of Service
SDU	Service Data Unit
SS	Subscriber Station
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
UL	Uplink
UL-MAP	Uplink MAP
URL	Uniform Resource Locators
WiFi	Wireless Fidelity
WMAN	Wireless Metropolitan Area Network
WMN	Wireless Mesh Network
WSN	Wireless Sensor Network
WWW	World Wide Web

Protocol Architectures for Wireless Networks

Chapter 1 Introduction

1.1 Wireless Networks

Wireless networks have experienced unprecedented development in the past decade. The Internet has become ubiquitous and there has been tremendous growth in wireless communications in recent years. Many wireless communication techniques are commercially available, such as the Wireless LAN, Bluetooth, GSM, GPRS, CDMA and TDMA. Because an all-IP network will be a trend, access to the Internet via wireless communication devices has become an important issue. One of the most rapidly developing areas is mobile ad hoc networks. Physically, a mobile ad hoc network consists of a number of geographically-distributed, potentially mobile nodes sharing a common radio channel. Compared with other types of networks, such as cellular networks or satellite networks, the most distinctive feature of mobile ad hoc networks is the lack of any fixed infrastructure. The network is consisted of mobile nodes only, and a network is created "on the fly" as the nodes transmit with each other. The network does not depend on a particular node and dynamically adjusts as some nodes join or others leave the network. Recently, static multi-hop wireless networks, or "mesh" networks, have attracted research [1, 2], commercial [3, 4] and standardization [5] interest. Based on their characteristics, wireless mesh networks (WMNs) are generally considered as a type of ad-hoc networks due to the lack of wired infrastructure that exists in cellular or Wi-Fi networks through deployment of base stations or access points. While ad hoc networking techniques are required by WMNs, the additional capabilities necessitate more sophisticated algorithms and design principles for the realization of WMNs. More specifically, instead of being a type of ad-hoc networking, WMNs aim to diversify the capabilities of ad hoc networks. Consequently, ad hoc networks can actually be considered as a *subset* of WMNs. Ad hoc networks will enable people to exchange data in the field or in a class room without using any network structure except the one they create by simply turning on their computers or PDAs, or enable a flock of robots to form a self-organizing group and collectively perform some tasks. As wireless communication increasingly permeates everyday life, new applications for mobile ad hoc networks will continue to emerge and become an important part of the communication structure. As mobile ad hoc networks provide the users unparalleled flexibility, they pose serious challenges to the designers. All nodes are essentially the same and there is no natural hierarchy or central controller in the network. Nodes must self-organize and reconfigure as they move, join or leave the network. All functions have to be distributed among the nodes. The bandwidth of the system is usually limited and a transmission has to be relayed by other nodes before reaching its destination. A network has a multi-hop topology, and this topology changes as the nodes move around. Many problems in these networks are inherently difficult (NP-complete). Among the various aspects of mobile ad hoc networks, medium access control and routing are two most active research areas. The multi-hop topology allows spatial reuse of the wireless spectrum. Two nodes can transmit using the same bandwidth, provided they are sufficiently apart. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an ad hoc network). This feature brings many advantage to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage. Conventional nodes (e.g., desktops, laptops, PDAs, PocketPCs, phones, etc.) equipped with wireless networks interface cards (NICs) can connect directly to wireless mesh routers. Customers without wireless NICs can access WMNs by connecting to wireless mesh routers through, for example, Ethernet. Thus, WMNs will greatly help the users to be always-on-line anywhere anytime and the gateway/bridge functionalities in mesh routers enable the integration of WMNs with various existing wireless networks such as cellular, wireless sensor, wireless fidelity (Wi-Fi) [6], worldwide inter-operability for microwave access (WiMAX) [7], WiMedia [8] networks. Deploying a WMN is not too difficult, because all the required components are already available in the form of ad hoc network routing protocols, IEEE 802.11 MAC protocol, etc. However, to make a WMN be all it can be, considerable research efforts are still needed. For example, the available MAC and routing protocols applied to WMNs do not have enough scalability. Researchers have started to revisit the protocol design of existing wireless networks, especially of IEEE 802.11 networks, ad hoc networks, and wireless sensor networks, from the perspective of WMNs. Industrial standards groups are also actively working on new specifications for mesh networking. For example, IEEE 802.11 [9, 10], IEEE 802.15 [11, 12] and IEEE 802.16 [13, 14, 15] all have established sub-working groups to focus on new standards for WMNs.

1.2 Contributions of this dissertation

This dissertation overviews recent developments in optimization based approaches for resource allocation problems in wireless systems. Specifically, attention is focused on multi-path routing and quality-of-service support. In wireless ad hoc networks, communication can be actuated with multi-hop technology through the use of the mobile device as transmitter, receiver and/or router of information. The dynamic nature of the network topology makes the medium access control (MAC) very challenging in terms of the routing, the quality of service (QoS) support, the security, etc. Quality of Service is a critical issue in ad hoc networks because of the difficulties of resource management in an environment with frequent topological changes and a fluctuating wireless channel. In the literature, there are some studies that attempt to address the problem of the reservation of bandwidth in order to offer some QoS mechanisms to the flow, through the introduction of a Time Division Multiple Access (TDMA) or Code Division Multiple Access (CDMA) over TDMA wireless channel. According to these approaches, a TDMA channel and a distributed TDMA MAC are considered here as the basis of deploying a routing protocol. Because frequent topological changes cause a lot of link breakage with consequence expensive route maintenance procedures and increased routing overhead, research in previous years has also addressed the problems of multi-path routing in order to give more robustness to single path routing and to improve some characteristic parameters of the network, such as the data delivery ratio, the end-to-end delay and the routing overhead. Numerous studies in the literature have focused on multipath routing, proposing different solutions and ways to see and solve the problem. The multi-routes between a source and a destination can be used to transmit the information over all the paths at the same time, in order to maximize the flow of data info, and to split the bandwidth request of a flow over multi paths in order to increase the success rate of the bandwidth request. Another approach with a different purpose is to use the multi-route not at the same time, but where one route is used as the primary route and the others as back-up routes in order to reduce the number of routes recoveries. Both of these approaches are improvements over uni-path routing protocols, because they have greater resilience to the host mobility in comparison with the relative uni-path version, reducing the delay and increasing the throughput. There are also some multipath routing protocols that reduce the routing overhead through a single route discovery process able to build more links or node-disjoint routes towards the destination. The novelty in this dissertation is the integration issues of a multi-path routing protocol and a distributed TDMA MAC for the Quality of Service (QoS) support [16]. The advantages of multi-path routing with back-up routes are combined with the challenging task of offering minimum bandwidth constraints to the route in chapter two. The approach that has been followed is to use the advantages of high throughput for heavy traffic offered by a novel MAC layer called E-TDMA and based on TDMA channel, with the advantages offered by a well-known multi-path routing protocol called Ad Hoc Multi-path Distance Vector Routing (AOMDV). The advantages of AOMDV are reduced routing overhead, increased throughput and reduced end-to-end data packet delay. AOMDV in its original version, to our knowledge, has been tested only on the standard IEEE 802.11 MAC layer, but does not offer a mechanism for QoS.. This approach requires the use of a TDMA MAC, so the AOMDV has been extended and changed in order to use the functionalities of the new E-TDMA MAC and to permit the bandwidth reservation in the route discovery process. Two new modalities to reserve the bandwidth over the multi-path have been proposed: the first one guarantees a minimum bandwidth level to all paths between source and destination; the second one, in order to increase the number of paths discovered in the route discovery phase, offers QoS only on the primary path, considering the other back-up paths as best-effort. Another important topic in the wireless network is energy consumption. An important challenge in the design of wireless and mobile systems is that two key resources – communication bandwidth and energy- are significantly more limited than in a tethered network environment. These restrictions require innovative communication techniques to increase the amount of bandwidth per user and innovative design techniques and protocols to use available energy efficiently. The advantage of multi-path routing in MANETs is not obvious because the traffic along the multiple paths will interfere with each other. The effect of the *route coupling* in this environment can severely limit the gain offered by multipath routing strategies. Route coupling refers to the interference between two or more multiple paths located physically close enough to interfere with each other during data communication. In this dissertation, we propose and design a new multipath distance-vector routing protocol, the Geographic Multipath Protocol (GMP) [17]. This reactive algorithm computes alternate routes loop-free and zone-disjoint paths. In this way the paths are more independent to each other and the correlation-interference is very low. This permits to have a higher load balancing in the network and a major effectiveness of the multiple paths as far as the performance measures considered. Simulation experiments have shown that GMP outperforms unipath distance vector routing (AODV) and multipath distance vector routing. In chapter three an application-specific protocol architecture is designed in order to obtain a system that achieves high performance and energy-efficiency in a wireless environment. A new hierarchical protocol is developed in which randomized, adaptive, self-configuring cluster formation is realized and localized control for data transfers is used. In our protocol we consider a randomized rotation of the cluster-heads and the corresponding clusters [18, 19]. As far as the energy constraint is concerned another cross-layered approach is considered. In chapter 3 we introduce a new Dynamic Management Algorithm (DMA). The scope of this work is to design a dynamic management strategy to better distribute the energy in the network varying dynamically roles of the nodes under different mobility conditions. Two different role dynamic management algorithms are proposed and applied to the cross-layered approach. These latter are dynamic in the sense that each node, through a particular technique perceives the mobility of the network and in a manner that is autonomous, decides whether it wants to change role (active-passive, or passive-active). These approaches are very scalable because the decision to change role is made in a local manner and periodically and the node does not have information about he rest of the topology [20]. The IEEE 802.16 Working Group created a new standard, commonly known as WiMax [21, 22], for broadband wireless access at high speed, at low cost, which is easy to deploy, and which provides a scalable solution for extension of a fiber-optic backbone. The standard IEEE 802.16 [23] defines two modes of operation, Point-to-Multipoint (PMP) and Mesh mode. In the PMP mode traffic is directed from the Base Station (BS) to Subscriber Station (SSs, i.e. a common user), or vice-versa. Different to that within the Mesh mode, traffic can occur directly among SSs, without being routed through the BS (Mesh BS). The Mesh BS is the entity that interfaces the wireless network to the backhaul links. It acts like a BS in PMP mode but not all the SSs have to be directly connected to the Mesh BS. As relatively new standard, IEEE 802.16 has been studied much less than access technologies as IEEE 802.11. The IEEE 802.16 has three mechanism to schedule the data transmission in mesh mode – centralized scheduling, coordinated distributed scheduling and uncoordinated distributed scheduling In centralized scheduling the BS works like a cluster head and determines how the SS's should share the channel in different time slots. Because all the control and data packets need to go through the BS, the scheduling procedure is simple, however the connection setup delay is long. Hence the centralized scheduling is not suitable for occasional traffic needs. In distributed scheduling, every node competes for channel access using a pseudo-random election algorithm based on the scheduling information of two hop neighbors. The distributed channel access control is more complex because every node computes its transmission time without global information about the rest of the network. In chapter 4 we resume the different scheduling schemes of the standard IEEE 802.16. In chapter 5 a new Distributed Scheduling Scheme (DSS) has been developed and implemented in a well known simulator ns2. Moreover, the IEEE 802.16 distributed scheduler has been investigated, developing the IEEE 802.16 Coordinated Distributed Scheduler (CDS) in ns2. The DSS is totally distributed and requires only local information to compute the schedules. Specifically, it addresses schedule updates in the face of network changes. The DSS protocol differs from the IEEE 802.16 standard in that it emphasizes the speed with which the schedules are calculated, provided a reasonably degree of bandwidth efficiency is achieved and a reasonable degree of fairness is kept. In this work performance comparison between the DSS and the IEEE 802.16 distributed scheduling mesh mode are evaluated in terms of delay and throughput. Furthermore, an ideal schedule has been simulated in ns2 in order to evaluate an ideal *lower-bound* in terms of delay. In order to obtain an estimation of the delay in an ideal TDMA we developed an analytical model and we compared results obtained using this framework and simulated results obtained considering the ideal schedule aforementioned. Both, the ideal simulated scheduling mechanism and the analytical model show how DSS permits good results in terms of delay to be realized.

1.3 Structure of thesis

This thesis is structured as follows.

Chapter 2 gives an exhaustive overview of multipath routing protocol. Specifically, we investigated the issue of multipath routing in MANETs. The relative advantages and disadvantages of multipath routing vs uni-path routing have been discussed. Key issues and trends will also be examined. Two different multipath protocols are developed in this chapter: a reactive on demand multipath protocol over a TDMA MAC protocol, the QAOMDV and a Geographic Multipath Protocol, the GMP.

Chapter 3 highlights the issue of the energy in Wireless Sensor Networks. Specifically, we consider a hierarchical protocol developed for a static wireless sensor network: LEACH. Through analytical considerations the adding of a new layer to the network is considered and it is shown how under certain analytical conditions it is possible to take advantage of a similar structure. A simulation study is proposed in order to validate analytical results obtained. Furthermore, a module called role Dynamic Management Algorithm (DMA) is proposed in order to increase the lifetime in networks where different roles are assigned to the nodes (i.e., hierarchical structure).

Chapter 4 is an overview of the IEEE Std 802.16. Specifically, we describe two different deployments in the standard: the Point-to-MultiPoint (PMP) and Mesh mode. Moreover, the different schemes of the Mesh mode are considered: 1) Centralized, 2) Coordinated Distributed Scheme and 3) Uncoordinated Distributed Scheme.

Chapter 5 this chapter is for the analysis of the characteristics of the Coordinated Distributed Scheme (CDS) of the IEEE 802.16. Moreover, we analyzed the reasons because the IEEE 802.11 MAC protocol does not work well in a multi-hop environment. Finally, we propose two different solutions that permit better performance in terms of throughput and average end-to-end data packets delay to be obtained.

Chapter 6 this last chapter focus on the conclusions and future work of this dissertation.

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2

Chapter 2 Multipath Routing in Wireless Networks

2.1 Introduction

In the literature there is much research on multipath routing for wireless networks and MANETs [1-6]. In [4] it can be found a useful overview of this research activity. Multipath routing offers the advantages of reducing the number of route discovery processes and the end-to-end delay, while increasing the data packet throughput. The main objective of using multipath routing in a wireless network is to use several *good* paths to reach destination, not just the one *best* path [7], without imposing excessive control overhead in maintaining such paths. Multipath routing has long been recognized as an important feature in networks to adapt to load and increase reliability [8, 9]. There are several philosophies that approach the problem of multipath in a different way. One of them is to use the multipath routing to make load balancing between the paths [10]; another approach, in the case of QoS support, is to split the bandwidth request among more paths towards the destination in order to increase the success rate of finding routes in the route discovery phase, thus offering QoS guarantees [1-3, 11]. In [1] Lee and Gerla propose a multipath routing algorithm called Split Multipath Routing (SMR) that represents an extension of the Dynamic Source Routing protocol. SMR uses two link-disjoint paths where the traffic is split. The traffic is distributed between the two paths through a per-packet allocation technique. The proposed scheme outperforms DSR because the multipath routes provide robustness to mobility. The multipath are more evident for high mobility speed. In [2], Chen et al. propose a new on-demand, link-state QoS multipath routing protocol in ad hoc networks. This work calculates the end-to-end path bandwidth of a QoS multipath routing under the CDMA-over-TDMA channel model [12, 13, 14]. This protocol can produce a unipath if there is enough bandwidth allocation in the network; otherwise, the path can be split into multi-routes with distributed bandwidth. This dynamic approach to split the bandwidth request over more routes and to use the link state information considered at the destination receiver permits the optimization of the slot allocation and leads to an increase in the success rate in satisfying the source bandwidth request. This routing scheme outperforms the well-known QoS routing protocol of Lin [14]. In [3] Liao, Tseng et al propose a scheme of multipath routing in which the bandwidth reservation is based on the ticket-approach derived by the distributed QoS routing of Narsthedt et al [11].This novel protocol is on-demand and does not collect the global information of the network. This approach offers better scalability for increasing the number of nodes, but reduces the success rate of path finding because of the reservation mechanism based on a hop-by-hop calculation. In [2], Tseng improves this scheme with the optimization of the slot reservation through the use of the link-state information considered at the destination receiver. In [15], Chen and Yu propose another scheme of multipath based on the concepts of spiral-paths. This approach proposed previously in [16], has been extended later for the multipath case. The proposed protocol gives a greater resilience to high mobility, offering an interesting on-line route recovery capability. The channel model used is CDMA over TDMA, as in other routing protocols with QoS constraints. In [17], Nasipuri et al. extend the DSR protocol in order to support the multipath routing. The authors show that the advantages of the proposed on-demand multipah routing are significant for a few numbers of built paths and for long path lengths. In this approach, the multipath is used only in terms of back-up routes. Thus, the traffic is sent on a path that, after its breakage, can be used as the back-up path. This approach reduces the frequency of route discovery, reducing the overhead and increasing the throughput. In [12],Lee and Gerla use a similar idea of multipath with back-up route, but with an application over another well-known routing protocol. The proposed protocol is called AODV-BR and it outperforms the corresponding single (AODV) [18] version in terms of end-to-end delay, throughput and overhead. A similar approach is proposed by Nasipuri and Das regarding the Ad Hoc On Demand Multipath Distance Vector Routing (AOMDV) [19] protocol. AOMDV extends the AODV protocol to the computation of disjoint and loop-free multi-routes. Also, in this case, the multi-routes are used after the breakage of the primary route. This reduces the packet loss by up to 40% and achieves a remarkable improvement of end-to-end delay. As well, the routing overhead is reduced by about 30% through the reduction of route discovery procedures. AODV-BR and AOMDV represent some extensions of the AODV protocol. In the literature, there are also extensions of DSDV or proactive protocol for multipath. For example, in [20], the authors propose a distance-vector multipath routing protocol called MDVA. This approach presents the advantages and the drawbacks typical of the proactive protocols. Thus, the multi-routes is quickly available for the table-driven information state, reducing the delay of the building of the multi-routes. However, the protocol can present the drawbacks of the scalability of the proactive protocol for network with a large size. In [21] a variant of the MDVA is proposed showing a novel protocol that uses the already available topology information to perform load balancing bottleneck avoidance and fairness. A multipath extension to DSR protocol is also proposed by Leung et al in [22], where the routing scheme calculates multi-routes towards a destination, based on end-to-end reliability. Also, for this protocol, the improvements in terms of greater successful packet delivery are shown in the simulation results. In these papers, a novel mechanism to split the bandwidth request among more paths was proposed, and a comparison of the multipath QoS routing with the unipath QoS routing of Lin [13, 14] was considered. In this dissertation we propose an integration of a well-known multipath routing protocol, the AOMDV, with a totally distributed TDMA MAC protocol in order to provide QoS support. The effectiveness of the multiple paths is not obvious because the paths can interfere with each other.. In fact, also two or more paths satisfy the *node-disjointedness* property, that is, they share no common nodes, the *route-coupling* phenomenon can be verified. The only research available addressed this phenomenon using a directional antenna to reduce the *route-coupling* effect. In this dissertation a new multipath algorithm based on the geographic locations is proposed. The use of the geographic locations permits two or more different paths satisfying the *zone-disjointedness* property to be created. Two paths are defined *zone-disjoint* if each node belonging to the first path is not in the transmission range of none of the nodes forming the second path. A correlation factor is inserted to take into account the number of nodes that do not respect this condition.

2.2 The QAOMDV protocol

2.2.1 Overview

This proposal [23], as explained in the following, is based on an integration of the AOMDV with a totally distributed TDMA MAC protocol, the E-TDMA [24]. in order to provide QoS support. Before giving details about this approach (in section 2.2.4, section 2.2.5 and section 2.2.6), some details about the distributed TDMA MAC are given in section 2.2.2 and details about multipath routing are given in section 2.2.3.

2.2.2 Distributed TDMA MAC layer

The bandwidth reservation problem is addressed in the literature through different kinds of MAC protocols such as time-division multiple access (TDMA) or code-division-multiple-access (CDMA) over TDMA [12, 14 , 25, 26, 27]. In [14] a particular node's use of a slot on a link is dependent only upon the status of its 1-hop neighbor's use of this slot. In the TDMA model assumed in this work a node's use of a slot depends not only on the status of its 1-hop neighbor's use of this slot, its 2-hop neighbor's current use of this slot must be considered as well. A brief overview of the MAC protocol and the conflict-free resolution protocol applied in this work are presented below.

2.2.2.1 Five-Phase Reservation Protocol (FPRP)

The Five-Phase-Reservation-Protocol (FPRP) is a distributed, contention-based protocol that establishes TDMA slot assignments using a five-phase reservation process in a rapid and efficient manner guaranteeing a small probability of conflict. The FPRP has no restriction on the topology of the network, except that it requires that every link be bi-directional. A node uses the FPRP to explore its neighborhood. By keeping the reservation process localized and running simultaneously over the entire network, the FPRP is insensitive to the network size. This makes the protocol suitable for a large network. The FPRP does not need the support of additional protocols for medium access control or network exploration. The protocol jointly and simultaneously performs the task of channel access and node broadcast scheduling. As far as the network is concerned the following assumptions are made:

- Nodes keep perfect timing. Global time is available to every node, and it is sufficiently tight to permit global slot synchronization;
- When multiple packets arrive at a node, all of them are destroyed;

A node keeps global time, and knows when a five-phase cycle starts. A reservation cycle has five phases:

- Reservation Request phase (RR): a node which wants to make a reservation sends a Reservation Request (RR). A node which does not transmit listens in this phase.
- Collision Report phase (CR): if a node receives multiple RR in phase 1, it transmits a Collision Report packet (CR) to indicate the collision. Otherwise it is silent.
- Reservation Confirmation phase: a reservation is established in this phase and a node sends a Reservation Confirmation packet to indicate a reservation has been established.
- Reservation Acknowledgment phase: a node acknowledges a Reservation Confirmation packet it just received by sending a Reservation Acknowledgment packet (RA). If a node that has made the request does not receive any RA packet it is isolated and no longer considers itself as a transmitter.
- Packing/Elimination phase: every node that is two hops from a transmitter node which has made its reservation since the last P/E phase

sends a Packing Packet (PP). A node receiving a PP therefore learns there is a recent success three hops away. As a consequence, some of its neighbors cannot contend further for this slot.

The first four phases bear a resemblance to the popular RTS/CTS exchange [28]. It solves the “hidden terminal” problem. If a collision from two hidden terminals occurs at some nodes, both transmitters are notified. It is a scalable scheme that uses a local method in order to involve only nodes within a two-hop radius in the reservation process; thus, it is appropriate for networks of large size. The FPRP’ s distributed nature makes possible multiple reservations at various parts in the network. It is very useful for networks with repeated changes in topology because any node in the network needs advance information about the network itself. It is possible to assign broadcast slots through the usage of the FPRP protocol. These slots are applied in the E-TDMA MAC as a permission to request info slots or broadcast slots. This last ones, called permanent color, is necessary to make the exchange of control schedules between neighbor nodes and it cannot be used to assign info slot (i.e. to exchange data info). For more details let refer to [29].

2.2.2.2 The Evolutionary-TDMA scheduling protocol (E-TDMA)

The E-TDMA is a conflict-free protocol that produces and maintains a transmission schedule, as fast as possible, in a distributed manner. Through it every node makes use only of local information in order to reserve time slots. E-TDMA is a very efficient and robust protocol with a low communication and computation overhead, it is evolutionary or incremental in the sense that updates regard only the parts involved in node mobility or where changes in bandwidth requirements occur. Here a scenario is supposed where an omni-directional antenna transmits on a broadcast channel. In order to avoid the so-called primary interference a node cannot transmit and receive at the same time.

To produce an optimal transmission scheduling is a “hard” problem , in fact to represent a transmission slot through a distinctive color is equivalent to a graph coloring problem, that is NP-complete [30].

A schedule can be:

1. Unicast: it is equivalent to edge coloring;
2. Broadcast: it is equivalent to node coloring;
3. Multicast: every edge connected to the same transmission node has to be colored.

The following assumptions about the network are made:

- Nodes keep perfect timing.
- Global time is available to every node and it is tight enough to permit global slot synchronization
- Every link is symmetric.

E-TDMA consists of two epochs: a Control Epoch when control schedules (*ctrl-schedule*) are produced, and an Information Epoch characterized by information-schedules (*info-schedule*). The first epoch consists of a Contention Phase and an Allocation Phase.

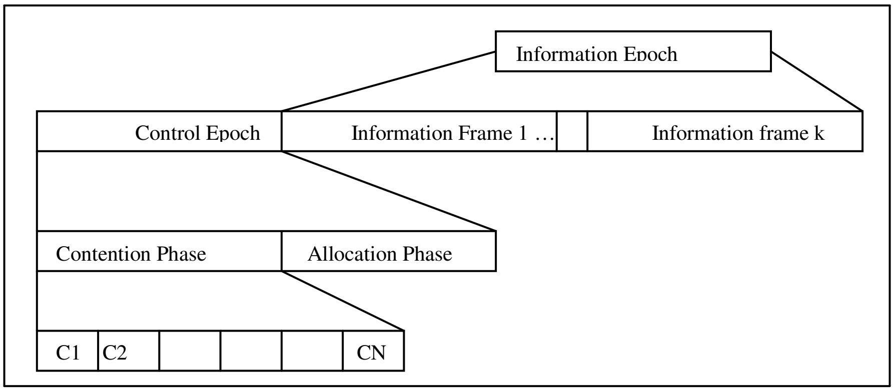


Fig. 2.1. Control schedule and information schedule structure in E-TDMA MAC protocol..

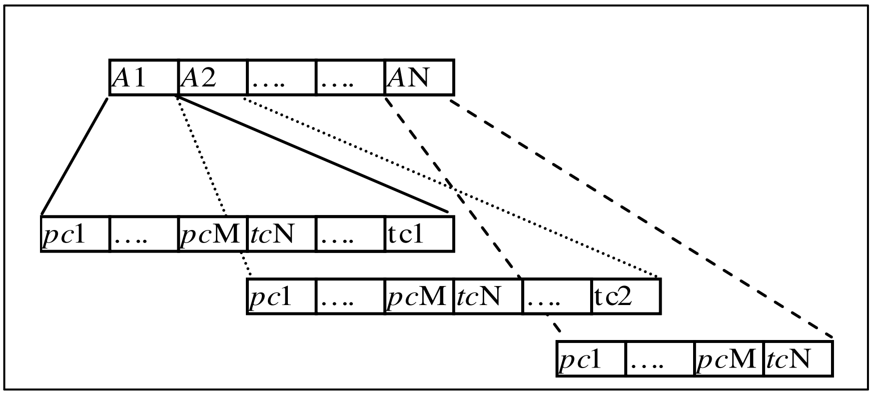


Fig. 2.2. Allocation phase structure (A1 … AN represent frames with different lengths. The first frame A1 has M permanent colors and N temporary colors. pc1….pcM are permanent colors and tcN….tc1 are temporary colors with different lengths. The first frame A1 has M permanent colors and N temporary colors pc1….pcM are permanent colors and tcN….tc1 are temporary colors).

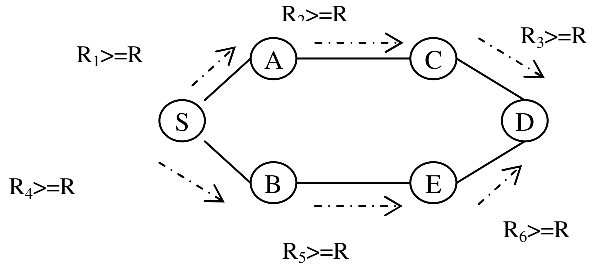
Through the second one, info slots are allocated for the information phase where every produced *ctrl-schedule* corresponds to a frame. In each epoch (each epoch consists of a Control Epoch and an Information Epoch), a contention slot, represented by C_i in Fig. 2.1 and matching to a temporary color, is allocated for every node using the FPRP protocol. Contention phase is divided into N contention slots, each of which is consisted of a number of Five Phase Reservation Protocol (FPRP) cycles. Through the FPRP a node contends to receive a kind of permission called temporary color. This permission is required to each node that have to reserve a permanent color or information slot. An allocation phase has N number of frames (N represents the number of temporary colors and M represents the number of permanent colors). In a frame A (Fig. 2.2), nodes exchange information with their one-hop neighbors by transmitting according to the *ctrl-schedule*. Each frame represents a temporary color (a broadcast slot obtained through the FPRP), an authorization to reserve new information slots or a permanent color. A node has at most one permanent color and one temporary color in the *ctrl-schedule*. Permanent color last is used by a node in the ctrl-schedule in order to permit the exchange of scheduling information between its neighbors (Fig 2.1). The second epoch (Information Epoch) uses info-schedules to transmit user produced traffic in the information frame. Different A frames have different lengths. The first A frame (A1 in Fig. 2.2) has M slots corresponding to the M permanent colors and N slots corresponding to the N temporary colors. The number of slots corresponding to the temporary colors decreases in each following A frame. No single node has global information as the size, the membership or the schedule of the entire network, and for this reason E-TDMA is limited by nodal density and not by the total number of nodes in the network. It works best when the nodes are dispersed and the nodal density is uniform. The contention phase increases as the number of temporary colors increases and the number of permanent colors increases. More details to the mechanism used to assign the color (temporary and permanent) can be found in [24, 29].

2.2.3 Multipath Routing

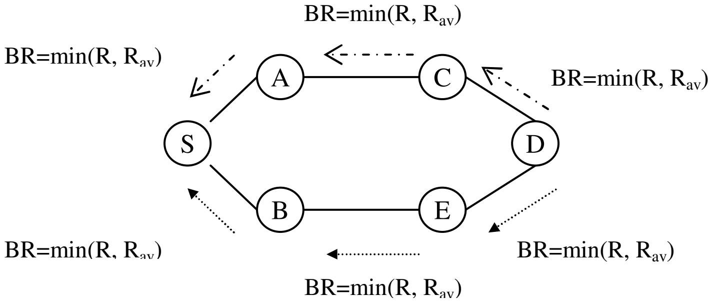
In this work an on-demand, multi-path distance vector protocol for mobile ad hoc networks is considered that is realized as an extension of a well-known, single path routing protocol called Ad hoc On-Demand Distance vector routing. In effect the AOMDV extends the AODV protocol to discover multiple paths between two source-destination nodes. Naturally, multiple paths have to be loop-free and link or node disjoint. The disjoint-ness property is obtained without the use of source routing. The AOMDV computes the multiple paths with minimal additional overhead, contrary to other multi-path routing protocols. It does this by exploiting already available alternate path routing information as much as possible. The simulation study conducted on AOMDV shows that there is a reduction, on the whole, of overhead in the network. Thus, in MANETs, the reduction of overhead is retained to be very important, especially when one considers an environment that is time-slotted, where the slot assignment control increases the overhead. In this way, the resources “consumed” by control packets can be used in a more effective way in the traffic of data. As the AODV is based on a hop-by-hop routing approach, the same is true for AOMDV. Really, AOMDV shares several characteristics with AODV. There is, in AOMDV, a route discovery procedure to find the paths. The fundamental difference between the protocols lies in the number of paths found in each route discovery. The AOMDV permits each intermediate node, not only the destination, to process more than one RREQ with the same sequence number, contrary to the AODV protocol. When a generic source needs of a route to send data traffic to a generic destination, it starts a route discovery process sending a RREQ packet. An intermediate node can receive several copies of the same RREQ packet. In AOMDV, all duplicate copies are examined, but only those which permit the preservation of the loop-freedom property and link-disjoint-ness are considered in building alternate paths. The integration between AOMDV and E-TDMA permit to eliminate the interference problem that is the main problem in wireless network. This is due to the E-TDMA capability to compute, on each path, slots that are conflict-free. In this way two or three parallel paths for a single couple source-destination are characterized by conflict-free slots and can not “interfere” to each other. AOMDV routing protocol does not use the concept of *hopcount*, but it needs a new field in the routing table, called *advertised-hopcount,* as a particular route update rule. A route to a destination, recorded in an intermediate node, can be applied if the RREP includes a forward path that was not utilized in any previous RREPs for this RREQ. If an intermediate node does not have any path to the destination, then it re-broadcasts the RREQ. When the destination receives the RREQ, it copies it and forms the reverse path in the same way as the intermediate nodes. The AOMDV’s authors choose to deploy multiple paths as backup routes. In this way, when a path breaks, if another one is available, it is applied to send data traffic. According to the AOMDV authors’ routing scheme, one path at a time is deployed in order to realize these schemes.

2.2.4 QoS Multipath Scheme 1

A bandwidth reservation mechanism has been considered for the multi-path version of AODV protocol. In particular, a bandwidth reservation algorithm, known in literature as Forward Algorithm (FA), has been applied in our proposal because it can easily match with AODV protocol such as shown in [30]. The FA algorithm has been changed in order to account the multiple routes computation of the AOMDV protocol. The available bandwidth is translated in a number of available slots that can be considered free through a mechanism known in literature as Forward Algorithm (FA). This FA has been adapted for the AOMDV protocol. It is assumed that in a certain instant of time, a generic source S wants to transmit to a generic destination node D and the source requires a minimum bandwidth R (that represents the number of slots required by the source). In our QAOMDV scheme 1, S broadcasts a RREQ packet in the network.



RREQ phase. The source S broadcasts the RREQ packet in which is indicated the bandwidth request R. If the bandwidth required is available along the route the RREQ packet is transmitted to the destination. In this phase the bandwidth is not reserved.



RREP phase. The destination D sends the RREP packet. The bandwidth reserved is the minimum bandwidth between the bandwidth required R and the bandwidth available. Note that the available bandwidth considered is the bandwidth computed in the RREQ phase.

Fig. 2.3. QoS Multipath scheme 1. In the RREQ phase there is the calculation of available bandwidth. Assume in this case that over each link there is a minimum available bandwidth greater or equal to the minimum requested bandwidth. The RREP phase provides the slot reservation.

This packet has to be extended to contain the *R* value and the other fields necessary to the bandwidth computation. We assume to have applications that

can work in a bandwidth interval between a minimum bandwidth R_{min} and requested bandwidth R. A packet extension is due as follows:
<*PB1, PB2, SRT, R,* R_{min},R_{av} >where:

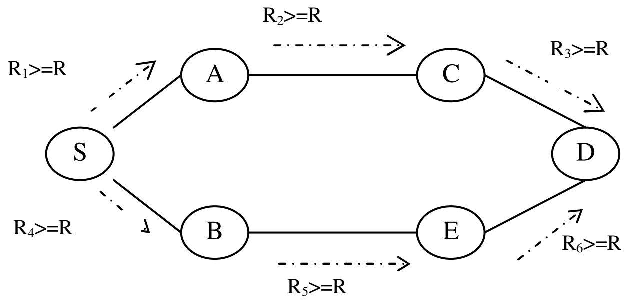
- *PB1 and PB2* are the sets of slots used respectively on a generic link (n_{i+2} -> n_{i+1}) and (n_{i+1} -> n_{i}) with i=m-2,..,k, to support a path $P^k = \{n_m -> n_{m-1} -> \ldots -> n_k\}$ where *m* is the source node and *k* is the *k-th* node belonging to P^k toward the destination..
- *SRT* is the set of slots when a node n_i can transmit without causing interference to its current receiving neighbours.
- *R* is the bandwidth required by the source application in terms of number of time slots.
- R_{min} is the minimum bandwidth level where the source application can work.
- R_{av} is the minimum number of slots available along a path (it represents the maximum available bandwidth).

When the RREQ packet propagates in the network, the algorithm computing the available slots to each link is applied and the bandwidth *R* is reserved if an available bandwidth is discovered on each link. Let us assume R_i is the minimum bandwidth available on each link *i* and $[R_{av}]_j = \min(R_i)$, with $i = m,\ldots,1$ and $m \rightarrow m-1 \rightarrow \ldots \rightarrow 1$ representing the path *j*. To satisfy the required bandwidth, it is necessary that $R_{\min} \leq R \leq R_{av}$ along the path. A source node can decide to set a bandwidth request *BR* and to calculate at the receiver the maximum available bandwidth R_{min}.If there is at least one a link that does not satisfy the condition to have a bandwidth *R,* then one searches for a path with R_{min}. Particularly in scheme 1, both paths (if they exist) are built with quality of service. In this way if a RREQ packet is broadcasted in the network, each intermediate node receiving this packet computes the available slot. Imagine the situation in Fig. 2.3 where two node-disjoint paths exist (note that two disjoint paths are link-disjoint) S-A-C-D and S-B-E-D. Assume that A receives the RREQ from S then A computes the available slot to S for A. The reason that this calculation is done by A and not S is to allow node S to broadcast the RREQ packet to all its neighbours. If A cannot satisfy the request of minimum available bandwidth, then it drops the RREQ packet; however, if there is the minimum available bandwidth, the RREQ packet propagates.

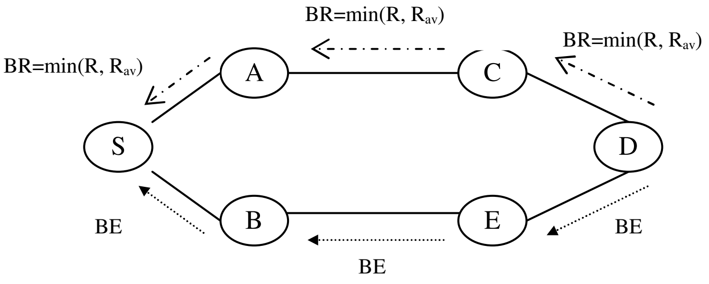
2.2.5 QoS Multipath scheme 2

In the second version of our QoS scheme, we consider that only one path is built with Quality of Service (the AOMDV protocol routing permits the computation of a generic number of paths but we limited the number of multiple paths to 2).

In this case, the RREQ packet is broadcasted by the source and each node receiving this packet computes the available bandwidth.



RREQ phase. The source S broadcasts the RREQ packet in which the bandwidth request R is indicated. Even if the available bandwidth is less than R the RREQ packet is transmitted. Eventually the route that does not satisfy the requirement of bandwidth can be used as backup route



RREP phase. The destination D sends the RREP packet. The bandwidth will be reserved only on the first path satisfying the requirement of bandwidth. The second path is a BE (Best Effort) path used as backup path.

Fig. 2.4. QoS Multipath scheme 2. It is assumed that through the AOMDV, two node-disjoint paths are found. S-A-C-D and S-B-E-D.

If there is no available bandwidth, the request can still propagate. The bandwidth calculation is done as in the scheme 1 but, in this case, when the RREQ packet arrives at the destination, only one path will be built with QoS and the other route will be a BE path.

In Fig.2.4 it is assumed that the RREQ packet traveling the path S-A-C-D arrives before that of the RREQ packet over the path S-B-E-D and that there is the minimum available bandwidth. Contrary to the scheme 1, here an intermediate node that has a path to the destination can reply to the source (with a RREP packet).

This is done here because a path with Quality of Service and another path BE is considered, and advantage can be taken of the intermediate reply for BE path.

When a packet arrives at the destination, it checks to understand whether a reply packet is built for a Quality of Service path. If it is, then the following path will be built as a BE route. In the route reply phase the source can receive more RREP packets indicating the built route.

If the first RREP is associated with a path without QoS (BE path), the application starts to send data packet on this path. However, if the second RREP associates with a QoS path that arrives at the source, the traffic can be switched to the QoS path considering this last one as a primary path. When a session is stopped or a route with reserved bandwidth breaks, the slots reserved on the path with quality are explicitly released. The extensions of the RREQ packet are the same as considered in the first scheme (scheme 1).

2.2.6 Cross Layering between Multi-path Routing and E-TDMA MAC

The interaction of routing and MAC is given by the translation of bandwidth request to routing level in terms of number of slots to MAC layer. Further, the control of the slot assignments that are two-hop away can be obtained through the scheduling updates of the MAC layer and the admission control of the network layer in the route request phase, as explained below.

The unit for bandwidth in E-TDMA is an information slot, which is equal to

$$slot = \frac{l_{\inf o}}{l_{\inf o} + l_{control}} = \frac{n_{\inf o\_slot}}{l_{\inf o\_frame}} (bits / s) \qquad (1)$$

where:

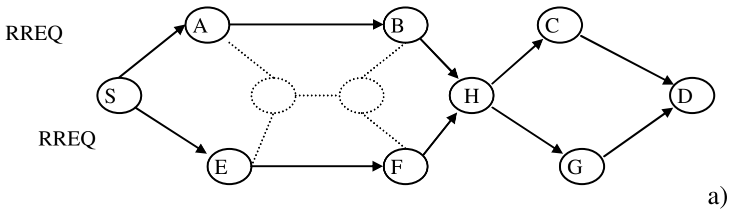
l_{info}=length of information epoch;

$l_{control}$=length of control epoch;

n_{info_slot}= number of bits transmitted in an information slot;

l_{info_frame}=length of information frame;

As is shown in the above formula, if the length of control epoch increases, the number of bits transmitted in the time unit decreases. In this way, if more temporary colors or permanent colors are considered the control epoch is augmented. The impact of the variations of the typical parameters on the AOMDV on MAC E-TDMA is analyzed in [25].



	is_1	is_2	is_3	is_4	is_5	pc
S	Trans (A, E)	Recv, A	Recv,E	Idle	Idle	pc1
A	Recv, S	Trans (B)	Recv, B	Idle	Idle	pc3
B	Block, t	Recv, A	Trans (H)	Block, t	Block, t	pc2
C	Recv, H	Trans (D)	Block, t	Block, t	Block, t	pc3
E	Recv, S	Block, t	Trans (F)	Recv, F	Idle	pc5
F	Block, t	Block,t	Recv, E	Trans (H)	Block, t	pc1
G	Block, t	Trans, D	Block, t	Block, t	Recv, H	pc5
H	Trans (C)	Block,t	Recv, B	Recv, F	Trans (G)	pc2
D	Block, t	Recv, C	Idle	Recv, F	Block, t	Pc4

b)

Fig. 2.5. Scheduling process in RREQ Phase. It is assumed that AOMDV refers to the link-disjoint version. a) Route request propagation in two link-disjoint paths. b) Schedule updates to propagate the RREQ packet to build two link-disjoint paths S-A-B-H-C-D and S-E-F-H-G-D. Assume that A-E, B-F and C-G are respectively two hops away.

The average frequency with which a node can make reservations is much lower than the frequency in which the control epoch is executed. Concerning the bandwidth request BR_i for transmission to an one-hop neighbor n_i, it is considered in bps and converted in number of slots. It can be calculated upon the arrival of a packet addressed to n_i with the following iterative algorithm. Where

L is the packet size and *T* is the time elapsed since the arrival of the last packet to n_i, α is a smoothing factor for the jitter of packet arrival, then the corresponding number of slots is given by

$$BR_i = ceil\left(\frac{BR_i}{slot}\right) \quad (3)$$

In the simulation, there will be used an α value of 0.1 according to the simulations of [14,17]. Naturally the mechanism described above is certainly used in the case of BE protocol to accommodate both the broadcast and the unicast slots. Referring to the QoS routing scheme the number of slots is given by

$$BR_i = ceil\left(\frac{\min(R, R_{av})}{slot}\right) \quad (4)$$

It is important for E-TDMA to upgrade the schedules as frequently as possible, provided that it does not incur too much overhead. When a node loses an information slot or its permanent colour if it still needs it will try to reserve another in the next control epoch. To reduce the duration of the collisions, it is desirable to update the schedules more often and, thus, have short information epochs. If the length of the control epoch is not reduced accordingly, this increases the overhead of E-TDMA. For this reason, the author of E-TDMA used in its simulations one temporary color.

Fig. 2.5 shows the propagation of the RREQ packet through the AOMDV protocol and the scheduling formation when the RREQ packet is transmitted in the network. 5 *information slots* (is_i) and 5 *permanent colors* (*pc*) are used. In this case, an intermediate node that has processed an RREQ packet does not discard another RREQ packet because it can contribute to building a backup path that is link or node disjoint. In the figure, we assume having two link-disjoint paths that are S-A-B-H-C-D and A-E-F-H-G-D.

The attribution of slots can be done in different frames. For this reason, a slot assigned to a node in a particular frame can be used in the next frame after its releasing. Here, assigned slots are broadcast because the RREQ needs to be flooded in the network

Different states are associated with the nodes:

- Trans: a node can transmit in the correspondent slot; it is a conflict-free slot. (i.e. in Fig 2.5 b), considering the first row and the first column we have that node S transmits to nodes A and E in the slot is_1).
- Recv, X: a node receiving by a generic node X. (Remember that we are in a radio environment; for this reason a node cannot transmit and receive simultaneously, i.e. in Fig. 2.5 b), considering the second row and the first column we have that node A receives from S in the slot is_1.
- Block, t: a generic node cannot transmit because there is a node transmitting two-hops away and a collision can happen if it transmits (i.e. in Fig. 2.5.b), considering the third row and first column, node B is

blocking transmission in slot is_1, this is due to the fact that S is transmitting in this slot to A and E)

- Idle: a node can, potentially, transmit or receive in the corresponding slot (i.e. in Fig. 2.5 b), considering the first row and the quarter column node S is Idle in the slot is_4, and no state has been fixed for this).

A cross-layering approach between AOMDV protocol, which permits finding multiple paths that are link or node disjoint, and a E-TDMA MAC layer with time-slotted management, is shown in Fig.5. The rows in Fig. 5 b) represent nodes in the network and the columns represent time-slots (is_i) and permanent colors (pc) respectively. The assignment slots are realized in this way: assume that S broadcasts a RREQ packet, in a time-slotted environment, to make it the source node S has to require a broadcast slot. This is done through the little contention in the channel realized through the FPRP cycles. If in a ctrl-schedule it is available a broadcast slot node S will receive this, which is called temporary color (remember that this slot is a kind of permission that a node has to receive to reserve other information slots [24]). Naturally the assigned slot is conflict-free in the sense that in the neighborhood there is not any other node that receives the same slot. The neighborhood is indicated as the nodes one-hops or two-hops away. This mechanism is propagating while the RREQ packet is propagating in the network. In this way the nodes A and E that receive the RREQ packet by S have to transmit this packet (if it is assumed that they do not have a route to the destination in the routing table) and they have to acquire a broadcast slot to re-broadcast this packet. In this example A and E are two-hops away. This is a complication because, in the same frame, they cannot have the same slot. In this example the RREQ packet propagation is realized in different frames.

In the same way the slots are assigned if the RREP packet that travels on the reverse path is considered. The difference between the travel of the RREQ packet in the network and the RREP packet is that the latter is propagated to a precise node; for this reason when an RREP packet is processed to a generic node the latter requires a unicast slot instead of requiring a broadcast slot.

2.2.6.1 Multipath Forward Algorithm (MFA)

It has been seen that to consider the maximum bandwidth for a given path is intractable so alternatives approximating the optimal solution are sought. Here an algorithm that searches for a local maximum is considered, which ends up to sub-optimality . This algorithm is called the Forward Algorithm (FA). The algorithm is simple and the information required for each iteration in this algorithm is limited and local; thus, this algorithm lends itself easily to distributed implementation. It is clear that the FA, called Multi-path FA (MFA) for the multi-path case, is not a routing protocol, and it needs to be used together with a routing protocol to perform QoS routing. In its original version, it is well matched to the route discovery mechanism of AODV and the main characteristic of this algorithm has been maintained to be suitable on AOMDV. The MFA is used in the route discovery phase to make an admission control (no reservation are made in the Route Discovery Phase). The reservation process is realized, instead, in the Route Reply Phase. Each node receiving an RREQ packet by a one-hop at the up-stream, calculates the available bandwidth. Suppose that a path is considered $\langle n_m \rightarrow n_{m-1} \rightarrow \ldots n_k \rightarrow \ldots \rightarrow n_0 \rangle$. The MFA iterates over the hops from the source to the destination; the term "forward" refers to the direction in which the iteration is carried out. Suppose the bandwidth is partitioned into a set of time slots $S = \{s_1, s_2, s_3, s_4, s_5, s_6, s_7\}$, which consists of a frame. Naturally, if node n_i transmits to node n_j in slot s_k, node n_j itself does not transmit and node n_i is the only transmitting neighbor of n_j in that slot. Let PB^k_i as the slots used on link ($n_i \rightarrow n_{i-1}$) to support FP^k = $\langle n_m \rightarrow n_{m-1} \rightarrow \ldots n_k \rightarrow \ldots \rightarrow n_0 \rangle$ where FP^k represents the partial path on entire path P (that originates from the source and extends to node n_k) and $FP^0 = P$. Referring to the variable PB1 and PB2 used at the network layer we have $PB1 = PB^{k+1}_{k+3}$ and $PB2 = PB^{k+1}_{k+2}$.

```
If  m = 1
        $PB^0_1 = LB^0_1$,  where LB = Link Bandwidth
If  m = 2
        $(PB^0_2, PB^0_1) = BW_2(LB_2, LB_1)$
If  m >= 3
        $(PB^{m-2}_m, PB^{m-2}_{m-1}) = BW_2(LB_m, LB_{m-1})$
                                        for k = m-3 to 0 do
        $(PB^k_{k+3}, PB^k_{k+2}, PB^{kl}_{k+1}) = BW_3(PB^{k+1}_{k+3}, PB^{k+1}_{k+2}, LB_{k+1})$
        end;
```

A set of transmission slots achieving BW(P) is

$$TS^p_k = \begin{cases} BW_1(PB^0_k, BW(P)), & k = 1, 2, 3. \\ BW_1(PB^{k-3}_k, BW(P)), & 4 <= k <= m \end{cases}$$

Where

$BW(P) = BW(FP^0) = |PB^0_1|$;

and

$BW_1(IN,n)$ is a function that chooses n elements from the input

$(OUT_2, OUT_1) = BW_2(IN_2, IN_1)$ is a function that outputs two disjoint sets of the same size and each output is a subset of the input

$(OUT_3, OUT_2, OUT_1) = BW_3(IN_3, IN_2, IN_1)$ is a function that requires two of the inputs, IN_2 and IN_3, to be disjoint and have the same size.

The output of BW_3 are three disjoint sets with the same size.

FA is substantially a greedy scheme because local maximal bandwidth from the source to the next hop is calculated. Only the set of slots on the three links closest to the end n_k are required for the input. The path bandwidth $BW(FP^k) = |PB^k_{k+1}|$ is determined by the three links closest to node n_k. Through the interaction of the Multi-path FA (MFA) with the multi-path protocol routing, we want to take advantage of the MAC scheme that permits the calculation of schedules that are conflict-free in an evolutionary manner, as well as the advantage of a protocol as AOMDV that outperforms in throughput delay, and overhead on a unicast reactive protocol well-known as the AODV.

2.2.7 Simulation Results

This section presents some simulation results. To evaluate the performance of the two multi-path QoS routing schemes with back-up routes on the same MAC protocol, an environment is considered that consists of 30 and 40 mobile hosts roaming uniformly in a square area of 1000X1000 m. Each node moves randomly with a velocity chosen uniformly randomly from [0.3 , v_{max}], v_{max} varying in the range 0.3 , 5, 10, 15 and 20 m/s. Radio transmission range for each node is fixed to 250 m. Simulation parameters adopted in the simulation campaign are summarized in Table 2.1. Random movement of the node is modeled according with the Random Way Point model. At the beginning, the nodes are randomly placed in the area and each node remains stationary for a pause time. The node then chooses a random point in the area as its destination and starts to move towards it. After reaching a destination, a node pauses again and starts to move towards another destination as previously described. The simulation study is realized with NS2 [31]. The data traffic is generated with CBR sources, where the source and the destination are chosen randomly. Each simulation of 500 seconds 10 times was run to get an average result for each simulation configuration (to enter in 95% confidence interval). The performance of our schemes of QoS multi-path routing was compared to the QoS unipath AODV and the correspondent BE versions. The main objective here is to evaluate the effectiveness of AOMDV on a new MAC protocol [26, 27] and, especially, evaluate the performance of a new multi-path QoS routing scheme in the presence of mobility-related route failures and elevated traffic. Other objectives include understanding the effect of traffic patterns. At the MAC layer, both the standard IEEE 802.11 [32] and the Evolutionary-TDMA are used. The simulation parameters are shown below:

- QoS Success-Request Ratio (QSRR): the number of successful QoS route requests divided by the total number of QoS route requests from source to destination

- Slot-Utilization (SU): is obtained by the ratio of number of unicast and broadcast slots over the requested number of slots.
- Throughput: is obtained by dividing the number of data packets delivered at each destination with the data packets originated by the sources.
- Normalized Overhead: the total number of “transmitted” routing packets over the delivered data packets.
- Average end-to-end delay: this includes all delays caused by buffering during route discovery phase, queuing delay at the interface, retransmission delay at the MAC, propagation and transfer times;

AOMDV in the plots refers to the link disjoint version of the protocol. QoS-Multipath-scheme2 (2_paths) the QAOMDV scheme2 were indicated as described above and the maximum number of multiple paths that can be built were simply specified in brackets. Unipath QoS indicates the AOMDV with the FA to calculate, at network layer, the available slots.

Table 2.1.Simulation Parameters

Input Parameters	
Simulation area	1000x1000 m
Traffic sources	CBR
Number of sources	28, 42
Sending rate	10, 20 packets/s
Size of data packets	64 bytes
Transmission range	250 m
Simulation Time	500 s
Mobility Model	
Mobility Model	Random Way Point
Pause time	10 s
Mobility average speed	0.3 ,5,10,15,20 m/s
Traffic pattern	Peer-to-peer
Simulator	
Simulator	NS-2 (version 2.1b6a)
Medium Access Protocol	E-TDMA, IEEE 802.11
Max Packets for a source	3000, 5000
Link Bandwidth	2 Mbps
Confidence interval	95%

Unipath-ETDMA is the AODV over the E-TDMA. The original AOMDV was indicated with Multipath-802.11 computing, in this case, two paths. The QoS-Multipath-scheme1(2-paths) is the QAOMDV scheme1. Multipath-ETDMA(2_paths) refers to the AOMDV calculating two paths on E-TDMA. Finally, the unipath-802.11 indicates the AODV on IEEE 802.11. Different scenarios were analyzed to validate our scheme. Here we consider the results of two different scenarios. Specifically heavy data traffic scenarios were considered, called Scenario 1, with 40 nodes, 42 sessions and a data rate of 20 pkts/sec and a light data traffic scenario called Scenario 2, with 30 nodes, 28 sessions and a data rate of 10 pkts/sec.

2.2.7.1 Scenario 1 (Heavy Traffic Load)

In Fig. 2.6 and Fig. 2.7, the percentage of delivered data packets on sent data packets and the average end-to-end delay in the network vs speed are shown. Our scheme proposed here outperforms the QoS unipath version in both parameters, throughput and delay. The percentage of delivered data packets over sent data packets is larger in the AOMDV with respect to the AODV because when a path fails there is another path available. On the contrary, AODV has to resort to a new route discovery when a path fails. This has a positive impact on the delay because the latency delay due to the route discovery is smaller if it is possible to have an alternate path available when the primary path fails.

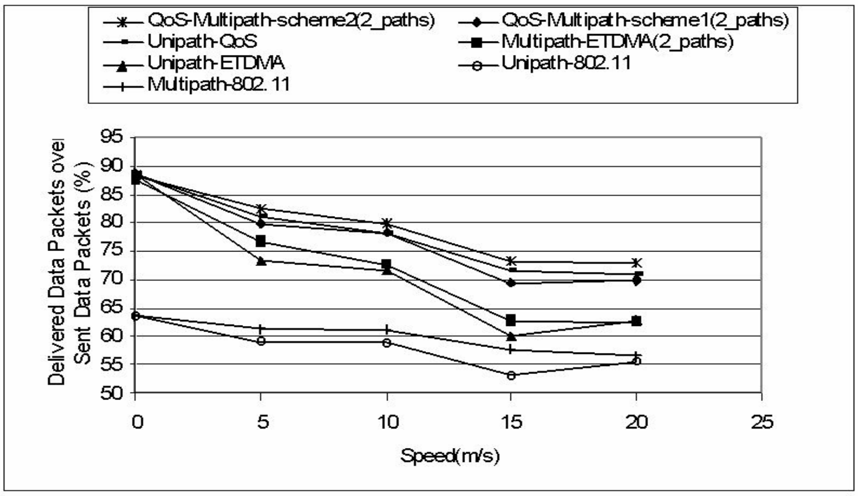


Fig. 2.6. Data throughput vs maximum speed for different routing scheme and MAC layers (E-TDMA and IEEE 802.11).

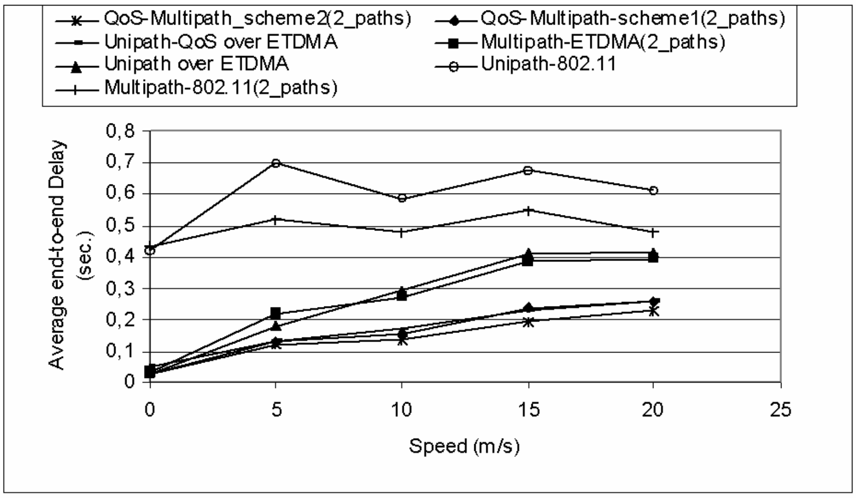


Fig. 2.7. Average end-to-end data packet delay vs maximum speed for different routing scheme and MAC layers (E-TDMA and IEEE 802.11).

Average route discovery latency is the time a data packet spends to wait for a route at the source and through the use of the multi-path we have a reduction of this parameter that has an effect on the whole delay. The original AODV changes routes too frequently. If there are frequent route changes this requires frequent bandwidth reservations and this implies a burden in E-TDMA. The QoS routing protocol permits congestion to be reduced. Fig. 2.7 shows that the quality of service has an impact that is very positive on the delay. In effect, if there is a path with quality of service, the delay introduced by the collision with the MAC layer to obtain the wireless channel is reduced through the slot reservation. In this way, a packet can be immediately sent. For this reason advantage can be taken of each mechanism together, the multi-path and the quality of service. The characteristics of quality of service were added to the positive characteristics of the multi-path routing. This quality of service is characterized by one slot. Through the scheme, if there is a path that has at least one slot, it is found. The normalized overhead vs speed is shown in Fig. 2.8. Even though AOMDV significantly reduces the number of route discoveries, it has more overhead per route discovery. This is because of the use of the additional RREPs used to form multiple paths. The Normalized Control Overhead increases when the Unipath over E-TDMA with respect to the Unipath over 802.11 is considered and the speed increases. This is due to the fact that when the speed increases and there are more route failures in the network, frequent bandwidth reservations are required and this puts a heavy burden on E-TDMA. The latency to obtain a new path increases.

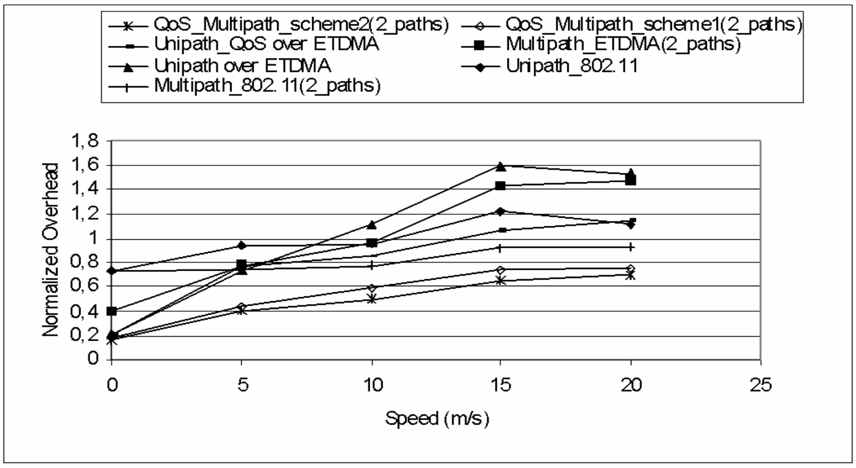


Fig. 2.8. Normalized Routing Protocol Overhead vs maximum speed for different routing schemes and MAC layers (E-TDMA and IEEE 802.11).

The impact on the delay is not effective because the paths obtained are better than paths obtained with the 802.11. As far as the throughput is concerned also when higher speed has been considered the E-TDMA is more effective than the 802.11 even if the unipath version of the routing protocol is considered. This is due to the fact that dropped packets depend also from the network congestion and not only to the temporary failure.

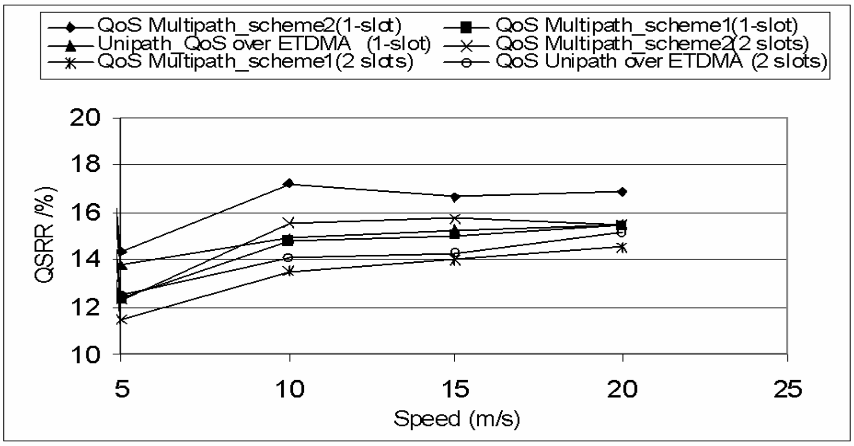


Fig. 2.9. Ratio between requested QoS paths and built QoS paths (QSRR) vs maximum speed for different routing scheme and MAC layers (E-TDMA and IEEE 802.11).

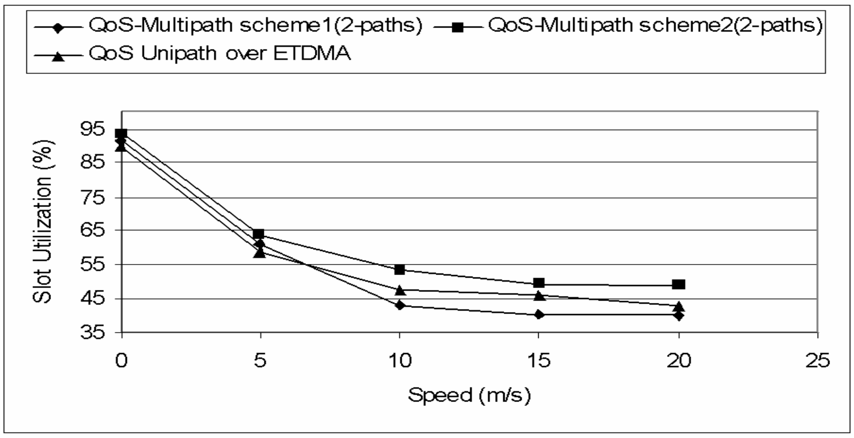


Fig. 2.10. Percentage of used slots during the simulation for the different schemes presented in this work.

The capability of E-TDMA to reduce the interference typical of IEEE 802.11 for heavy traffic permits a further gain in terms of data throughput and in reducing the end-to-end delay.

Through the use of the E-TDMA the congestion of the network is very limited because the TDMA paradigm permits paths to be built in which the probability of the slots being conflict-free is very high.. The ideal condition for E-TDMA is a static network, because once a slot is reserved it remains conflict-free. Average route discovery latency is the time a data packet spends waiting for a route at the source. In Fig. 2.9, we can see a parameter called QoS Success Request Ratio (QSRR), that is the number of built QoS paths divided by the number of required QoS paths vs speed. Naturally, an efficient QoS routing is achieved with a high QSRR. As expected from the results obtained above, better QSRR for the proposed QoS scheme 2 is obtained. In Fig. 2.10 the Slot Utilization is shown for Scheme 1, Scheme 2and E-TDMA. Scheme 2 permits a better usage of slots to be obtained.

2.2.7.2 Scenario 2 (Light Traffic Load)

In Fig. 2.11 the Data Throughput for a light traffic load with 28 sessions is represented. It is possible to observe that the routing protocol over E-TDMA always offers better performance in comparison with AODV (called unipath over 802.11) and the AOMDV (called multi-path 802.11) over 802.11. This is due to the higher throughput offered by the MAC layer as shown also in [26]. The multi-path scheme 2 is always better than the corresponding multi-path scheme 1 and the unipath with QoS over E-TDMA of Corson [24].

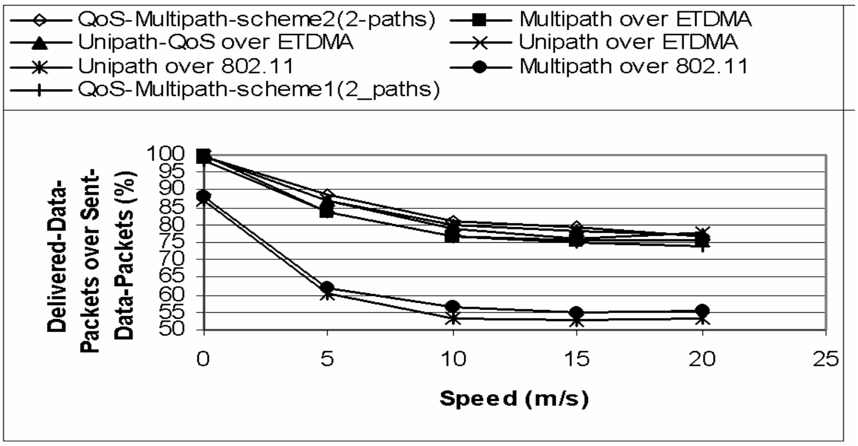


Fig. 2.11. Data Throughput vs maximum speed for different routing schemes and MAC layers (E-TDMA and IEEE 802.11), 28 sessions.

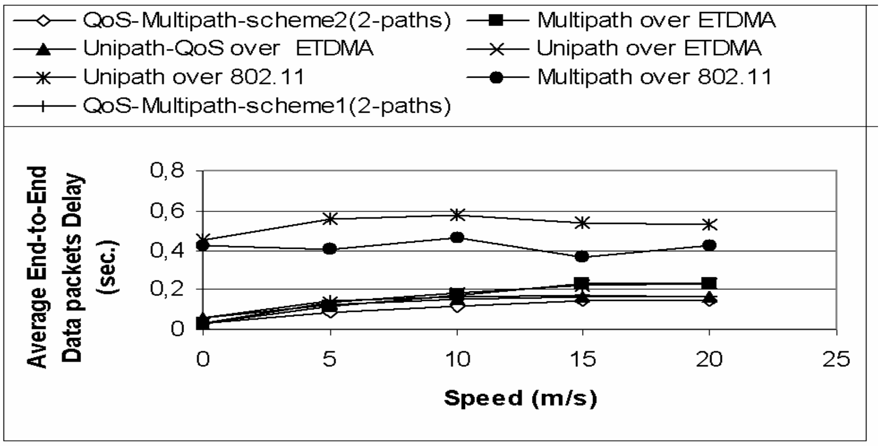


Fig. 2.12. Average end-to-end data packet delay vs maximum speed for different routing scheme and MAC layers (E-TDMA and IEEE 802.11), 28 sessions.

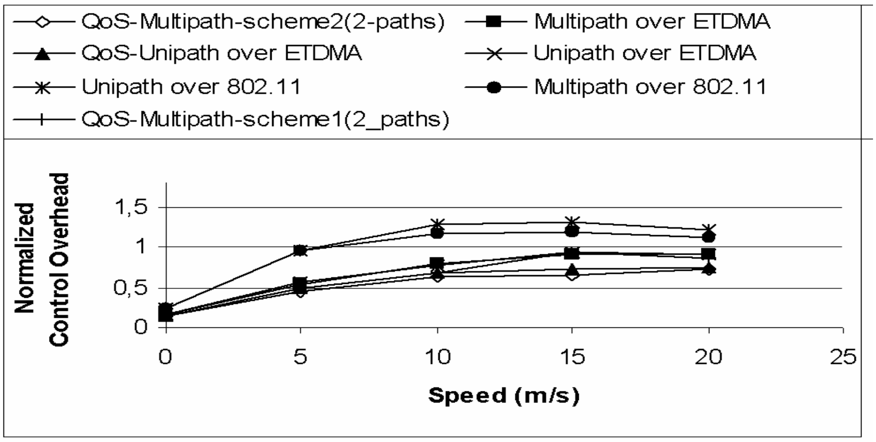


Fig. 2.13. Normalized Routing Protocol Overhead vs maximum speed for different routing scheme and MAC layers (E-TDMA and IEEE 802.11), 28 sessions.

Light traffic load does not emphasize the improvement of multi-path in comparison with unipath. Specifically, using multi-path scheme 1 is worse than using unipath with QoS. This is due to the reduced success rate in finding the multi-route with QoS constraints. Average end-to-end delay (Fig. 2.12) and normalized control overhead (Fig. 2.13) show a similar slope of the scenario with heavy data traffic. The reduction of the delay in routing protocols considered over E-TDMA with respect to IEEE 802.11 (Fig. 2.12) is due to the fact that with E-TDMA every transmission is collision-free, which means also that its packet throughput increases steadily until every slot is reserved. Naturally because a CBR source always transmits at the same rate, under heavy traffic E-TDMA cannot reserve enough slots. The network becomes over-loaded and packets are delayed and dropped. In these latter scenarios no meaningful difference of performance is obtained as far as the multipath and the unipath is concerned. This is due to the fact that the number of nodes considered in the network is smaller than in the previous case. In this way a smaller number of multiple paths can be found and the impact of multiple path is less. This is shown also in Fig 2.13 where Normalized Control Overhead is shown. In fact, the difference between the multipath version of routing protocol and the unipath version is slight with respect to the previous scenario considered. If we monitor the number of multiple paths found in the latter scenario compared to the first scenario we find a small number of multiple paths available. For this reason the throughput (Fig. 2.11) is just a little better compared to the unipath version, the delay (Fig. 2.12) is just a little better with respect to the unipath version and finally the impact of overhead is just a little better with respect to the unipath version (Fig. 2.13). In summary, the multi-path routing over E-TDMA offers good performance for heavy traffic load and in the case of the multi-path scheme

2 the benefits are served also for a light traffic load. Regarding the E-TDMA we can conclude that this protocol permits conflict-free slots to be reserved and even if at the higher speed there is a higher latency to find slots and consequently to permit the data communication to start, this protocol outperforms the IEEE 802.11.

2.3 The Geographic Multipath Protocol

The problem of selecting an optimal set of paths from all available paths is nontrivial and often debated. Throughput, delay, path reliability and control overhead are some common optimization objectives for using multipath routing. One of the most used criteria in selecting paths is the disjointedness between paths. There are different types of disjointedness: two or more paths are node-disjointed if they share no common nodes except the source and destination nodes. Similarly, paths are link-disjointed if they share no common links. Node-disjointed paths are also link-disjointed. These criteria do not ensure a high effectiveness because the *route-coupling* phenomenon can be verified during the simultaneous use of multiple paths. The *route-coupling* phenomenon is caused by interference during the simultaneous communication through multiple paths between a pair of source and destination. This phenomenon severely limits the performance gained by multipath routing. Using *node-disjointed* multiple paths to avoid the *route-coupling* phenomenon is not at all sufficient to improve the routing performance. In this work a new reactive, geographic multipath protocol, the Geographic Multipath Protocol (GMP) routing for ad hoc networks is proposed. A first work addressing the problem of the *route-coupling* was realized in [33]. The approach used by the authors is to consider the use of the directional antenna to compute disjointed paths. In the GMP multiple paths that are *zone-disjointed* are built (if two or more similar paths exist). In order to ensure the paths built through GMP are *zone-disjoint* they have to be *node-disjoint*. The *node-disjointedness* property and the *loop-free* property are based on a mechanism analogous to this used in AOMDV protocol [34]. Two or more paths are *zone–disjointed* if they share no nodes that are in the transmission range with each other. GMP searches for multiple paths that are physically twice the transmission range from each other. The GMP is based on a simple approach. Each node knows its own geographical location and each node knows the physical location of its neighbor. When a source node S has to transmit data packets to a destination node D, S verifies whether there is a fresh path to this destination in its routing table. If there is not a similar path the source node S broadcasts an RREQ packet. The RREQ packet contains the geographic location of the source node. Each node receiving this RREQ packet controls whether a path to the destination is present in its routing table. If a similar path is not

present in the routing table the packet is broadcast again. Two different list of nodes are considered: the first-hop and the last-hop node lists. When an intermediate node receives an RREQ packet from a node it verifies whether it is "first-hop" node (neighbor to the source) and if it is, it records its ID and its location in the first-hop list. When an intermediate node receives an RREQ packet it controls whether an RREQ packet with the same first-hop has already been examined. If not it records the neighbor receiving the RREQ and broadcasts the RREQ packet if a path to the destination required is not present in the routing table. Once an RREQ packet arrives at the destination two different situations are possible: 1) a path already exists; 2) a path does not exist. If the first situation is verified the destination node examines the geographical location of the node from which it received the RREQ and the geographical location of the first-hop. If either the first-hop and the last-hop are sufficiently far (the distance between the two first-hop nodes is at least twice the transmission range and the distance between the two last-hop nodes is at least twice the transmission range) from, respectively the first-hop and the last-hop of the other path, it records the node (its ID and its geographical location) from which it received the RREQ in the last-hop list and sends an RREP packet. If the geographical location of the node that has sent the RREQ is not sufficiently far away from the last hop of the other path or the location of the first-hop of the first path is not sufficiently far away from the first-hop of the second path the destination sets a *WAITING* state for the request to examine eventually other RREQs for different paths. This *WAITING* state is managed through a timer. When this timer elapses the different requests are examined by the destination that chooses the better path on basis of the geographical distance between the first-hop and the last-hop of the first path and respectively the first-hop and the last-hop of the second path. The pseudo-code of our approach is shown in Fig. 2.14. To better understand the algorithm an example is made (Fig.2.15 and Fig. 2.16).
Assumption: all the nodes in the networks have the same transmission range.

Definition 1: the *interference-factor* represents the number of nodes, in two paths, whose distance is less than twice the transmission range of the nodes.
Definition 2: two multiple paths satisfy the *zone-disjointedness* property if its *interference-factor* is null.

In practice, through the *interference-factor* we measure how much the two paths interfere with each other. It can be considered as a quantification of the *route-coupling* phenomenon. The GMP searches for multiple paths satisfying the *zone-disjointedness* property; hence the GMP searches for multiple paths with the *interference-factor* null (Fig. 2.17). If two similar paths are not found in a reasonable time, GMP searches for two paths with the minimum *interference-factor*. It is reasonable to conclude that the intermediate nodes in a generic path will be far away from each other if the first-hop nodes and last-hop node are far.

```
Algorithm: An intermediate node y receives an RREQ packet from a node x

A node y receives an RREQ packet from a node x
if (y is not the destination)
        if (y is a first-hop)
                y inserts its ID and its geographical location in a first-hop list
        else if (in the Routing Table of y does not exist a path to the destination)
if (the same RREQ packet with the same first-hop has already received from y)
                y drops the packet
else
/*y has received the same packet with a different first-hop or y has not yet received the RREQ packet*/
                1) y records the ID's neighbor from which it received the RREQ packet
                2) y broadcasts the RREQ
else //y is the destination
if (a path already exists)
                1) y computes the distance $d_1$ between the first-hop nodes of the two paths (the first path and the path we will build)
                2) y computes the distance $d_2$ between the first-hop nodes of the two paths (the first path and the path we will build)
                if (d1 >= TR and d2 >= TR)
                //TR is the transmission range
                y sends an RREP packet immediately
                else
                        y sets the WAITING state for x
```

Fig. 2.14. Pseudo-code of the algorithm to compute zone-disjointed paths.

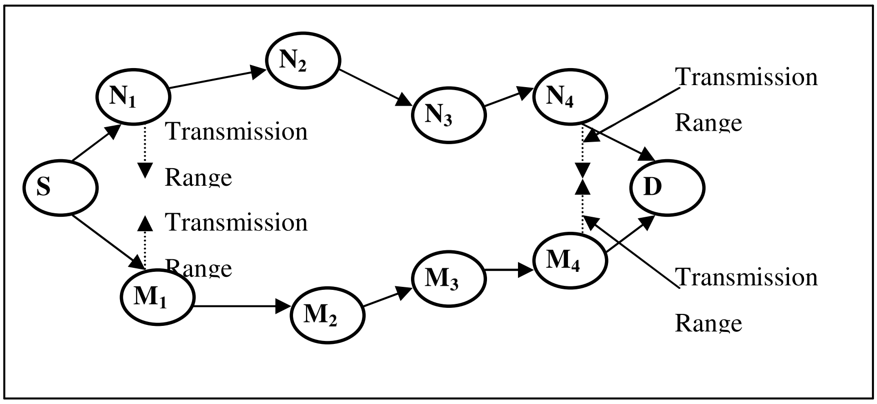


Fig. 2.15. The first path is S-N1-N2-N3-N4-D. When the second RREQ packet arrives at the destination, D computes the distance between the N1 and M1nodes that are the first-hop nodes respectively for the first and the second path. Moreover, D computes the distance between N4 and M4. In this case the distance between the firs-hop nodes and the last-hop nodes is at least twice of the transmission range, then D can reply with an RREP packet to build the S-M1-M2-M3-M4-D path.

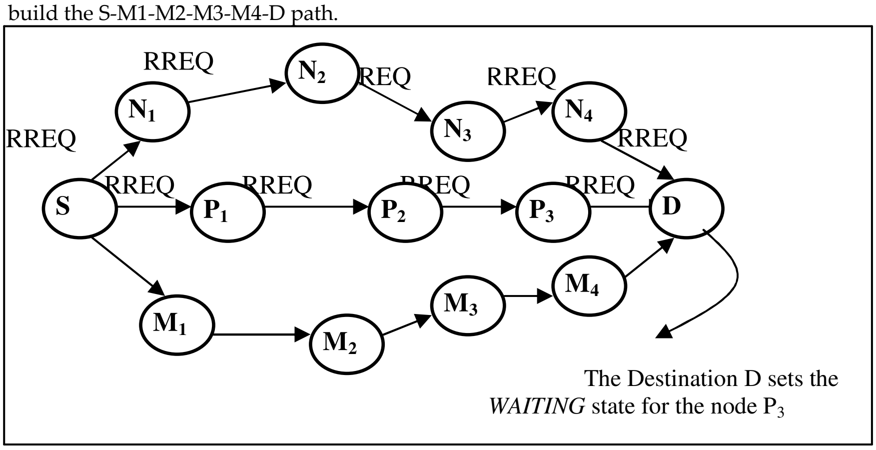


Fig. 2.16. The first path is S- N1-N2-N3-N4-D. A second RREQ packet arrives at the destination D from P3. D computes the distance between the first-hop nodes N1 and P1 and computes the distance between the last-hop nodes N4 and P4. Both distances do not satisfy the zone-disjointedness property. D places the P3 node in the WAITING state. In this case another request arrives at destination D from M4 and GMP will choose this as the second path.

2.3.1.1 Performance Evaluation

The simulations are conducted using NS2 [31]. The effectiveness of the proposal was studied on the standard MAC protocol IEEE 802.11 [32]. Different simulation campaigns were conducted varying the number of nodes in the simulation area to show the effectiveness of our approach in order to diminishes the *interference*-factor. In fact, the number of nodes considered is 20, 30 and 40 nodes in the same simulation area. Two different algorithms were compared: 1) the algorithm introduced in the above section characterizing the GMP routing protocol that will be called here GMP; 2) a Multipath algorithm based on the AOMDV in which data are sent at the same time on two different multiple paths.

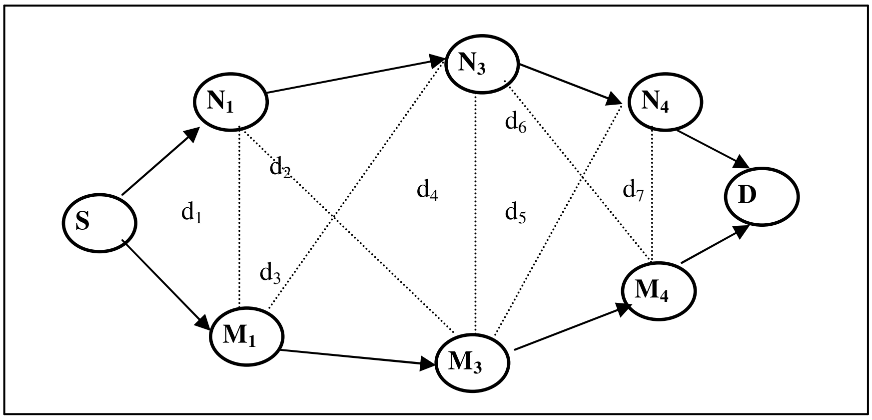


Fig. 2.17. Assume d_1 is the distance between N_1 and M_1, d_2 the distance between N_1 and M_3, etc. Moreover, assume all the distance from $d_1$to d_6 are greater than twice the transmission range of each node. d_7 is smaller than the twice the transmission range. In this case the interference-factor is 1.

This latter protocol does not consider the computation of the distance to choose the second path but selects simply the first request to build the second path and it will be called here Multipath. Nodes are randomly placed over 300 x 600 sq. meter area. 25 nodes are randomly chosen to be CBR (constant bit rate) sources, with a time lag, each of which generates a 64-byte data packets to a randomly chosen destination. Each source is characterized by a rate of 20 pkts/sec. The transmission range of a node is constant and is 100 m. Random movement of the node is modeled according to the Random Way Point model. At the beginning, the nodes are randomly placed in the area and each node remains stationary for a pause time. The node then chooses a random point in the area as its destination and starts to move towards it. After reaching a destination a node pauses again and starts to move towards another destination, as previously described. The speed of the movement follows a uniform distribution between 0 and the maximal speed *v*. Different network scenarios for *v* = 0, 5, 10, 15, 20 m/s are generated. This process is repeated for the duration of the simulation, which is 1000 seconds. The set of parameters used is listed in Table 2.2.

2.3.1.2 Results

In Fig. 2.18 the comparison of the *interference-factor* of the GMP and the Multipath is shown. The node density is varied. As the number of nodes in the system increases the *interference-factor* too increases in both the protocols. The *interference-factor* of the Multipath is higher than those of the GMP.

Table 2.2.Simulation Parameters

Input Parameters	
Simulation area	300x600
Traffic sources	CBR
Number of nodes	20, 30, 40
Sending rate	20 packets/s
Size of data packets	64 bytes
Transmission range	100 m
Simulation Time	1000 s
Mobility Model	
Mobility Model	Random Way point
Pause time	10 s
Mobility average speed	0.5 ,5,10,15,20 m/s
Simulator	
Simulator	NS-2 (version 2.1b6a)
Medium Access Protocol	IEEE 802.11
Link Bandwidth	2 Mbps
Confidence interval	95%

When the number of nodes increases the *interference-factor* of the multipath increases more rapidly than in the GMP. This is due to the GMP using the *WAITING* state and "wait" before creating a second path. In a denser network the probability that two nodes are neighbors is higher but also the probability of having an alternative path with a lower *interference factor* increases. Finally, the GMP computes the second path on the basis of the distance between the first-hop nodes of two paths and last-hop nodes. In this way it is likely the intermediate nodes forming the first path will be farther than the intermediate nodes forming the second path.

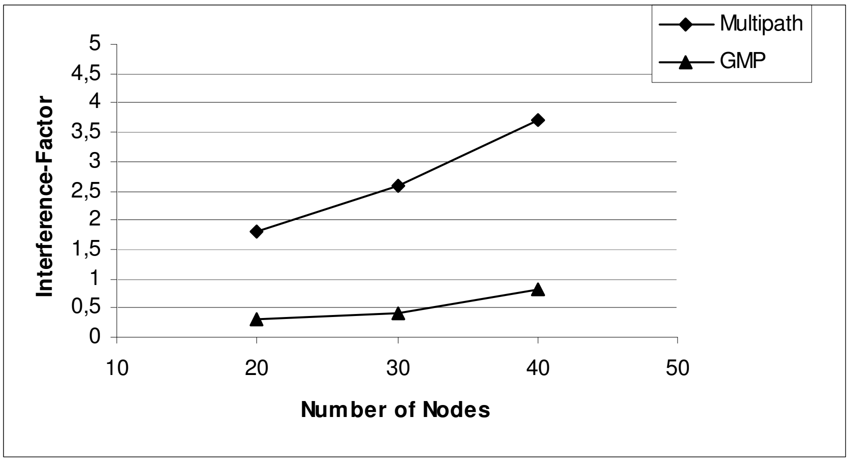


Fig. 2.18. Average Interference-Factor at different number of nodes.

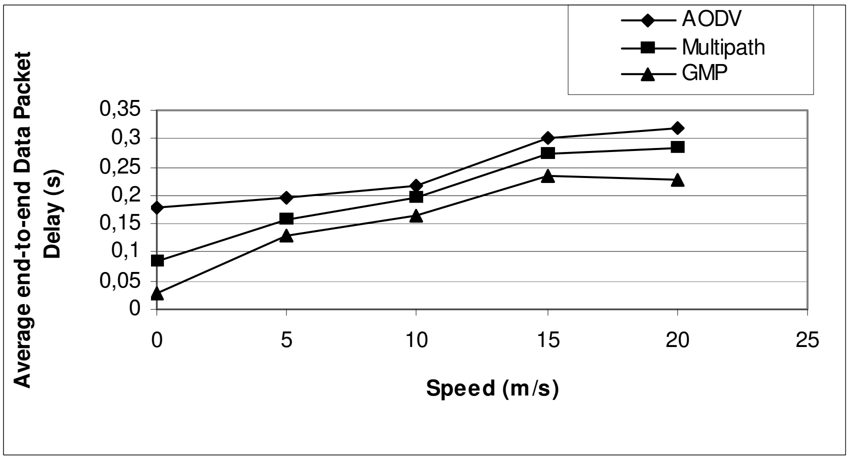


Fig. 2.19. Average End-to-End data packets delay (40 nodes).

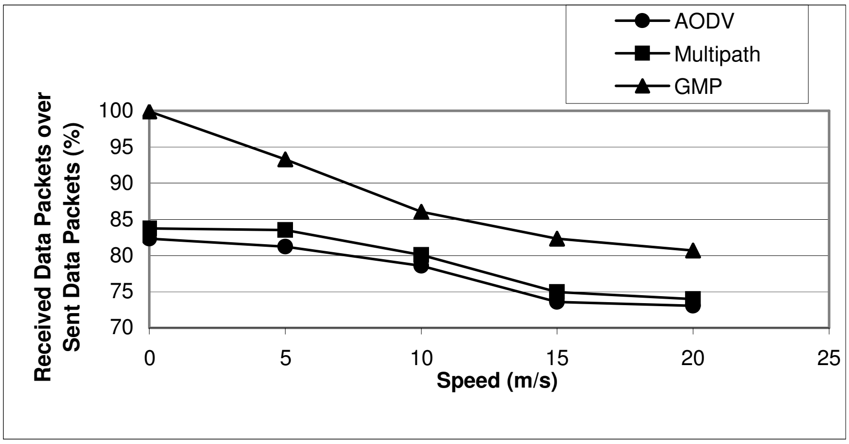


Fig. 2.20. Received Data Packets over Sent Data Packets (%) (40 nodes).

In Figs. 2.19 and 2.20 two different parameters, the delay of data packets and the throughput are shown. The comparison among the algorithms proposed and the unipath protocol AODV and a reactive non source-routing Multipath protocol that permits node-disjointed multiple paths to be created, is shown. It can be concluded that our approach, in terms of delay and throughput, outperforms the other protocols considered, because there is a lower interference between the multiple paths created with our approach. In practice, our approach permits the route-coupling effect to diminish that can severely limit the gain offered by multipath routing strategies. Large path length (number of hops) also contributes to the performance degradation resulting in a great end to end delay. For this reason simulation campaigns conducted here consider an area of 300 x 600 meters in which the length of a path, in the worst case can be sufficiently great. In this situation there is a greater probability that the two paths interfere with each other and it is important to build two paths as far away as possible. Naturally, a high mobility influences the performance because a node can move far away from another node but the link is not broken. In this case the *interference-factor* computed initially when a path is created can change during the data communication.

2.3.2 Conclusions

In this work, a new QoS multi-path routing scheme called QAOMDV is presented. The scheme can take advantage both of a well-known multi-path routing protocol, the AOMDV, and an evolutionary and distributed TDMA MAC layer, the E-TDMA. The interaction between the two-layers leads to get benefits of AOMDV in terms of reduced control overhead and lower average end-to-end data packet delay. Further advantages are obtained by E-TDMA in terms of higher offered throughput and the capability to reserve time slots. The novel QAOMDV can be deployed through two routing schemes. The first one offers more bandwidth constraints but it is no so suitable for high mobility and heavy traffic load. The second ones loses the bandwidth guarantees in the back-up route but permits the better use of the time slot for other connections, increasing the overall throughput in the network and reducing the normalized overhead and the average end-to-end delay. Further interesting analysis could be to extend the proposed routing scheme with the bandwidth splitting mechanism based on a ticket based approach to increase the success rate of the bandwidth request when the bandwidth resource is scarce and the mobility is high. The contribution of the paper shows the advantage of introducing a multi-path scheme with QoS reservation over a time-slotted environment. Other work could be addressed to regarding the optimal resource allocation among more paths and the integration of two proposed schemes with bandwidth splitting and a QoS ticket-based mechanism. Also, the integration of multi-path routing with power consumption and QoS constraints can be outlined. Another important topic is represented to the possibility to use coordinated geographic in a multipath routing approach. In order to make an effective use of multipath routing protocols in the mobile ad hoc network environment, it is imperative to consider the route-coupling phenomenon. In this work a new multipath routing protocol called GMP has been proposed. Specifically, this is a reactive protocol routing based on the geographical locations of the nodes. A concept of *zone-disjointedness* property is considered to build multiple paths that interfere with each other at a minimum level. The concept of *interference-factor* was introduced to measure the effectiveness of our protocol. The performances of our approach was considered through the NS-2 and this approach was shown to significantly outperform the original AODV and a reactive Multipath protocol routing in terms of delay and throughput.

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3

Chapter 3 Energy Issue in Wireless Sensor Networks

3.1 Introduction

Wireless ad-hoc networks and wireless sensor networks are also known as "networks without network" since they do not use any fixed infrastructure. Participating nodes in these networks are typically battery operated, and thus have access to a limited amount of energy. In similar networks, once nodes are deployed, their batteries cannot be easily recharged. Sensor networks are a typical example as some of them have very limited battery life; moreover, once deployed, a sensor network may be left unattended for its entire operational lifetime. This is due to the fact that sensor networks may be deployed in wide, remote, inaccessible areas. The energy-constrained nature of ad hoc networks in general, and sensor networks in particular, calls for protocols that have energy efficiency as a primary design goal. Research on power-aware protocols has been very active and spans multiple layers of the protocol stack. As a result, several energy-efficient medium-access control (MAC) and routing protocols have been proposed. In order to evaluate and compare power-aware protocols in terms of their energy efficiency as well as assess the effectiveness of cross-layer mechanisms to achieve energy savings, accurately accounting of the energy consumed by data communication activities is crucial. In [1] the power consumption of some network interface cards (NICs) was measured when used by different end-user devices. They also report on transport and application-level strategies to reduce energy consumption by NICs. Later, [2] reported detailed energy consumption measurements of some commercially available IEEE 802.11 NICs operating in ad hoc mode. Energy consumption models using linear equations were also introduced. For example, $E = m * size + b$ models data transmission and reception, where the coefficients m and b depend on the type of communication, i.e, broadcast, unicast, or packet discarded, and were determined empirically. Wireless sensor networking is an emerging technology that has a wide range of potential applications including environment monitoring, smart spaces, medical systems and robotic exploration [3, 4]. Such a network normally consists of a large number of distributed nodes that organize themselves into a multi-hop wireless network. Unlike traditional sensor systems, sensor networks depend on *dense sensor deployment* and *physical co-location* with their targets to accomplish their goals. *Dense deployment* implies the use of 100s or 1000s of sensor nodes in small areas and is enabled by low-cost devices and short-range wireless communication. Dense deployment allows the use of redundancy [5] and can reduce communication costs [6]. It is desirable to make these nodes as cheap and energy-efficient as possible and rely on their large numbers to obtain high-quality results. Network protocols must be designed to achieve fault tolerance in the presence of individual node failure while minimizing energy consumption [7]. Routing protocols for these networks should be able to perform local collaboration to reduce bandwidth requirements. Sensor networks contain too much data for the end-user to process. Therefore, automated methods of aggregating the data into a small set of meaningful information is required [8, 9]. Large energy gains can be achieved by performing the data fusion or classification algorithm locally, thereby requiring much less data to be transmitted to the base station. LEACH [10, 11] is an energy-efficient communication protocol which employs a hierarchical clustering. In this work the TL-LEACH [12, 13] is introduced, which is an extension to the LEACH, based on considering two hierarchy-levels. Two different methods are introduced to add another level of hierarchy and it is demonstrated that the setup phase (phase to build two hierarchy levels) is very important to obtain better results. Before building the protocol some analytical considerations are made. Through the analytical approach, related to the energy dissipation both in the original LEACH and in the TL-LEACH, it is shown how the adding of a new hierarchy level can lead to having better performance in term of energy consumption when some conditions are verified. Wireless Sensor Networks have emerged as a new information-gathering paradigm based on the collaborative effort of a large number of sensing nodes [14]. Nodes will act in response to environmental events and relay collected and possibly aggregated information through the dynamically formed multi-hop wireless network in accordance with desired system functionality [15, 16]. Such networks are envisioned to be large-scale, dense deployments in environments where traditional centrally-wired sensors are impractical. For example, ubiquitous wiring is infeasible for microclimate studies [17, 18], groundwater contaminant monitoring, precision agriculture, and condition-based maintenance of machinery in complex environments. One of the fundamental characteristics in the design of such sensor network systems is their finite energy source. Where traditional communication protocol stacks assume an excess of resources and can spare the energy and memory to send many messages, sensor nodes need to save on energy bit transmitted to ensure an acceptable network lifetime [19, 20]. The difference in constraints of sensor networks compared to the Internet focus a very different software architecture [21]. Many successful Internet systems can nearly ignore the network topology (for example FreeNet [22]), and find that a strictly end-to-end architecture is important for rapid deployment in the heterogeneous Internet. Although the constraints of sensor networks force an architecture [23] different from that used for event-notification services in traditional networks it is true that as Internet-based event services become very large and distributed, in-network processing can aid scalability. In this work a cross-layered approach for networking in WSNs is considered [24, 25]. This approach is based on a medium access control (MAC) protocol in which an algorithm to create a connected network based on local information only is used. The MAC protocol decides the grade of participation of each node in order to obtain a connected network and this represents a limit when a static or a quasi-static network is considered. In fact, the role of nodes is decided at the beginning and its role changes over time only if a collision or a conflict is verified. In this way a non uniform energy consumption is obtained and some nodes, which are active, waste more energy than others. In a similar scenario two role dynamic management algorithms are proposed [26]. These latter are dynamic in the sense that each node, through a particular algorithm perceives the mobility of the network and in a manner that is autonomous, decides whether it wants to change role (active-passive, or passive-active). These approaches are very scalable because the decision to change role is made in a local manner and periodically and the node does not have information about the rest of the topology.

3.2 A Two-Layer Protocol for Wireless Sensor Networks

3.2.1 Motivations

Before designing the TL-LEACH some analytical considerations have been made to establishes whether it was possible to take advantage by adding a new hierarchy level. The energy dissipation required to perform local data aggregation in a two-level structure network and send the aggregate data as against sending the aggregation data in a one-level structure network have been compared. Suppose that the energy dissipation for data aggregation is E_{DA}, the energy dissipation per bit to transmit to the Base Station is E_{TX}, the energy dissipation for transmit a bit among secondary CHs and primary CHs is $E_{TX(CH)}$ and finally the energy dissipation to transmit a bit from Simple Nodes to secondary CHs is $E_{TX(SN)}$. In addition, assume that the data aggregation method can compress the data with a ratio of L:1, in which L represents the number of bits that have to be aggregated. This means that for every L bits that must be sent to the Base Station from the primary CH when no data aggregation is performed, only 1 bit has to be sent through the approach here considered. Let us indicate $E_{TX(SN)\text{-}1\text{-}AGGR}$ the energy dissipation to transmit from simple nodes to the CHs when only one-level is considered (original LEACH). Without a loss of generality it can be assumed:

$$E_{TX(CH)} \approx E_{TX(SN)} = E_{TX\text{-}2\text{-}AGG} \qquad (1)$$

Indicated as N the total number of Simple Nodes (SNs) in a cluster and M the total number of Secondary Cluster Heads (CHs) in a cluster if L bits have to be sent in a unit of time the equation $(M+N) = L$ is valid if we consider that each node transmits a bit. Therefore, the energy to perform local data aggregation in a two-level structure network and transmit the aggregate signal for every L bits of data will be:

$$E_{LDA\text{-}2L} = L^*E_{DA} + M\ E_{TX(CH)} + E_{TX} + N\ E_{TX(SN)}. \qquad (2)$$

and the energy to perform local data aggregation in a one-level structure network and transmit the aggregate signal for every L bits of data will be:

$$E_{LDA\text{-}1L} = L^*E_{DA} + E_{TX} + L^*E_{TX(SN)\text{-}1\text{-}AGG}. \qquad (3)$$

Therefore, performing local data aggregation in a two-level network requires less energy than sending data aggregate in a one-level network when:

$$ELDA\text{-}2L < ELDA\text{-}1L \qquad (4)$$

Through a few of simple passages:

$$(M+N) * ETX\text{-}2\text{-}AGG < L^*ETX\text{-}1\text{-}AGG \qquad (5)$$

$$L^*ETX\text{-}2\text{-}AGG < L^*ETX(SN)\text{-}1\text{-}AGG \qquad (6)$$

And finally:

$$ETX\text{-}2\text{-}AGG < ETX(SN)\text{-}1\text{-}AGG \qquad (7)$$

This signifies that our approach is available when the amount of energy consumed to transmit the data from the Simple Nodes (SNs) to the Secondary Cluster Heads (CHs) or from the Secondary Cluster Heads to the Primary Cluster Heads is less than the energy dissipated to transmit the data from the Simple Nodes to Cluster Heads (CHs). In effect the probability that this is satisfied is very high on the basis of the setup phase of our protocol. In fact, the choice of primary CHs is realized on the basis of the signal strength of the ADV message, as explained as follows. In this way, when data have been sent the power can be "adjusted" related to the distance between two generic nodes. The same considerations can be made regarding the choice of the secondary CHs. In this way, through our protocol it is possible to have a more compact structure network and the signal power used is generally less than the signal power used in the one-level network.

3.2.2 TL-LEACH Algorithm Details

In this work the use of a hierarchical structure of sensor network is considered. Specifically, a hierarchical structure with two levels is designed. The use of clusters for transmitting data to the Base Station takes advantage of small transmit distances for most nodes, requiring only a few nodes to transmit great distances to the base station. In our protocol a Primary Cluster Head called CHi (in which “i” is the i^{th} cluster in the network) is considered. These latter communicate directly with the Secondary Cluster Heads generically called Chij. Finally, the Secondary Cluster Heads communicate with Simple Nodes indicated here as SNs. Once the two-levels hierarchical structure is completed the data transmission can start. The data transmission starts from the SNs that send your sensing data to your Secondary Cluster Head. This latter, after aggregating the data using an opportunistic aggregation algorithm, sends the aggregated data to its Primary Cluster Head. This latter executes the aggregation algorithm on data received from each of your Secondary Cluster Heads and sends the aggregated data to the Base Station (BS). Naturally, a node that is a cluster head will consume higher energy than a simple node. In our sensor network it was considered that each node is energy-constrained and for this reason if a node is permanently a CH (cluster head) both at the second or at the first level, it will consume the energy more rapidly. For this reason a protocol with a randomized rotation of cluster and cluster-head was considered here. To better manage the energy in the clusters a specific medium access control algorithm was considered based on the combined use of a TDMA technique and a CDMA technique. The use of a TDMA technique permits a “sleep” state or “stand-by” state to be considered in which a node does not consume energy. Through the use of the TDMA technique the “intra-cluster” interference can be avoided. The TL-LEACH is characterized through the round. Each round starts with a setup phase, in which the clusters formation is realized. After this the steady-state phase happens. The steady-state phase is sub-divided into frames. During each frame the data transmission is realized from the nodes to the Secondary CHs, from the Secondary CHs to the Primary CHs and finally from the Primary CHs to the Base Station. In Fig. 3.1 the temporal evolution of the protocol is shown. We assume the nodes are synchronized to start the setup phase simultaneously. Naturally, the setup phase in our protocol is more complex than the LEACH setup phase. For this reason a longer steady-state phase is realized and a longer round is considered.

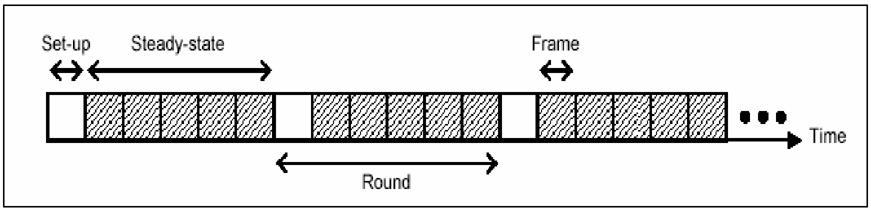


Fig. 3.1. Temporal Evolution of the protocol.

3.2.2.1 Cluster Head Choice

In the TL-LEACH algorithm the groups creation is realized considering a distributed algorithm without a centralized controller. Through an approach such as those considered, a distant transmission to the base station is only required to a low number of nodes and the groups creation can be realized without knowing the positions of each node in the network. During the time the formation algorithm is running it is not necessary to know the current nodes state. In this way the protocol proposed can structure the network simply on the basis of the local and autonomous decisions of each node. The main objective is to introduce an algorithm that permits the energy for each node in the network to be equally distributed. In TL-LEACH a node can being CH (at the primary or at the secondary level) at the beginning of a round “r” on the basis of a probability Pr(t) in which “t” is the starting time round. This probability is related to the number “N” of nodes in the network, of the current round “r” and of the number of total groups that we want to consider in the network. Two different thresholds have been considered: the first one for the Primary CHs and the second one for the Secondary CHs. Through these thresholds a node can establish what is its role in a current round. Let k be the maximum number of clusters that can be built, a node that recently has not been CH, that is a node that in the last ones “r mod (N/k)” rounds has not been CH and has some amount of energy to be CH it will have a higher probability of being CH. In this work each node starts with the same energy and each node has to send data. If we consider that nodes start the algorithm with different levels of energy or an event-driven model is adopted, then a different criteria has to be adopted to select the CHs at each level.

3.2.2.2 Cluster Setup Phase

Once the nodes, on the basis of the algorithm considered in previous section, has chosen each of its roles (Primary CH, Secondary CH or Simple Node), the setup phase of our protocol starts. This phase permits each node to auto-organize in a hierarchical structure with two levels. The first nodes starting this phase are the Primary CHs. Once a node has chosen to be a Primary CH in the current round, then it “gossips” its new state to Secondary CHs to make the first level of the network. To do it, each Primary CH broadcasts an Advertisement Message to each node in the network based on a non-persistent CSMA MAC protocol. The message dimensions are very small. In fact, this message contains only the ID of the node sending the message and a header to distinguish this message from the other broadcast messages. At this moment the Primary CH does not know the secondary CH. This message is managed by the Secondary CHs in the network and it is discarded by the others. The Secondary CHs have to make the choice about the primary CH to belong to. This choice is made on the basis of the signal strength of the ADV message. Each Secondary CH will choose the Primary CH for which it wants a smaller transmission power. Once a node (Secondary CH) has chosen its Primary CH to belong to, it will send a Join-Request message using a non-persistent CSMA MAC protocol to make it. This message is very small because it contains the identity of the node sending the message (ID), the identifier of the node receiving the message and a little header to distinguishes the message. Once the Primary CHs have received each Join-Request message from the secondary CHs, they know each member in your group. In this way the first layer of the network, that is the network layer constituted by the Primary CHs and the Secondary CHs, is realized. Subsequently the Secondary Cluster Head nodes send their advertisement to the Simple Nodes (SNs). The Primary CHs have to wait until the second layer of the network is completed. At this point the Secondary CHs "gossip" your state of Secondary Cluster Heads sending an Advertisement message received from the Simple Nodes and discarded by the other nodes in the network. The procedure is similar to the one previously described. In fact, the Simple Node receiving the Advertisement message on the basis of the signal strength will choose which of your Secondary Cluster Heads to belong to. To inform each Secondary CHs a Join-Request message is used. Once each Secondary CH has received each Join-Request message the setup phase is completed and the network is well-organized in a two-levels hierarchical structure. Each node on the network has a precise role. To realize the data transmission a TDMA schedule is designed to avoid collision. In this way each node is assigned a time slot to transmit the data in a current round. At this moment the Primary CHs does not know the member's group. A specific message containing a nodes list of the components of the cluster is sent from the Secondary CHs to the Primary CHs. Both the CDMA and the TDMA schedules were realized in the following manner: to each level a different CDMA code was assigned. Each Primary CH assigns a CDMA code to the first level constituted by the Secondary CHs and each Secondary CH assigns a CDMA code to its sub-group. The TDMA schedule creation is realized by primary CHs. Each Primary CH knows member group, both Secondary CHs and Simple Nodes, hence it creates a schedule for Secondary CHs and a schedule for Simple Nodes in a way that at the level of SNs permits frequency reuse thanks to the use of a different CDMA code. In this way smaller frame can be obtained and the transmission delay will be lower. The TDMA scheme is resumed in Fig. 3.2. To each sub-group a different CDMA code is assigned. Specifically, in Fig. 3.2 is shown how the node belonging to the CH11 will send with the C2 code, and those belonging to the CH12 will send with the C3 code. Instead, the secondary CHs will send using the same code C1. This CDMA scheme is combined with a TDMA scheme permitting a time slot to each node to be assigned. Through the TDMA scheme the "intra-cluster" collision is avoided. In this way a partial TDMA schedule is created by the primary CHs and another partial TDMA schedule is created by the Secondary CHs. A TDMA approach permits a sleep state to be introduced through a node that can reduce to zero the energy consumed. In fact, this state is introduced in the TL-LEACH protocol.

The setup phase can be seen in Fig. 3.3. Through this mechanism each Primary Cluster Head CH is not constrained to wait that each node in its group transmit in order to send the data to the BS. Said SCN (Secondary Cluster-Head Number) the number of cluster-head nodes at the second level and SNNi (Simple Node Number) the number of simple nodes in a generic cluster "i", the waiting time is:

$$\textit{Waiting-Time} = \textit{time-slot} * (\mathrm{SCN} + \max[\mathrm{SNNi}]) \qquad (8)$$

Being

$$\mathrm{SCN} + \max[\mathrm{SNNi}] \ll (N-1). \qquad (9)$$

In this algorithm a "stratified" approach is considered. In particular, the primary CH creates a partial schedule used by the secondary CHs and these latter have to create another partial TDMA schedule used by the SNs. In this way it is possible an higher sensing frequency to be realized and consequently the number of packets sent to the base station increases, and the energy consumption diminishes because the dimension of the packets exchanged both in the creation and the transmission of the TDMA schedule is less.

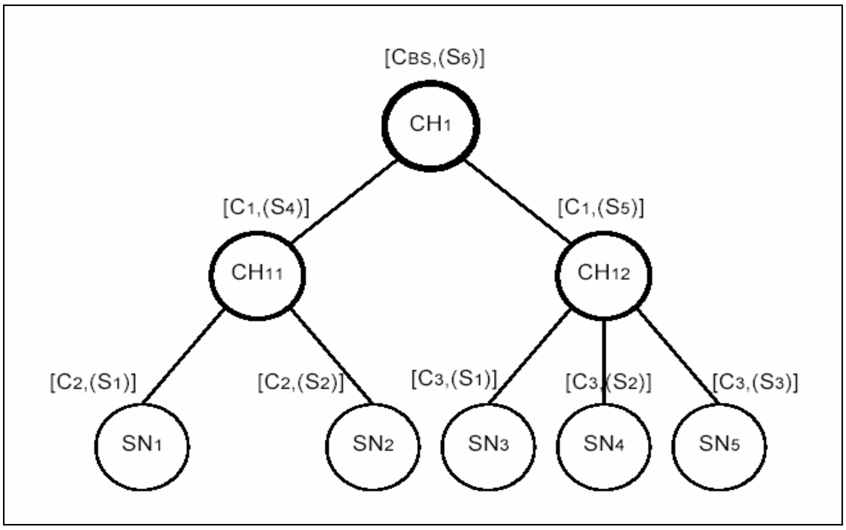


Fig. 3.2. TL-LEACH TDMA scheme.

3.2.2.3 Steady State Phase

Once the network infrastructure is created the data transmission can start. This is known as the Steady-State Phase. This phase is sub-divided into frames, during

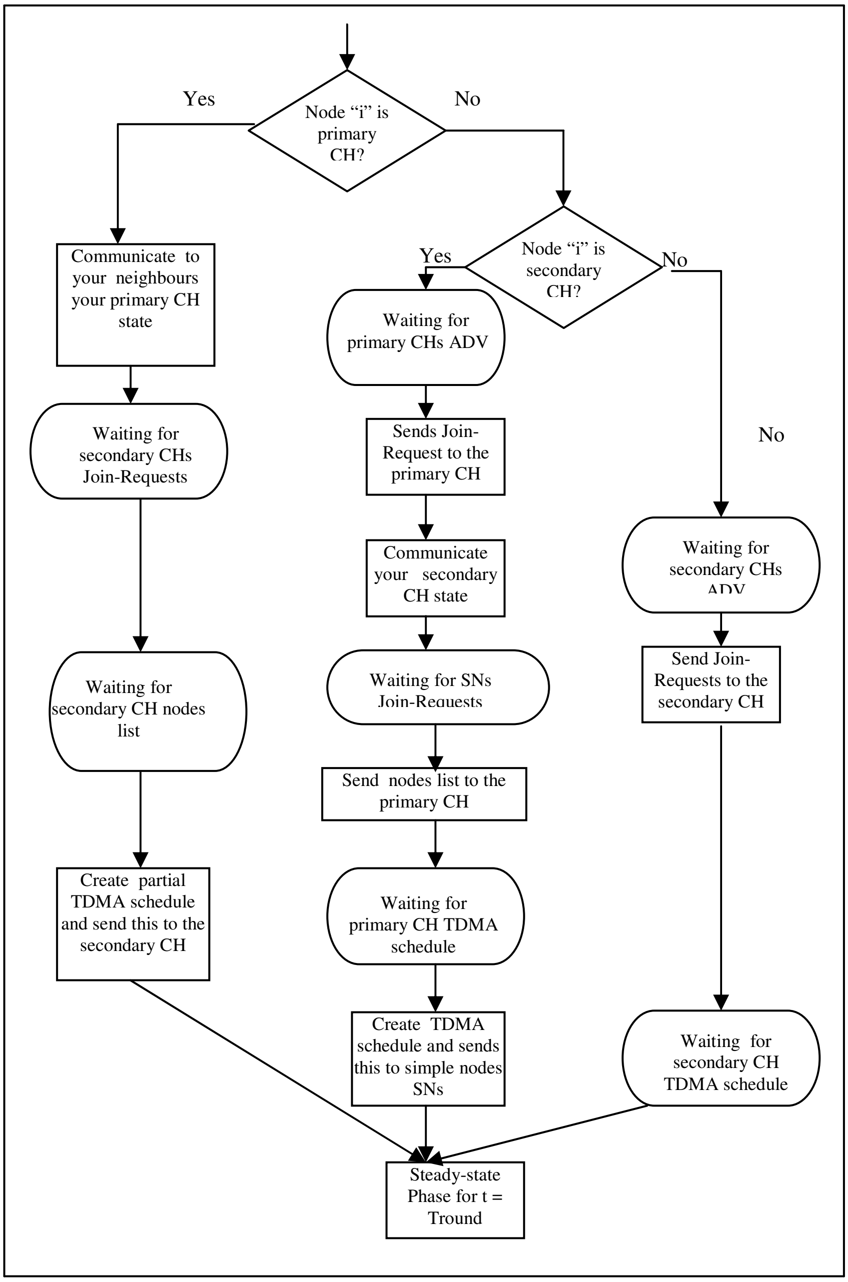


Fig. 3.3. Setup Phase Flow-Diagram.

nodes send your data (only a time in each frame), in their slots. The slot has the same duration and the frame is related, in this way, as the number of nodes constituting the cluster. To diminish the energy consumption, each node uses a power control to regulate the transmission signal strength on the basis of the advertisement strength. The simple nodes can utilize the sleep state thanks to the TDMA schedule considered. In fact, each simple node can be wake-up in correspondence to your time slot, to realize the sensing activity and to send the data in your time slot to your secondary CH. This permits the energy consumption to be reduced. The CHs, both to first and the second levels, have to maintain their own circuitry active, because they have to receive the data from the simple nodes and from the secondary CHs. In Fig. 3.4 the Steady-State Phase is summarized. In Fig. 3.1 it is possible to note the temporal evolution of a single TL-LEACH round. The transmission data described previously is related to the data transmission among the nodes belonging to the same cluster. Both the routing and the MAC protocols have been designed to diminish the energy consumption and to avoid collisions during the data transmission. Really the transmission in a cluster can degrade the transmission of another cluster. To reduce the interferences "inter-cluster" each group in the TL-LEACH communicates using a DS-SS (Direct-Sequence Spread Spectrum) technique. Specifically, each sub-group uses a different "spreading-code" as was seen previously (see Fig. 3.2). Nodes belonging to a same sub-group (for us a sub-group is a set of nodes at the same level, i.e. in Fig. 3.2 SN1-SN2 is a sub-group and CH11-CH12 is another sub-group). To limit the collision "inter-clusters" nodes belonging to the same cluster (or group) can limit your transmission power. To implement this method it is sufficient for each CH (both at the first and at the second level) to have a single filter-coupled correlator, because all the signals arrive at a generic CH with the same code. The combined use of the DS-SS and the TDMA techniques permits the "inter-cluster" interferences to be reduced and to nearly eliminate completely the "intra-cluster" collisions simply adding a coupled-filter to the equipment of each node. In conclusion, the data sent to the Base Station from each primary CH have been sent using a fixed CDMA code and a CSMA approach. This signifies that once a frame is finished a primary CH has to "hear" the channel to verify the channel is free. If the channel is busy because another communication is happening the primary CH has to wait some time before realizing your communication.

3.2.3 Energy Model

In this work we assume a simple energy model where the transmitter dissipates energy to supply both the radio electronics and the power amplifier while the receiver dissipates energy to supply only the radio electronics [15]. We consider that the power attenuation is dependent on the distance between the transmitter

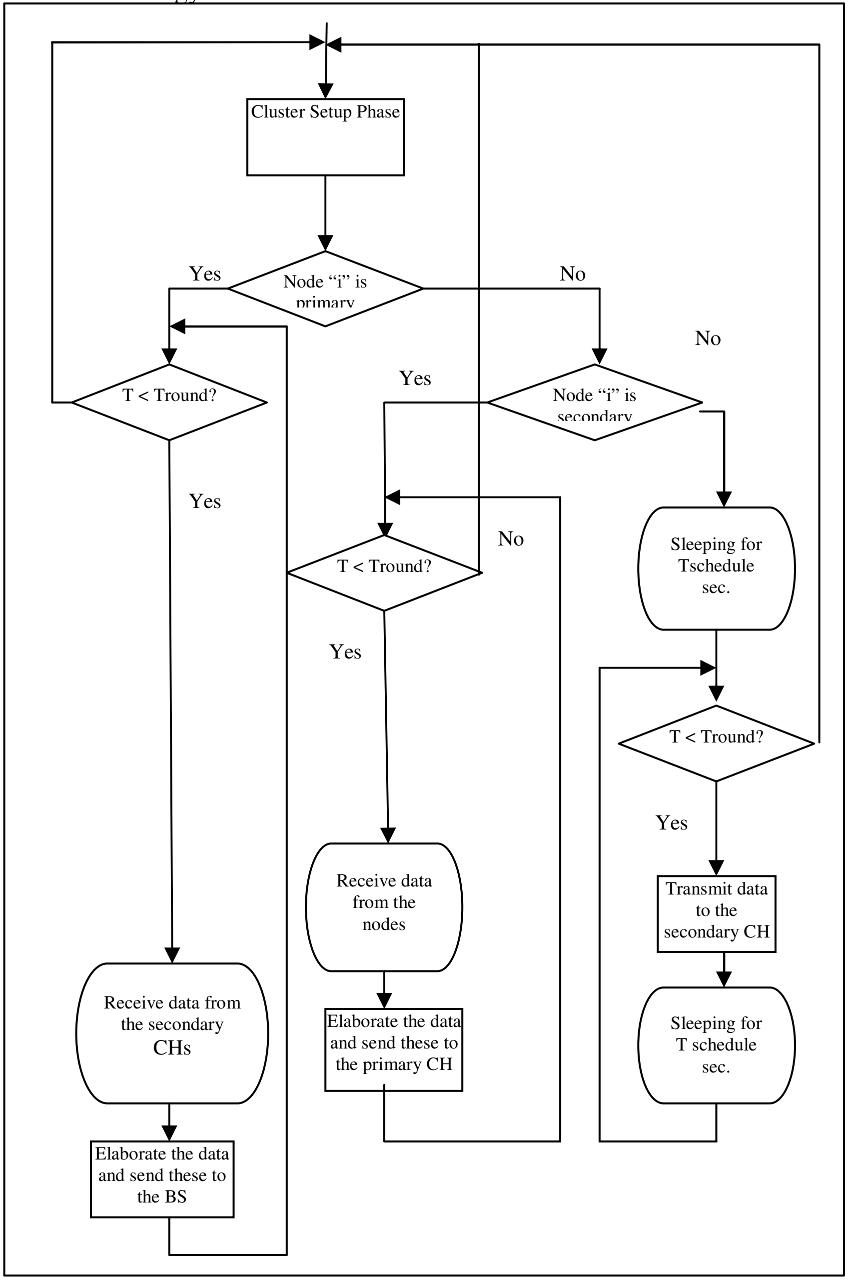


Fig. 3.4. Steady State Flow-Diagram.

and receiver. For short distances, the propagation loss can be modeled as inversely proportional to d^2 where d represents the distance between the sender and the receiver. Whereas for longer distances, the propagation loss can be modeled as inversely proportional to d^4. Power loss can be used to invert this loss by setting the power amplifier to ensure a certain power at the receiver. Finally, to transmit l-bit message to a distance d, the energy dissipated is equal to:

$$E_{Tx}(l, d) = E_{Tx\text{-}elec}(l) + E_{Tx\text{-}amp}(l, d)$$

$$E_{Tx}(l,d)= \begin{cases} lE_{elec} + l\epsilon_{friss\text{-}amp}d^2 \ : \ d<d_{crossover} \\ lE_{elec} + l\epsilon_{two\text{-}ray\text{-}amp}d^4 \ : \ d>d_{crossover} \end{cases}$$

The cross-over point is defined as follows :

$$d_{crossover} = \frac{4\pi\sqrt{L} \cdot h_r h_t}{\lambda}$$

where

- L >= 1 is the system loss factor not related to propagation
- h_r is the receiver antenna height,
- h_t is the transmitter antenna height,

λ is the wavelength of the carrier signal.

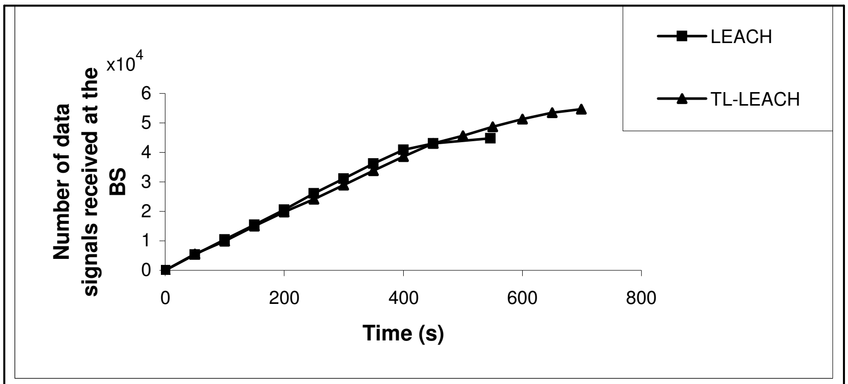
3.2.4 Simulation Results

To validate, what we obtained analytically in the previous section, simulation campaigns are conducted considering a well-known simulator NS2 [32]. The objective of these simulations is to show that the extension introduced permits less energy consumption to be obtained and the lifetime of the network to be increased. This confirms the considerations made above. In order to obtain more realistic results energy spent to exchange control overhead packets in order to realize the setup phase, has been taken into account. Indeed, both control packet and data packet are considered to consume some amount of energy and in our simulations we decrease the amount of energy when a control packet is sent. In this way a more accurate analysis is conducted. Simulation parameters are summarized in Table 3.1. For the experiments described in this section we considered LEACH and TL-LEACH. Once the clusters are formed, in LEACH, the cluster-head aggregates all the data into a representative signal to send to the base station. This protocol has the advantage of being distributed, self-configuring, and not requiring location information for cluster formation. In the TL-LEACH a different CDMA code is associated with each different level (as described in the previous section). For our experiments each node begins with only 2 J of energy and an unlimited amount of data to send to the base station. Each round lasts 30 seconds in TL-LEACH and 20 seconds in LEACH. This is due to the longer time required from the setup phase in our protocols. We tracked the rate at which the data are transferred to the base station and the amount of the energy required to get the data to the base station. Once a node runs out of energy, it is considered dead and can no longer transmit or receive data. Here we considered that the energy is removed whenever a node transmits or receives data packets and control packets and whenever it performs data aggregation. Fig. 3.5 a. shows the total number of data signals received at the base station over time. This figure shows that the TL-LEACH sends much more data to the base station than the original LEACH. In the TL-LEACH the TDMA schedule adopted permits a greater quantity of data to the Base Station to be sent, but the energy consumption is diminished during the data exchange phase among the nodes of the network layers. In our protocol the nodes transmit to shorter distances compared to the LEACH and this permits better energy distribution. In Fig.3.5 b. data signal delivered on energy dissipated is shown. It is possible to observe that increasing the energy consumption a greater data is delivered to the Base Station with TL-LEACH in respect to the LEACH. This is due to the better energy distribution that adding a new hierarchy level permits to obtain. Fig.3. 5 c. shows the total energy dissipated over a period of time. In reality, greater complexity in the setup phase is introduced when a new hierarchy level is considered, but this complexity is compensated for in the data transmission phase in which the two-level structure is used.

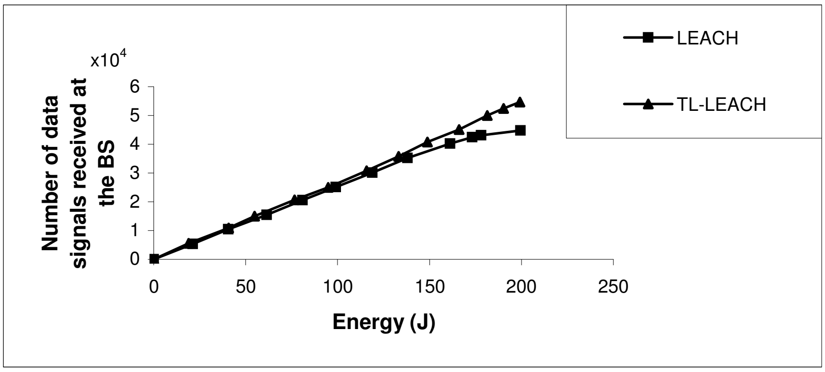
Table 3.1.Simulation Parameters

Parameter	**Value**
Number of nodes	100
Simulation area	100m x 100m
Base Station position	(50, 175)
Processing delay	25 μs
Transmission rate	1 Mbps
Packet size	500 bytes

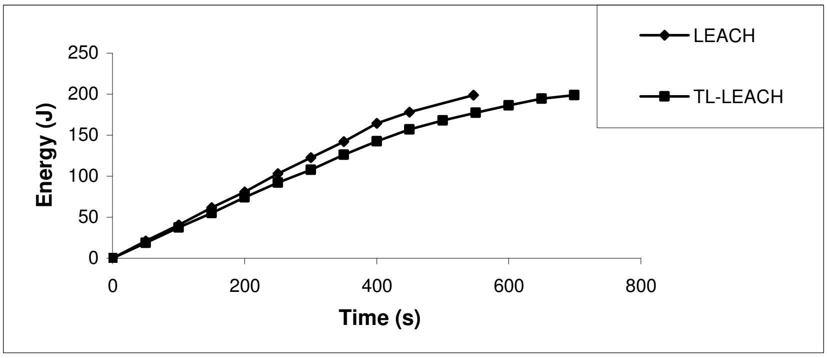
The gain obtained in terms of energy introducing a new level of hierarchy, despite to the increased complexity that adding a new level of hierarchy requires,



a. Data Received to the Base Station over the time.



b. Data Received to the Base Station over the energy.



c. Energy dissipated over the time.

Fig. 3.5. Simulation Results.

confirms analytical results obtained in the section 3.2. Other simulation campaigns were conducted in order to verify the effectiveness in adding other hierarchy levels. These latter show how the greater complexity introduced in the setup phase is not compensated of better results. Indeed, considering three hierarchy levels we obtained results about energy that are a few better than LEACH energy consumption but are not better than TL-LEACH. This is due to the number of overhead control packet introduced in order to manage the adding of a new phase. The control overhead implementing a three layers hierarchy protocol is excessive to the respect of the improvements that can be obtained.

3.2.5 Related Work

Other works were presented in which a hierarchical approach is considered. In PEGASIS [27] all nodes communicate with its neighborhood surrounding and alternate the data transmission to the Base Station. In this way the network lifetime can be extended. In order to reduce the power, once a transmission round with the Base Station ends another transmission round starts and so on. In this way the power consumption is equally distributed among all the nodes. Compared with LEACH in PEGASIS a node does not perform the group forming but it uses only a node among all the other nodes in the so-called transmission "chain" to send data to the Base Station. In order to detect neighbor nodes, each node uses the signal power to detect the distance and it manages the power in a way that only this node will receive the packet. In this way PEGASIS builds a "chain" composed by nodes adjacent to each other and the built path permit to reach the Base Station. In particular the Base Station will receive aggregated data from each node belonging to this path. In PEGASIS a dynamic topology change is required because each node has to know the energy of its neighbors in order to know where the data packet should be routed. Moreover, if a high traffic network is considered, there will be an increased overhead . Finally, a great delay is introduced with this protocol when there are nodes far away from the Base Station and nodes that have to transmit to the Base Station can suffer of a bottleneck problem. In SOP [28] the authors propose a protocol where some nodes sensing and send data to some other stationary nodes in the network that are like routers and create a sort of transmission backbone. Each sensor has to send data to at least one router and the authors proposed a routing architecture n which each node is identified through the address router belonging to. In this protocol some additional cost related to the maintenance of the routing tables and the network hierarchy has to be taken into account. In [29] a data delivery to more than one sink nodes is considered. In this protocol each source proactively builds a grid used to disseminate data to different mobile stations. Each node is supposed stationary and location-aware. The routing approach used in this protocol is efficient but the length of the paths built is greater than the short-path. Data delivery delay introduced in this protocol is significant and the overhead due to the grid building (i.e. a topological change happens) can be excessive. In [30] sensors in a cluster-based sensor network can determine the distance to their cluster head. Distance information can be obtained via location information (but the reverse is not true).

3.3 A role dynamic management algorithm: DMA

3.3.1 Overview

The protocol considered here to develop and test our dynamic role management algorithm (DMA) is a cross-layered approach for networking in WSNs (Wireless Sensor Networks). It has been developed as part of the ongoing European research project EYES (IST 2001-34734, http://eyes.eu.org) [24, 25]. A self-organizing medium access control (MAC) protocol is addressed in this approach, which uses an algorithm to decide the grade of participation of a sensor node in creating a connected network based on local information only. Moreover, a tightly integrated efficient routing protocol is developed to work with this MAC protocol. This latter consists of a fully distributed and self-organizing time-division multiple access (TDMA) scheme in which each active node periodically listens to the channel and broadcasts a short control message. This control message is needed for medium access operation and it is also used to piggyback various types of information at low energy costs. In this approach two main types of node can be individuated: active and passive nodes. Active nodes create a connected network using the central message to form this. There are other nodes that are passive nodes and save energy by exploiting the active nodes. The low-cost energy message is used to create and to maintain efficient routes in a dynamic topology. In order to decide which nodes have to remain active to ensure a connected network, ideas from clustering techniques are used. As we have seen the medium access protocol is based on TDMA paradigm. Time is divided into time slots, which nodes can be used to transfer data without having to contend for the medium or deal with energy wasting collisions of transmissions. A time slot is further divided into three sections: communication request (CR), traffic control (TC), and the data section. The owner of a time slot will always transmit a TC message in the time slot, regardless of whether or not a request was filed. All nodes within one-hop distance of the controller of the current time slot will put effort into receiving this message, since this message is used for synchronization purposes and control information. Four different roles are identified in the protocol: Anchor node, Bridge, Undecided active and

Nonmember but we are interested only on the distinction in the passive and active role. A local decision algorithm runs to attribute the right role to each node. Once a node enters the network , it has to decide, through the local decision algorithm whether it is needed as part of the connected active set (it is a set of active nodes). A node that participates in the network as part of the connected active set consumes more energy than a passive node. Therefore the authors have inserted in its scheme the principle of role rotation, that is an active node can drop its status and become inactive and neighboring nodes create a new anchor if needed for connectivity.

3.3.2 The Dynamic Management Algorithm

In this work a scenario in which a WSN typically created in an ad hoc manner, with the sensors that can auto-configure and that alternate, during its life, in a greater energy consumption phase (active phase) and in a lower energy consumption phase (passive) is considered. The active phase has to be considered as the phase in which a node participates in the elaboration process and in the information routing. The passive state has to be considered as the phase in which a node diminishes its energy consumption and manages only fundamental operations, i.e. sensing, etc. In this way it is possible to obtain a lower energy consumption that permits the lifetime in the network to be prolonged. Typically, the phase in which a node decides its role (active or passive) is periodic and synchronized, that is all the nodes in the network are synchronized to start the **setup** phase. In this phase the cluster with cluster-head can be created. Generally the setup phase is followed from the **steady-state** phase where each node executes its role. Of course, the setup phase frequency cuts into the performance of the network and on the energy consumption. Higher frequencies permit better topological changes to be managed in the network due to the network mobility, but introduce too much overhead. The DMA (Dynamic Management Algorithm) is a totally distributed and local algorithm and it does not require any synchronization among the nodes in the network. In the DMA there is a SETUP phase and each node runs this phase in an independent manner from each other. The DMA is a generic algorithm that can be applied to different protocols for WSNs. In the next section a case study will be proposed: the DMA with the cross-layered ESR+EMAC[24, 25]. In Fig. 3.6 a general scheme of the DMA is shown. DMA does not do assumption about synchronization of nodes because each node separately to other nodes in the network can run the DMA protocol in different times. In this way each node can adapt itself and its behavior to the mobility of the network without synchronize with the others nodes in the network.

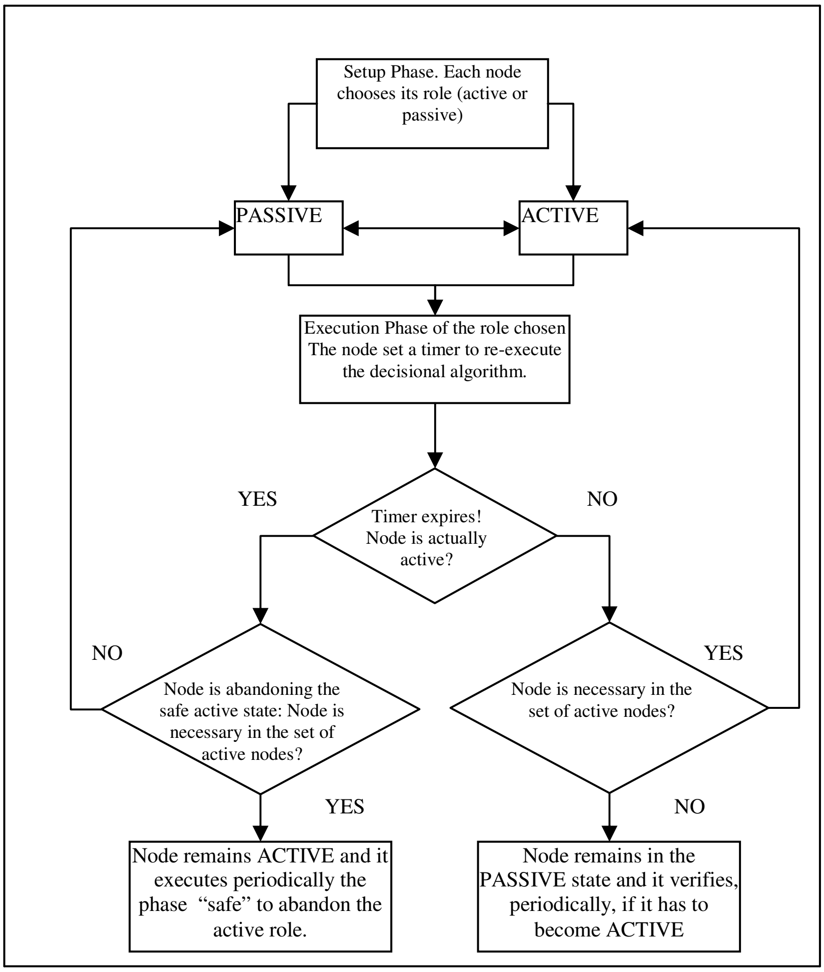


Fig. 3.6. General Scheme to represent the fundamental operations in the DMA.

3.3.2.1 A case study: The EYES Source Routing EYES-ADAPTIVE MAC (ESR+EA-MAC_v1): First Approach

When a node enters the network it can decide if its state has to be an active or a passive state, based on information of its neighborhood. When a node moves from a location to another location its state can be re-evaluated depending on its neighborhood. Indeed, if a node enters a hierarchical structure where is not needed an active node (in the ESR [24] is an anchor node, in the LEACH protocol is a cluster-head node [10, 11]) its state will be set as passive state, otherwise its state can be set as active state. The details how the particular state is assigned, are strongly dependent on the particular algorithm running with the DMA. The aim of this work is to find an algorithm that dynamically and in a distributed and local manner can change the roles of nodes in a hierarchical structure. Specifically, our algorithm can be applied to different hierarchical structures in WSNs, and the above described protocol (in section III) was used to show the effectiveness of our approach. In the ESR and EMAC protocol there is a random rotation of roles of the nodes but this rotation happens when a topological change due, for example, to mobility of nodes happens. In fact, comparing the behavior of this protocol when the mobility is considered and in the case of static network the results show that the protocol works better under mobility conditions. The protocol is developed as follows: a new timer, called ROUND-TIMER is introduced for each node and it is set the first time when a node establishes its role for the first time. Once this timer expires a node has to re- consider its current role. If a node has been active in the previous round it can choose to be passive in the next round and vice-versa. The role change of the node is not immediate because network connectivity has to be maintained. This algorithm is simple, local and works in a distributed manner. A node executes the SETUP phase as in the original protocol in which a node that wakes-up or a node that enters the network decides its role. Once the choice is made a node sets a timer called ROUND-TIMER (in order to indicate the starting of a period for each node called ROUND). This timer will be fixed to an ACTIVE-TIME if the node chooses to be active, vice-versa this timer will be set to PASSIVE-TIME. Two different cases are distinguished:

- in the latter round a node has been an active node (anchor or bridge). In this case a node will try to be a passive node once the timer expires. It can be passive node on basis of the role in the previous round:
    1. Anchor Node: if another anchor node is detected nearby then the node can switch to the passive state.
    2. Direct Bridge: the node has to verify whether the anchor nodes in the surrounding area active. In this case the node will verify whether it has been substituted by another node, that is, another active node is a bridge among the same anchor nodes. If this latter condition is true the node can switch to the passive state.
    3. Distributed Bridge: the node has to verify that it is redundant in the active set of nodes. If this condition is true it can switch to the passive state.

If one of the conditions above considered is not verified the node will remain in an active state called PTP-active (Prepare-to-Passive mode) and it will set its ROUND-TIMER with a PTP-TIME value (PTP-TIME < ACTIVE-TIME) and it will continue to transmit in its time slot the TC (Traffic Control) message where we added a bit flag PTP that will be fixed to 1. In this way the surrounding area will be informed about the need for the node to change state. If the ROUND-TIMER expires or some new active node is near then the node will execute this procedure anew. The node behavior can be described by a finite state machine (Fig. 3.7).

- The node in the latter round has been a passive node.
  In this case when the timer expires the node, for a duration frame period will listen to the surrounding area to detect the active neighbors. Passive nodes detect periodically active neighbors. The node verifies in this way whether it is necessary in the active set nodes. Specifically, if no anchor node is detected or some neighbor nodes in the PTP state or no bridge (if more anchors are detected) will be detected then the node will be active and it will choose the specific active role (i.e., if a node detects an anchor node in the PTP state then it can be anchor node and in this way it permits the node in the PTP state to verify its condition to become a passive node. If the node remains a passive node it will set its ROUND-TIMER with a PTA-TIME (Prepare-To-Active Time < PASSIVE-TIME) and it will execute the described procedure when the timer expires.

The times, ACTIVE_TIME, PASSIVE_TIME, PTA_TIME and PTP_TIME were chosen making simulation considerations. Of course, if some topological changes happens in the network, the original protocol will be normally adopted. The PTP and the PTA states have to be considered as extensions of the states A (ACTIVE) and P (PASSIVE), respectively. They have been introduced in order to permit a node to change state without causing a lack in connectivity in the network. In some particular cases, when the density of the network is low (i.e., when more nodes have exhausted its energy) a node can remain indefinitely in the PTP state. Through our approach each node can autonomously decide when and if to change state. It is a very important characteristic considering some network scenarios in which a portion of the network is static and another portion of network is dynamic. In this way, each node can adapt its behavior on the basis of the dynamicity of the network and for this reason our approach has to be considered a role management dynamic approach. When a portion of the network is dynamic the nodes change their role on the basis of the network destination chosen, i.e., if a node has an active role and it moves towards a destination where an active node is not necessary, then the node changes its state into the passive state on the basis of the mobility of the network.

3.3.2.2 *A case study: The Extended EYES Source Routing EYES ADAPTIVE MAC (ESR*+ EA-MAC_v2), second approach*

The modifications introduced in the protocol in order to obtain a better distribution in terms of energy consumption in the network try to “force” nodes to change their role.

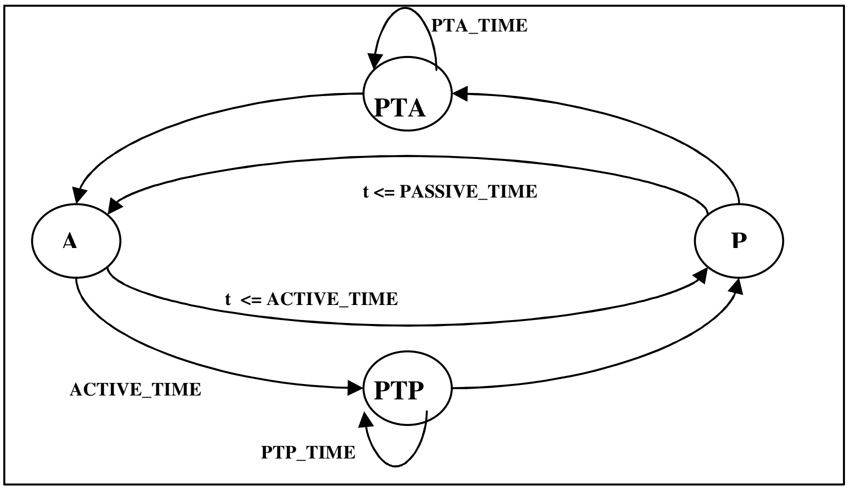


Fig. 3.7. State Finite Machine representing the behavior of a node in its life.

It is equivalent introducing a pseudo-mobility in a static network. In fact, a node changing its role from active mode to passive mode can be seen as a node moving far from its surrounding area. In this way each node, periodically, can change its active state (that implies a greater amount of energy consumption) to a passive state. There are some drawbacks to introduce these changes. In fact, there is a more frequent updating in the routes due to the greater breakage along the links, this is typical when a node changes its state from the active to the passive state. Consequently, if a better distribution in the network is obtained through this approach a greater latency delay can be introduced and a greater percentage of lost packets. In fact, in this first approach a node does not consider whether it belongs to a route from a source to a destination. A different approach (the second approach introduced here) consists in considering before hand whether to “abandon” the network (change its state from active to passive state) a node searches for another node that can substitute it in the active route for the same couple source-destination. Another phase is introduced in order to realize it. The original EMAC packet was modified as shown in Fig. 3.8 in order to support the DMA protocol in the second version. In order to diminish energy consumption and to reduce the “*route setup*” phase in which a flooding with “*route requests*” messages are required when a path is broken due to the topological changes or states changing in a node (active->passive) the ESR and the EA-MAC protocol have been extended with some modifications.

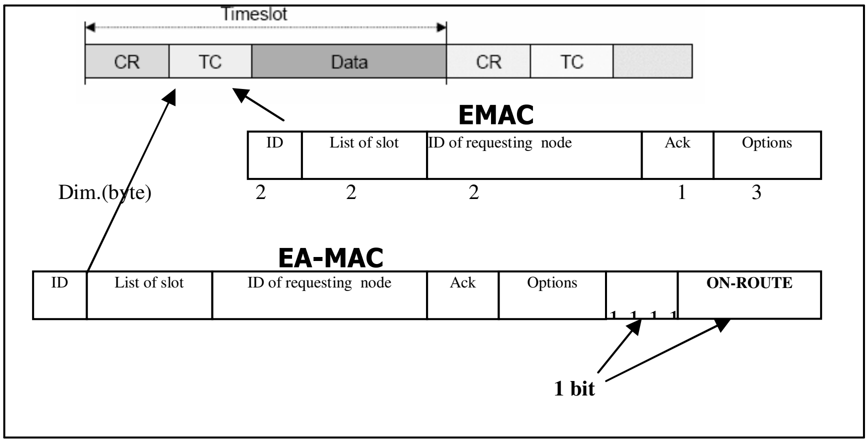


Fig. 3.8. Two fields, PTP and ON-ROUTE fields were added to the original EMAC packet.

When an active node is waiting to switch into the passive mode it will verify whether it belongs to a path linking a source with the sink node. The routing protocol has all the information to detect this condition. If the node does not belong to any active route the node will set the PTP field in the section TC (Traffic Control) to 1 and it informs its surrounding area(active and passive nodes) and it considers whether to switch to the passive mode as described above. If a node belongs to some routes from a source to a destination it will execute the following procedure:

1) the fields ON-ROUTE and PTP (fields added in the original control frame of EMAC packet) in the section TC will be set to 1. In this way the neighbors that are able to substitute the current node can send some information about the active node neighbors. Each node has to send the ID of the active neighbors. In order to limit the amount of information sent, the current node sends some information only if the number of active neighbors known is greater than 3. This is due to the fact that the node has to be able to directly connect to another two nodes (the last-hop node and the next-hop node) in order to be an available substitute. The field ON-ROUTE can be set to 1 independently of the change state condition, because the MAC is informed by the routing when a node belongs to a certain route. In fact, a node can be a candidate itself only if PTP = 1 and ON-ROUTE = 1 in the section TC of the node that it will substitute. In this way, the passive node will send only the ID of the known nodes and ON-ROUTE.

2) A node in the PTP state will wait for some information (list of the active node neighbors). When the first message arrives a timer will be set and when this

timer expires the current node searches for an available substitute, that is a node that satisfies the greater number of routing instances (for routing instance we intend a route between a source node and a destination node, i.e. the sink in this case).

3) The tables routing will be sent to the chosen node. These tables are constituted from: source node ID, Destination Node ID, Nexthop ID, Lasthop ID, sequence number of the routing instance (it is necessary to know the new route-request messages for a couple source-destination)

4) We have to consider 4 different scenarios:

- ➢ If the chosen node satisfies each routing instance and it is already active then the PTP node (current node) can become *passive*.
- ➢ If the chosen node satisfies each routing instance and it is passive, then the PTP node has to wait until the chosen node becomes active before switching into the passive state. If this latter does not happen in a certain interval of time the procedure will be deleted and the current node remains in its role and it will continue to transmit the PTP and ON-ROUTE fields in the section TC set to 1.
- ➢ If the chosen node does not satisfy all the routing instances and it is already active then the PTP node will be in its active state in order to satisfy the residual instances routing and it will transmit the PTP and ON-ROUTE fields in the TC section set to 1.
- ➢ If the chosen node does not satisfy all the routing instances and it is passive then the PTP node will stay in its state to satisfy the residual routing instances and it will continue to transmit the PTP and ON-ROUTE fields in the TC section set to 1. Moreover, it will verify that the chosen node will be active within a certain time. If it does not happen the whole procedure will be deleted.

If the current node in step 2 does not receive any message from its neighborhood or if there is no node that can substitute the current node it will stay active and it will transmit the fields PTP and ON-ROUTE set to 1 in the TC section. A passive node detecting a TC section in a time slot with the PTP fields and ON-ROUTE set to 1, and that is not a candidate to substitute another node, will execute the following procedure:

1) it will listen for a PASSIVE-LISTEN-TIME in order to detect the active neighbors (it is in the PTA state at this moment);

2) it will transmit the active neighbors list to the active node PTP;

3) It will wait for the next TC section of the current PTP node to verify whether it is chosen (if it satisfies all the routing instances);

4) if it has been chosen it will wait for the routing tables and will switch into the active mode.

If in step 3 the node verifies that it has not been chosen or if a certain amount of time has passed, it will switch to its passive state. An active node (neither in PTP or ON-ROUTE) that is not a candidate to substitute another node and that detects a TC section in a time slot with the fields PTP and ON-ROUTE to 1, it will execute the following procedure:

1) it will transmit the active neighbors list to the active PTP node;
2) it will wait for the next sections TC of the PTP node to verify whether it has been chosen (if it satisfies all the routing instances);
3) if it has been chosen it will wait for the routing tables or else it will stay in its state.

Of course, if a node has not been chosen , it will avoid candidate anew to substitute the same node, while a new node is not detected. The cost associated to the designed protocol, in both of the approaches is minimal and it has been taken into account in the simulation campaigns.

3.3.3 Simulation Results

Simulation campaigns were conducted in order to verify the effectiveness of the proposed algorithm DMA. The simulation tool used is an Object Oriented simulator OMNeT++ [31]. In the simulator a physical layer was implemented in order to consider an energy model to compute the energy consumption of the transceiver in the transmitting phase and in the receiving phase. Additionally, delays and energy consumption spent switching from the transmission state to the receiving state were considered. Two different scenarios were considered: a dynamic scenario and a static scenario. In both scenarios 45 sensor nodes were positioned in a rectangular area of 5.5 X 3.5 times of the transmission range. Five nodes were chosen as sources nodes to send data and the packet length was 5 byte. An active node is a data sink and it receives data from the source nodes. The parameters evaluated to verify the effectiveness of the DMA are: lifetime, throughput and latency in the network. The lifetime has to be considered as the amount of the time spent so that a fixed percentage of the nodes consumes its energy. Both the source nodes and the sink node have unlimited energy, also they do not influence the lifetime. During the simulation campaigns when 30% of the sensor nodes has consumed its energy (fixed to 3 Joule), the whole network is considered dead. Timer periods varying randomly in an interval between a minimum value and a maximum value that have been found experimentally.

3.3.3.1 Static Scenario

In Fig. 3.9 results about a scenario with 5 sources nodes and a 1 sink node are considered. Specifically, the lifetime is shown in the Fig. 3.9. In all the figures, ESR+EMAC represents the protocol structure constituted of the Eyes MAC [24] and the Eyes Source Routing [25]; ESR+EA_MAC_v1 represents the structure constituted of the Eyes Source Routing and the Eyes Adaptive MAC (the first approach considered above) where the decision of a node to change role does not consider whether the current node belongs to an active route or not; the last protocol structure considered is constituted of the Eyes Adaptive MAC considered in the previous section and the Eyes Source Routing in which the decision of a node to change its state depends on whether it belongs or not to an active route (the second approach in the previous section) and it is ESR^*+EA_MAC_v2. The minimum lifetime in the network is obtained with the ESR+MAC. This is due to the fact that in the original protocol the role choice in the decisional mechanism of the EMAC is related to the topological changes in the network. In the static case these topological changes simply are a breakage link due to a node that has consumed its energy.

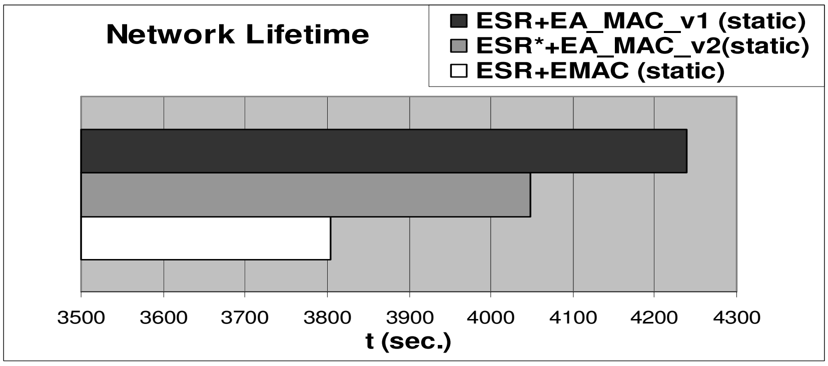


Fig. 3.9. Network Lifetime of the three different schemes considered in the static case (Network load 9msg/min).

The differences between the ESR+EA_MAC_v1 and the ESR^*+EA_MAC_v2 are due to the different mechanism applied to change the role. Nodes that do not detect any topological change in the network have to re-consider its role. In the first approach nodes simply consider the network connection, indeed in the second approach also they consider the importance of preserving the active routes in the network. This latter implies a smaller routes updating request and a smaller number of flooding phases in the network. In the first case it is possible to realize a better distribution of the energy in the network (the case of changing role is realized more frequently than in the second approach, where a certain number of conditions have to be verified) which balances the greater energy consumed in the flooding phases. As far as the throughput is concerned the results are shown in Fig. 3.10. The worst results are with the ESR+EA_MAC_v1 and it is due to the fact that nodes alternate periodically between the active and the passive state and more interruptions in the routes are present and consequently more data are lost. The better results are with ESR^*+EA_MAC_v2 (9% more with respect to the ESR+EMAC).

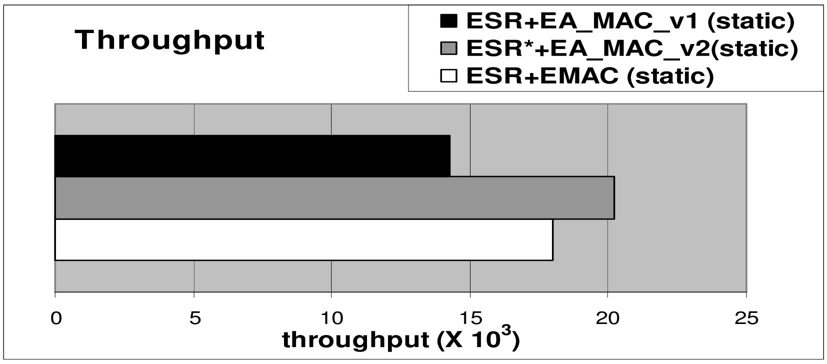


Fig. 3.10. Throughput of the three different schemes considered in the static case (Network load 9msg/min).

In this case the roles are changed but the paths are preserved and for this reason a lower number of data are lost. In addition, there is a better energy distribution. In fact, in the ESR+EMAC the probability of a node consuming its energy while it is ON-ROUTE is greater than in the case of when a role-changing algorithm is applied. An active node transmitting data will consume its energy more rapidly than a "normal" node in a passive state and it causes loss of data when it dies. A node that is placed before it in the sending chain (from the source to the destination) will detect that the node has died when it does not detect the TC sections in the time slot belonging to the dead node. In the Fig. 3.11 results about the latency have been obtained. The latency has to be considered as the time between sending a message and receiving it at the sink. Similar considerations as those made about the throughput can be made for the latency. The greater latency obtained in the ESR+EA_MAC_v1 is due to the fact that there is a greater frequency of updating of the routes. Better results are obtained for ESR+EMAC_v2 where a lower amount of updating is required. As far as the static case is concerned we can conclude that the second approach proposed is better in all of the parameter indexes considered. Also it can be noted how the evaluation of a protocol based on only a single parameter can be wrong.

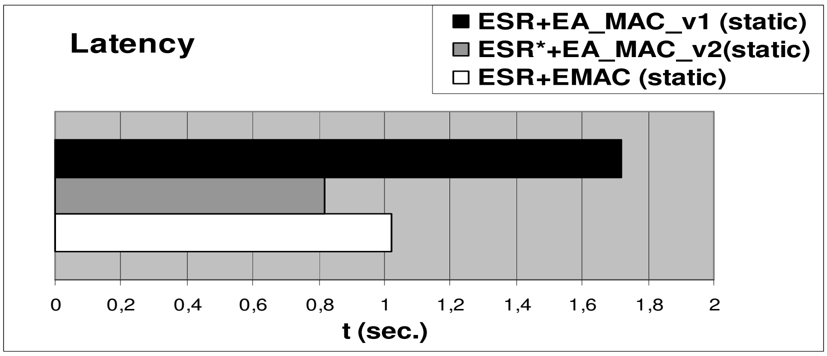


Fig. 3.11. Latency of the three different schemes considered in the static case (Network load 9msg/min).

3.3.3.2 Mobile Scenario

The simulation campaigns executed considering mobile nodes were obtained considering a random position of nodes. As in the previous case 5 sensor nodes were chosen as sources nodes and a sink node or destination node. The frequency of data sent is the same in the static case (9 msg/min). The sources nodes and the sink node are considered with unlimited energy. Nodes move randomly based on the Random Way Point (RWP) with a speed value between 2 and 10 m/s and waiting time between 10 and 30 sec.

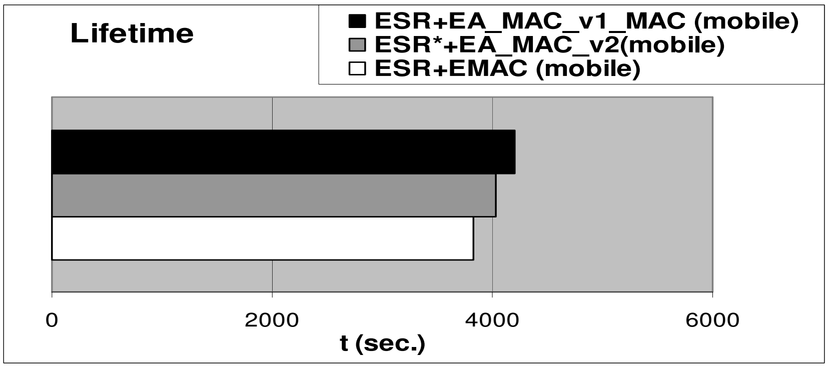


Fig. 3.12. Network Lifetime of the three different schemes considered in the mobile case (Network load 9msg/min).

A node arrived at destination waits for a certain time before moving again. In this way a different combination of static and dynamic nodes is realized. In Fig. 3.12 the lifetime is shown. The decisional mechanism used when mobile nodes are considered is based on detecting topological changes. These topological changes permit the re-assignment of different roles in the network to be started. In the scheme ESR*+EA_MAC_v2 the additional mechanism to assign the DMA roles is considered, but the DMA is added to the mechanism with the topological changes in such a manner that if some re-assignments have been made due to the topological changes the DMA mechanism is not applied. This permits values of lifetime to be obtained that are a little better than the original mechanism, because the DMA manages all the situations in which the topological changes are limited and does not imply changes in the role for a node for too long. As far as the latency is concerned in Fig. 3.13 it can be seen how the latency is the same when we consider the ESR*+EA_MAC_v2 and the original ESR+EMAC.

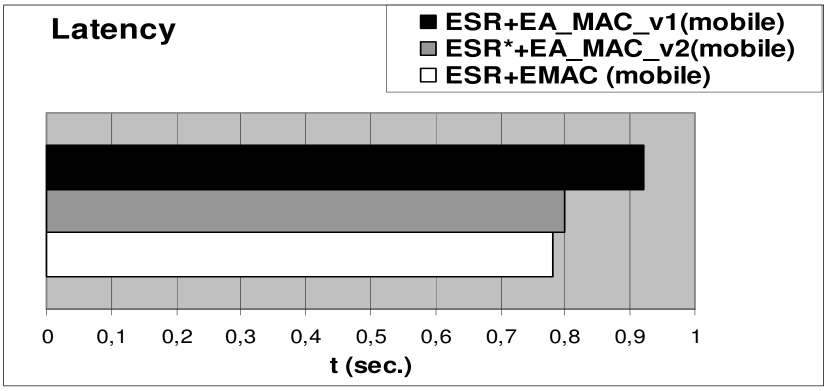


Fig. 3.13. Latency of the three different schemes considered in the mobile case (Network load 9msg/min).

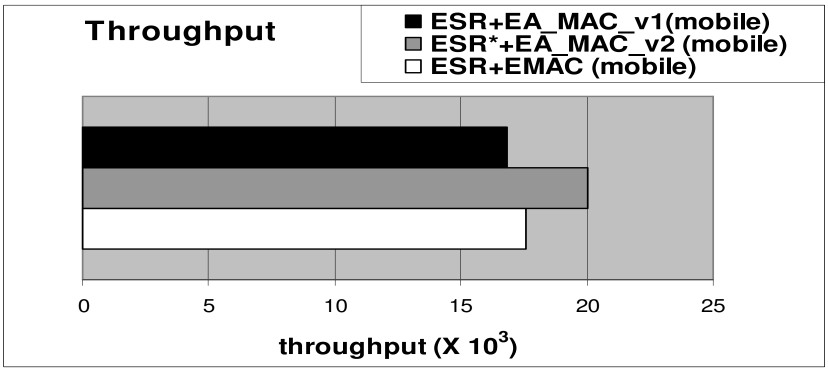


Fig. 3.14. Throughput of the three different schemes considered in the mobile case (Network load 9msg/min).

This is due to the fact that a node does not made any controls before changing its state and if a node is in a routing instance and the node that will substitute it does not support those routing instances, a flooding has to be realized in order to establish a new route. This implies that an increased delay is registered and some lost packets happen in the network. In fact, if we consider the throughput in the Fig. 3.14 better results are obtained when considering the mechanism with an additional role change (ESR*+EA_MAC_v2), that is the DMA, but also if the extension routing protocol (ESR*) is considered, which retains the substitution available only if a valid node substitute is found (based on the instance routing, that is, a node is considered more available if it satisfies a greater number of routing instances, see the mechanism described in the previous section). In fact, a greater number of lost packets are registered with the ESR+EA_MAC_v1 where the roles are re-assigned both if some topological changes happen or the timer of the DMA expires, but there is an amount of time necessary to find a new route if a node candidate to substitute another node is chosen that does not satisfy some or all the routing instances.

3.4 Conclusions

In this chapter the energy problem of wireless networks has been investigated. Specifically, different solutions have been proposed in order to improve energy usage. In section 3.2 a new protocol (TL-LEACH) considering a two cluster level architecture has been proposed. Some analytical considerations about the energy dissipation to justify a similar approach have been drawn. The setup and the Steady-State phase have been considered. Finally, a simulation tool was used to validate the analytical results obtained. Both through an analytical approach and a simulation tool the better performance of our approach has been demonstrated. The energy dissipation is lower than in the original protocol and the costs associated with the realization of our extension are minimal compared to the better results obtained in terms of energy consumption. Through simulation it is shown how our choice outperforms the original protocol in energy consumption and in lifetime. Specifically, our mechanism permits more data packets than in the LEACH protocol to be delivered. In section 3.3 a different solution has been proposed in order to improve the energy usage. In this section a Dynamic Management Algorithm (DMA) to periodically re-assign roles for nodes in a sensor network has been proposed. This approach is general and can be applied in different environments where nodes have a different role (we distinguish roles in active and passive). Specifically, this approach has been applied to a known cross-layered approach, the EYES Source Routing (ESR) and the EYES MAC protocol (EMAC). Two different approaches have been considered to apply the DMA in the ESR+EMAC, a first approach ESR EYES-Adaptive MAC (ESR+EA_MAC_v1) that does not consider the instances routing in the decisional mechanism and another approach ESR* EYES-Adaptive MAC (ESR*+EA_MAC_v2) in which the original was extended (ESR*) to add, in the decisional mechanism, the instances routing. Through a simulation tool (OMNeT++) simulation campaigns were conducted that showed the effectiveness of the proposed algorithm, above all in the ESR*+EA_MAC_v2 and above all in the static scenario. A possible extension of this work could be to introduce a mechanism, in each node, to evaluate the topological changes in the network in a local and distributed manner and consequently change the duration of the timer introduced to manage the role changes.

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4

Chapter 4 The IEEE 802.16 Technology

4.1 Introduction

The broadband wireless world is moving towards the adoption of WiMAX (the commercial name of the IEEE 802.16 standard) as the standard for broadband wireless Internet access. The IEEE 802.16 standard [1] promoted by the WiMAX (Worldwide Interoperability for Microwave Access) forum (http://www.wimaxforum.org), will be the leading technology for the wireless provisioning of broadband services in wide area networks. Such technology is going to have a deep impact on the way Internet access is conceived, by providing an effective wireless solution for the last mile problem. The market is experiencing an increasing demand for broadband multimedia services [2], pushing towards the adoption of broadband access technologies. In such a situation, Broadband Wireless Access (BWA) represents an economically viable solution to provide Internet access to a large number of clients, thanks to its infrastructure-light architecture, which make it easy to deploy services where and when it is needed. The IEEE standard defines the air-interface specifications for Wireless Metropolitan Area Networks (WMANs) operating between 10 and 66 GHz. The IEEE Standard 802.16a [3] amends the previous IEEE Standard 802.16 [4], designing physical layer (PHY) specifications for frequencies from 2 to 11 GHz and enhancing the Medium Access Control layer (MAC). It defines two modes of operation, Point-to-Multipoint (PMP) and Mesh mode. In the PMP mode traffic is directed from the Base Station (BS) to Subscriber Station (SSs, i.e. a common user), or vice-versa. Different to that within the Mesh mode, traffic can occur directly among SSs, without being routed through the BS (Mesh BS). The Mesh BS is the entity that interfaces the wireless network to the backhaul links. It acts like a BS in PMP mode but not all the SSs have to be directly connected to the Mesh BS. It is expected that one important feature of a new air-interface for very high data rates is the support of multi-hop communication. As relatively new standard, IEEE 802.16 has been studied much less than access technologies as IEEE 802.11. Eklund et al. presented an system level overview of 802.16 standards family in [5]. Redana and Lott modeled and compared the control message overhead between centralized and distributed scheduling mechanisms in [6]. From a different angle, Cao et al. proposed a theoretic model to compute the schedule interval of 802.16 coordinated distributed scheduling in [7].With the algorithm to grant data requests left open in the standard, the schedule interval is an important common performance metric that reflects the scheduling latency of coordinated distributed scheduling. Other related topics include QoS support in mesh mode [8], and cross-layer scheduling behaviors [9, 10, 11]. The IEEE 802.16 has three mechanisms to schedule the data transmission in mesh mode – centralized scheduling, coordinated distributed scheduling and uncoordinated distributed scheduling. In centralized scheduling, the BS works like a cluster head and determines how the SS's should share the channel in different time slots. Because all the control and data packets need to go through the BS, the scheduling procedure is simple, however the connection setup delay is long. Hence the centralized scheduling is not suitable for occasional traffic needs [12] In distributed scheduling, every node competes for channel access using a pseudo-random election algorithm based on the scheduling information of the two-hop neighbors. The distributed channel access control is more complex because every node computes its transmission time without global information about the rest of the network. Other important concepts of Mesh systems in IEEE 802.16 are neighbor, neighborhood and extended neighborhood. The stations that have direct links with a node are called neighbors. Neighbors of a node form a neighborhood. A node's neighbors are considered to be "one hop" away from the node. An extended neighborhood contains, additionally, all the neighbors of the neighborhood. In a mesh system, adopting the distributed scheduling, all the nodes including the Mesh BS coordinate their transmissions in their two hop neighborhood and broadcast their schedules (available resources, requests and grants) to all their neighbors. Optionally, the schedule may also be established by directed uncoordinated requests and grants between two nodes. These nodes ensure that the resulting transmissions do not cause collisions with the data and control traffic scheduled by any other node in the two hop neighborhood. There is no difference in the mechanism used in determining the schedule for downlink and uplink. This chapter is organized as follows. In section 4.2 an overview on WiMAX Technology is presented. The reference model is reported in section 4.3. Section 4.4 focuses on QoS issues in Wireless Mesh Networks for PMP and Mesh modes. In section 4.5 frame structure is presented for both, PMP and Mesh mode. In section 4.6 an overview on MAC is done. In section 4.7 Network Entry and Synchronization mechanisms are considered.

4.2 WiMAX Technology Overview

WiMAX is the commercial name of products compliant with the IEEE 802.16 standard. Effectively replicating the successful history of IEEE 802.11 and Wi-Fi, an industrial organization, the WiMAX Forum has been set up to promote the adoption of such technology and to ensure interoperability among equipment of different vendors. This forum, which includes all the major industrial leaders in the telecommunication field, is expected to play a major role in fostering the adoption of IEEE 802.16 as the *de facto* standard for BWA technology. The general protocol architecture of the IEEE 802.16 standard is depicted in Fig. 4.1.

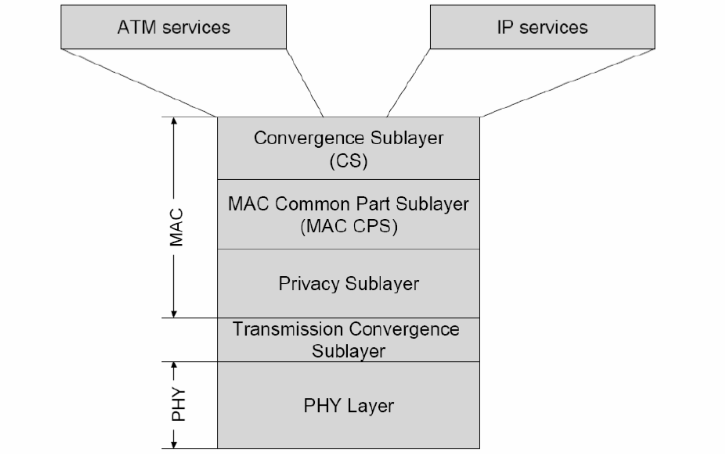


Fig. 4.1. IEEE 802.16 protocol architecture.

As can be seen, a common media access control (MAC) is provided to work on top of different physical layers (PHY). The interface between the different PHYs and the MAC is accommodated as a separate sub-layer, the transmission convergence sub-layer. A Convergence Sub-layer (CS) is provided on top of the MAC, to accommodate both IP as well as ATM-based network technologies. A basic privacy support is provided at the MAC layer. WiMAX technology can reach a theoretical 50 Km coverage radius and achieve data rates up to 75 Mb/s, although actual IEEE 802.16 equipments are still far from these performance characteristics. As an example, in [13], the authors report the outcomes of some bit-level numerical simulations performed assuming a channel width of 5 MHz and a Multiple-Input Multiple-Output (MIMO) 2X2 system (which reflects the most common actual equipment), showing that, under ideal channel conditions, data rates up 18 Mb/s are feasible.

Duplexing is provided by means of either Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD). In TDD, the frame is divided in two sub-frames, devoted to downlink and uplink, respectively. A Time-Division Multiple

Access (TDMA) technique is used in the uplink sub-frame, the BS being in charge of assigning bandwidth to the SSs, while a Time Division Multiplexing (TDM) mechanism is employed in the downlink sub-frame. In FDD, the uplink and downlink sub-frames are concurrent in time, but are transmitted on separate carrier frequencies. Support for half-duplex FDD SSs is also provided, at the expense of some additional complexity. Each sub-frame is divided into physical slots. Each TDM/TDMA burst carries MAC Protocol Data Units (PDUs) containing data towards SSs or BS, respectively. The transmission convergence sub-layer operates on top of the PHY and provides the necessary interface with the MAC. This layer is specifically responsible for the transformation of variable-length MAC PDUs into fixed length PHY blocks [5]. Since IEEE 802.16 uses a wireless medium for communications, the main target of the MAC layer is to manage the resources of the radio interface in an efficient way, while ensuring that the QoS levels negotiated in the connection setup phase are fulfilled. The 802.16 MAC protocol is connection-oriented. All traffic, including inherently connectionless traffic, is mapped into a connection which is uniquely identified by a 16-bit address. The common part sub-layer is responsible for the segmentation and the reassembly of MAC service data units (SDUs), the scheduling and the retransmission of MAC PDUs. As such, it provides the basic MAC rules and signaling mechanisms for system access, bandwidth allocation and connection maintenance. The core of the protocol is bandwidth requests/grants management. A SS may request bandwidth, by means of a MAC message, to indicate to the BS that it needs (additional) upstream bandwidth. Bandwidth is always requested on a per-connection basis to allow the BS uplink scheduling algorithm (which is not specified in the standard) to consider QoS-related issues in the bandwidth assignment process. As depicted if Fig 4.1, the MAC includes a convergence sub-layer which provides the main functionalities:

1. Classification. The CS associates the traffic coming from upper layer with an appropriate Service Flow (SF) and Connection Identifier (CID).
2. Payload Header Suppression (PHS). The CS may provide payload header suppression at the sending entity and reconstruction at the receiving entity.
3. Delivering of the resulting CS PDU to the MAC Common Part Sub-layer in conformity with the negotiated QoS levels.

4.3 Reference Model

In Fig. 4.2 the reference model of the IEEE Std 802.16 is illustrated. The MAC comprises three sub-layers. The Service-Specific Sub-layer (CS) provides any transformation or mapping of external network data, received through the CS service access point (SAP) into MAC SDUs received by the MAC Common Part

Sub-layer (CPS) through the MAC SAP. This includes classifying external network service data units (SDUs) and associating them to the proper MAC service flow identifier (SFID) and connection identifier (CID). It may also include such functions as payload header suppression (PHS). Multiple CS specifications are provided for interfacing with various protocols. The internal format of the CS payload is unique to the CS, and the MAC CPS is not required to understand the format of or parse any information from the CS payload. The MAC CPS provides the core MAC functionality of system access, bandwidth allocation, connection establishment, and connection maintenance. It receives data from various CSs, through the MAC SAP, classified to particular MAC connections. The MAC also contains a separate security sub-layer providing authentication, secure key exchange, and encryption. Data, PHY control, and statistics are transferred between the MAC CPS and the PHY vs the PHY SAP (which is implementation specific).

4.4 QoS Architecture

The IEEE 802.16 specifies two modes for sharing the wireless medium: Point-to-Multipoint (PMP) and mesh (optional). With PMP, the BS serves a set of user (SSs) within the same antenna sector in a broadcast manner, with all SSs receiving the same transmission form the BS. Transmissions from SSs are directed to and centrally coordinated by the BS. In mesh mode, traffic can be routed through other SSs and can occur directly among SSs. Access coordination is distributed among the SSs. In PMP mode, uplink (from SS to BS) and downlink (from BS to SS) data transmissions occur in separate time frames.

Network that utilizes a shared medium shall provide and efficient sharing mechanism. Two-way PMP and Mesh topology wireless networks are examples for sharing wireless media. Here, the medium is the space through which the radio waves propagate. Though the MAC specification invokes IP protocols, they are required only as a standard basis for management rather than MAC operation, since, in all practicality, element management is necessary in this type of network.

4.4.1 PMP

The downlink, from the BS to the user, operates on a PMP basis. The IEEE Std 802.16 wireless link operates with a central BS and a sectorized antenna that is capable of handling multiple independent sectors simultaneously. Within a given frequency channel and antenna sector, all stations receive the same transmission, or parts thereof. The BS is the only transmitter operating in this direction, so it transmits without having to coordinate with other stations, except for the overall time division duplexing (TDD) that may divide time into uplink and downlink transmission periods. The downlink is generally broadcast. In cases where the message that defines the access to the downlink information (DL-MAP) does not explicitly indicate that a portion of the downlink sub-frame is for a specific SS, all SSs capable of listening to that portion of the downlink sub-frame shall listen. Subscriber stations share the uplink to the BS on a demand basis. Depending on the class of service utilized, the SS may be issued continuing rights to transmit, or the right to transmit may be granted by the BS after receipt of a request from the user. Within each sector, users adhere to a transmission protocol that controls contention between users and enables the service to be tailored to the delay and bandwidth requirements of each user application. This is accomplished through four different types of uplink scheduling mechanisms. These are implemented using unsolicited bandwidth grants, polling, and contention procedures. Mechanisms are defined in the protocol to allow vendors to optimize system performance by using different combinations of these bandwidth allocation techniques while maintaining consistent interoperability definitions. For example, contention may be used to avoid the individual polling of SSs that have been inactive for a long period of time. The use of polling simplifies the access operation and guarantees that applications receive service on a deterministic basis if it is required. In general, data applications are delay tolerant, but real-time applications like voice and video require service on a more uniform basis and sometimes on a very tightly-controlled schedule. The MAC is connection oriented and for this reason all data communications are in the context of a connection. Service flows may be provisioned when an SS is installed in the system. Shortly after SS registration, connections are associated with these service flows (one connection per service flow) to provide a reference against which to request bandwidth. Additionally, new connections may be established when a customer's service needs change. A connection defines both the mapping between peer convergence processes that utilize the MAC and a service flow. The service flow defines the QoS parameters for the PDUs that are exchanged on the connection. The concept of a service flow on a connection is central to the operation of the MAC protocol. Service flows provide a mechanism for uplink and downlink QoS management. Specifically, they are integral to the bandwidth allocation process. An SS requests uplink bandwidth on a per connection basis (implicitly identifying the service flow). Bandwidth is granted by the BS to an SS as an aggregated of grants in response to per connection requests from the SS. Connections, once established, may require active maintenance. The maintenance requirements vary depending upon the type of service connected. For example, unchannelized T1 services require virtually no connection maintenance since they have a constant bandwidth allocated every frame. Channelized services require some maintenance due to the dynamic (but relatively slowly changing) bandwidth requirements if compressed, coupled with the requirement that full bandwidth be available on demand. IP services may require a substantial amount of ongoing maintenance due to their burst nature and due to the high possibility of fragmentation. As with connection establishment, modifiable connections may require maintenance due to stimulus from either the SS or the network side of the connection. Finally, connections may be terminated. This generally occurs only when a customer's service contract changes. The termination of a connection is stimulated by the BS or SS. All three of these connection management functions are supported through the use of static configuration and dynamic addition, modification, and deletion of connections.

4.4.2 Mesh

The main difference between the PMP and Mesh (optional) modes is that in the PMP mode, traffic only occurs between the BS and SSs, while in the Mesh mode traffic can be routed through other SSs and can occur directly between SSs. Depending on the transmission protocol algorithm used, this can be done on the basis of equality using distributed scheduling, or on the basis of superiority of the Mesh BS, which effectively results in centralized scheduling, or on a combination of both. Within a Mesh network, a system that has a direct connection to backhaul services outside the Mesh network, is termed a Mesh BS. All the other systems of a Mesh network are termed Mesh SS. In general, the systems of a Mesh network are termed nodes. Within Mesh context, uplink and downlink are defined as traffic in the direction of the Mesh BS and traffic away from the Mesh BS, respectively. In a Mesh system not even the Mesh BS can transmit without having to coordinate with other nodes. Using distributed scheduling, all the nodes including the Mesh BS shall coordinate their transmissions in their two-hop neighborhood and shall broadcast their schedules (available resources, requests and grants) to all their neighbors. Optionally the schedule may also be established by directed uncoordinated requests and grants between two nodes. Nodes shall ensure that the resulting transmissions do not cause collisions with the data and control traffic scheduled by any other node in the two-hop neighborhood. There is no difference in the mechanism used in determining the schedule for downlink and uplink. Using centralized scheduling, resources are grants in a more centralized manner. The Mesh BS shall gather resource requests from all the Mesh SSs within a certain hop range. It shall determine the amount of granted resources for each link in the network both in downlink and uplink, and communicates these grants to all the Mesh SSs within the hop range. The grant messages do not contain the actual schedule, but each node shall compute it by using the predetermined algorithm with given parameters. All the communications are in the context of a link, which is established between two nodes. One link shall be used for all the data transmissions between the two nodes. QoS is provisioned over links on a message-by message basis. No service or QoS parameters are associated with a link, but each unicast message has service parameters in the header. Traffic classification and flow regulation are performed at the ingress node by upper-layer classification/regulation protocol. The service parameters associated with each message shall be communicated together with the message content via the MAC SAP.

Mesh systems typically use omni-directional or 360° steerable antennas, but can also be co-located using sector antennas. At the edge of the coverage area of the Mesh network, where only a connection to a single point is needed, even highly directional antennas can be used.

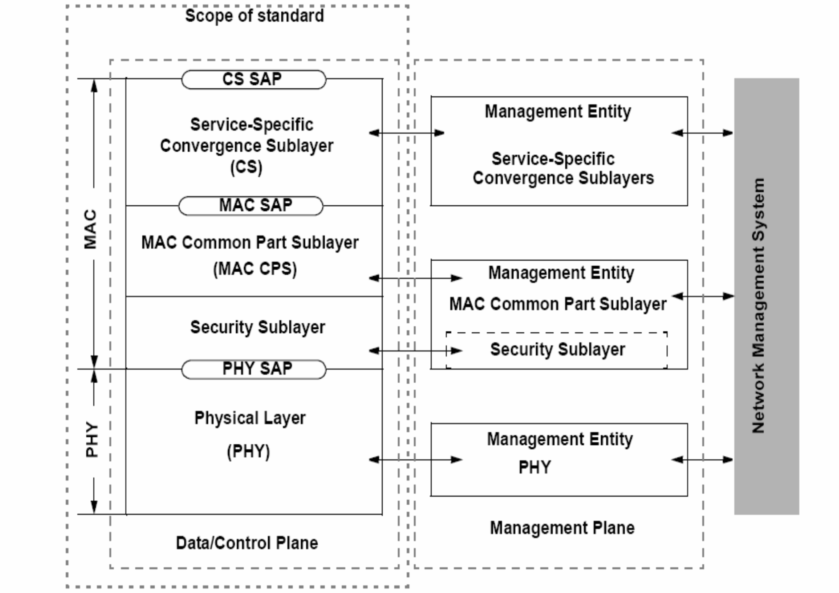
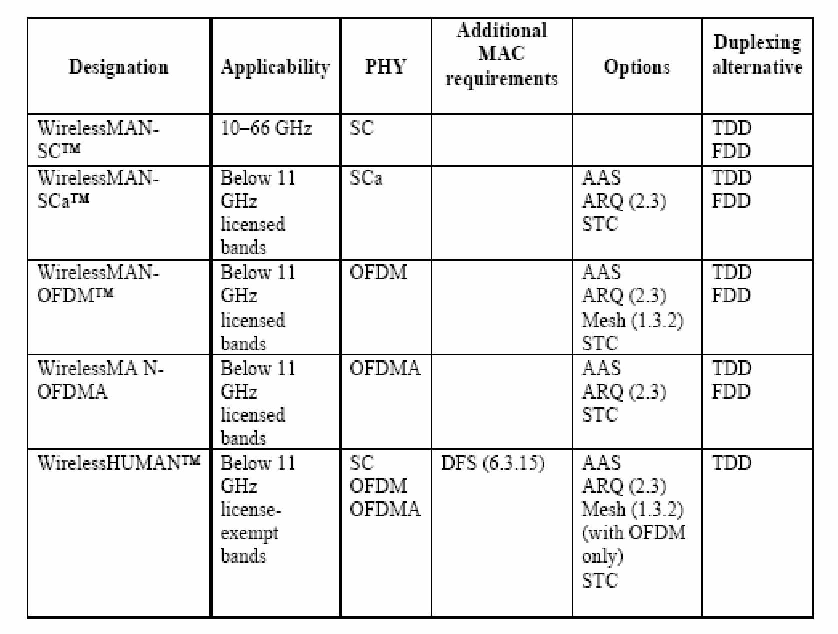


Fig. 4.2. IEEE Std 802.16 protocol layering, showing SAPs.

4.5 Frame Structure

In licensed bands (Fig. 4.3), the duplexing method can be either FDD (Frequency Division Duplexing) or TDD (Time Division Duplexing). In license exempt bands, the duplexing, the duplexing method can be only TDD. We have considered in this work only the TDD method since it is common in PMP and Mesh mode. In the following section the different frame structures are presented.

In the IEEE Std 802.16 there are various air interface specifications. All of the are shown below:



Designation	Applicability	PHY	Additional MAC requirements	Options	Duplexing alternative
WirelessMAN-SC™	10–66 GHz	SC			TDD FDD
WirelessMAN-SCa™	Below 11 GHz licensed bands	SCa		AAS ARQ (2.3) STC	TDD FDD
WirelessMAN-OFDM™	Below 11 GHz licensed bands	OFDM		AAS ARQ (2.3) Mesh (1.3.2) STC	TDD FDD
WirelessMA N-OFDMA	Below 11 GHz licensed bands	OFDMA		AAS ARQ (2.3) STC	TDD FDD
WirelessHUMAN™	Below 11 GHz license-exempt bands	SC OFDM OFDMA	DFS (6.3.15)	AAS ARQ (2.3) Mesh (1.3.2) (with OFDM only) STC	TDD

Fig. 4.3. Air Interface Nomenclature.

There are four different physical layers (PHY) as it can be seen in the previous table: SC, SCa, OFDM and OFDMA. Only SC physical layer performs over 10-60 GHz licensed bands. The rest of the physical layers work over frequencies below 11 GHz.

When there is a common air medium which must be shared , an efficient sharing mechanism has to be used to utilize it in an efficient way. In IEEE Std 802.16 there are two different sharing wireless media; Point-to-Multipoint (PMP) and Mesh topology wireless networks.

4.5.1 PMP air-interface

This topology operates with a central Base Station (BS) (Fig. 4.4) and its sectorized antenna which has the capability of handling multiple independent sectors simultaneously. Within a given frequency and antenna sector, when the BS transmits all the Subscriber Stations (SSs) receive the same transmission. The BS owns the control of the downlink. Respect the uplink, all the transmissions are directed to the BS. The BS manages the network by coordinating the transmission of the SSs. It does not require to coordinate its transmission with other stations. The frame interval contains transmissions (PHY PDUs) of BS and SSs and guard intervals.

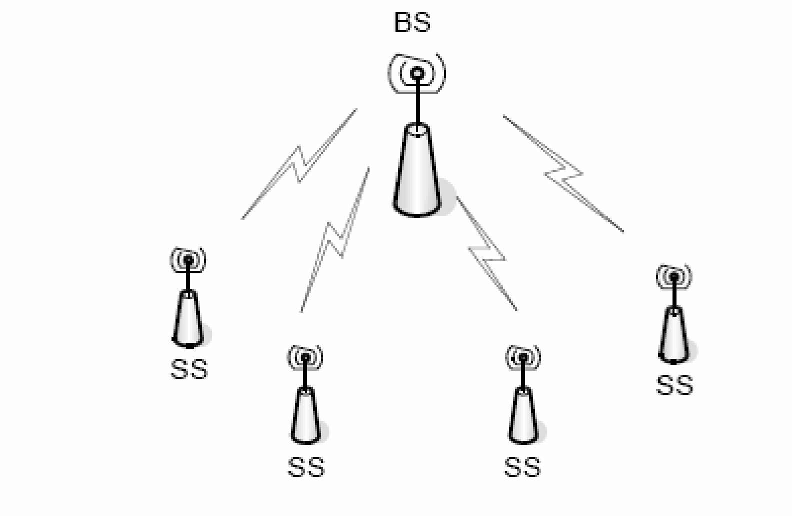


Fig. 4.4. PMP Network Topology.

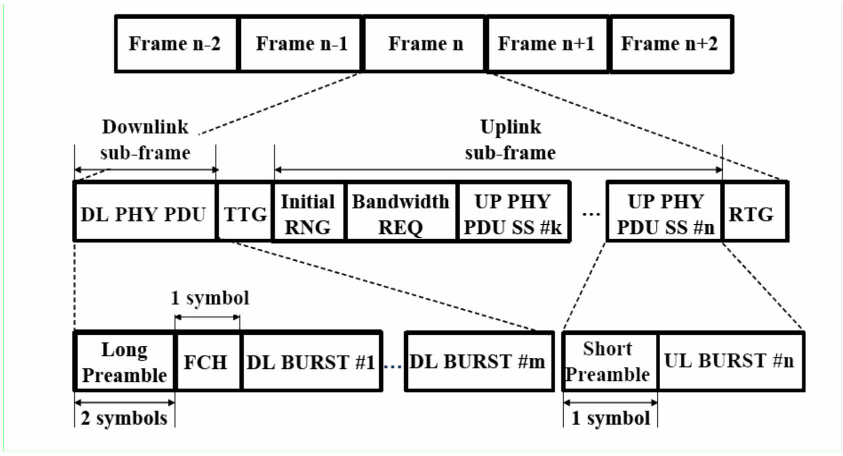


Fig. 4.5. PMP frame structure with TDD.

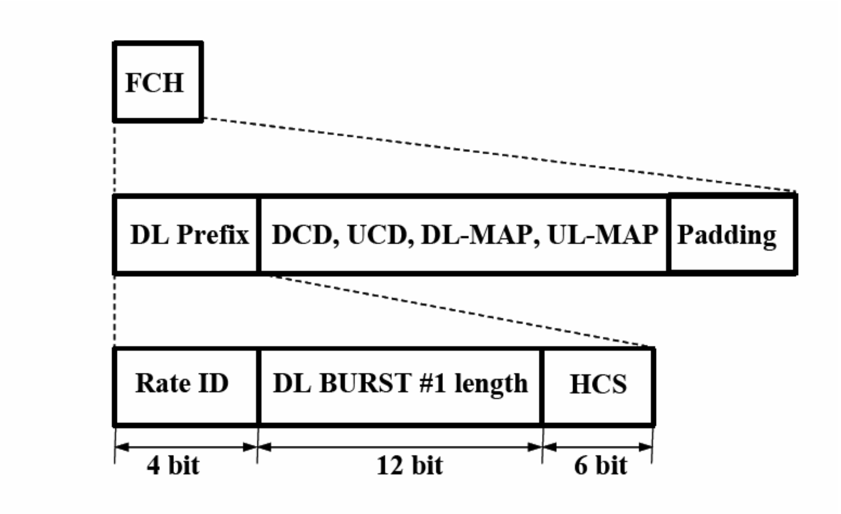


Fig. 4.6. FCH burst.

A frame consists of a Downlink sub-frame (DL sub-frame) and an Uplink sub-frame (UL sub-frame) (Fig. 4.5). A DL sub-frame consists of only one DL PHY PDU. An UL sub-frame consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple UL PHY PDUs, each transmitted from a different SS. Every UL PHY PDU consists of only one burst, which is made up of a short preamble and an integer number of OFDM symbols. The physical parameters of an UL PHY PDU are specified by a 4 bit UIUC (Uplink Interval Usage Code) in the UL-MAP (Uplink MAP). The DLU PHY PDU starts from a long preamble, which is used for PHY synchronization. The preamble is followed by FCH (Frame Control Header) burst. The FCH burst is one OFDM symbol long. The FCH contains (see Fig. 4.6):

- DL Frame Prefix: this specifies the burst profile (Rate ID) and length of the DL BURTS #1. The burst profile specifies the coding and modulation scheme used in the downlink;

and may also contain:

- MAC (Medium Access Control) control messages: such as DCD (Downlink Channel Descriptor) and/or UCD (Uplink Channel Descriptor). DCD and UCD are transmitted by the BS to define respectively the characteristics of a downlink and an uplink physical channel;
- MAP messages: such as DL-MAP (Downlink MAP) and UL-MAP (Uplink MAP). DL-MAP and UL-MAP message allocate access to respectively the downlink and the uplink channel defining bandwidth allocations.

The following are the fields of DL Frame Prefix:

- Rate ID: this defines the burst profile of the DL BURST #1;
- Length: number of OFDM symbols in the DL BURTS #1 immediately following the FCH burst. The minimum value is 6;
- HCS: an 8-bit Header Check Sequence used ti detect errors in the DL Frame Prefix.

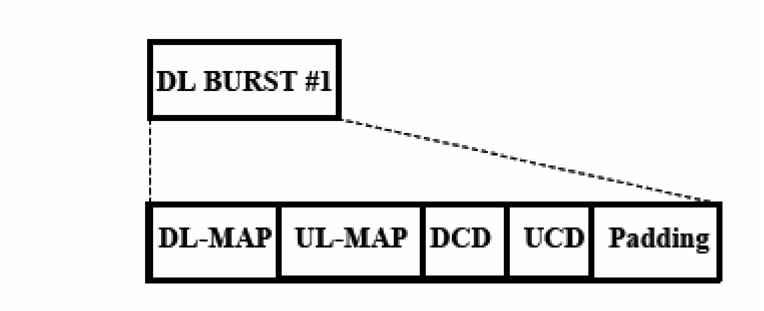


Fig. 4.7. DL BURST #1 format.

Although the DL BURST #1 (Fig. 4.7) contains broadcast MAC control messages, it is not needed to use the most robust coding. A more efficient coding may be used if it is supported and applicable to all the SSs of a BS. The FCH is followed by one or multiple DL BURSTs, each transmitted with different burst profiles. Each DL BURST consists of an integer number of OFDM symbols, and its burst profiles are specified by a 4 bit DIUC (Downlink Interval Usage Code) in the DL-MAP (Downlink MAP). Both a DL PHY BURTS or an UL PHY BURST consists of an integer number of OFDM symbols, carrying MAC messages or MAC PDUs. To form an integer number of OFDM symbols, a burst payload may be padded by the bytes 0xFF.

4.5.2 Mesh air-interface

The main difference between the PMP mode and Mesh mode is related with the link among the stations. In PMP all the transmission occur between the BS and SSs, whereas in Mesh mode the traffic can be placed directly between two SSs and the SSs do not must have direct links with the BS. The traffic can be en-routed through other SSs. In Mesh mode the concept of BS refers the station which has direct connection to the backhaul services outside the Mesh Network. All the other Stations are termed SSs. Within the Mesh Networks (Fig. 4.8) there are not down-link or up-link concept. Nevertheless a Mesh Network can perform similar as PMP, with the difference that not all the SSs must be directly connected with the BS. The resources are granted by the Mesh BS and this option is termed Centralized Scheduling. There is another manner to schedule the transmissions, the Distributed Scheduling. In this case all the SSs even the Mesh BS must coordinate their transmissions with the others and all the Stations shall broadcast their schedules. A Mesh frame consists of a Control sub-frame and a Data sub-frame, which are fixed in length. Two types of Control sub-frames exist, the Network Control sub-frame and the Schedule Control sub-frame. The Network Control sub-frame serves primarily for new terminals that want to gain access to the network. This type of Control sub-frame is transmitted periodically, whereas the period is a network parameter that can be varied.

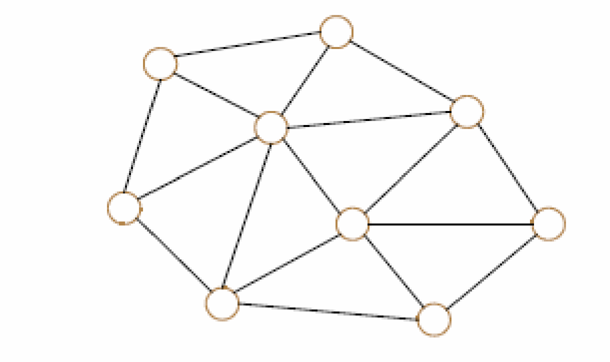


Fig. 4.8. Mesh mode topology.

Within the other Control sub-frames a Schedule Control sub-frame is transmitted. It is used to determine the amount of allocated transmit resources for a link, which is served within the data sub-frame. All the communications are in the context of a link, which is established between two nodes (SSs). The data transfer within the Data sub-frame is connection-oriented and, hence, a connection (link) is established beforehand by means of a resource request, which is initiated by a SS, and a resource grant. A resource grant corresponds to a fraction of time in the Data sub-frame. If the centralized scheduling scheme is selected, the BS assigns the granted resource for each link in response to resource requests. The grant messages do not contain the actual schedule, but each SS should compute it by using a predetermined algorithm with given parameters. In case of distributed scheduling the neighboring SS responds to the request with a corresponding grant for the link between the involved two SSs. The centralized and distributed scheduling method can be deployed simultaneously. The length of the Control sub-frame is expressed as number of OFDMA symbols as:

$$L_{CS} = 7.MSH\_CTRL\_LEN \tag{4.1}$$

Where MSH_CTRL_LEN is a 4 bit field indicated by the Mesh BS in the MSH-NCFG (Mesh Network Configuration) message [3]. The MSH_CTRL_LEN can assume a value between 0 and 15. Two types of Control sub-frames exist, the Network Control and Schedule Control sub-frame. They serve two basic functions:

- Network Control sub-frame: creates and maintenances the cohesion between different entities in the network. In the Network Control sub-frame MSH-NCFG and MSH-NENT (Mesh Newtork Entry) messages are transmitted [3]. MSH-NCFG message provides a basic level of communication between nodes in different nearby networks and MSH-NENT message provides the means for a new node to gain synchronization and initial network entry into a Mesh network;
- Schedule Control sub-frame: coordinates scheduling of data transfers between nodes.

Frames containing a Network Control sub-.frame occur periodically and all other frames have the Schedule Control sub-frame.

Network Control sub-frame

During a Network Control sub-frame (see Figs. 4.9 and 4.10):

- first 7 OFDM symbols are allocated for network entries,

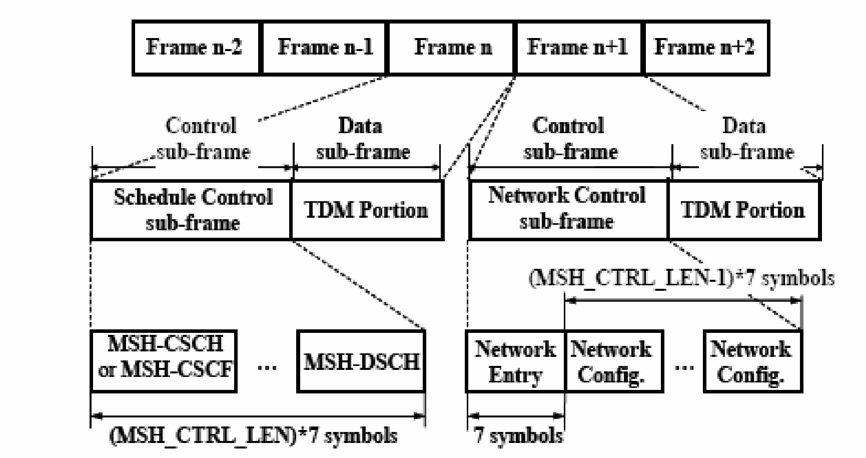


Fig. 4.9. Mesh frame structure with TDD.

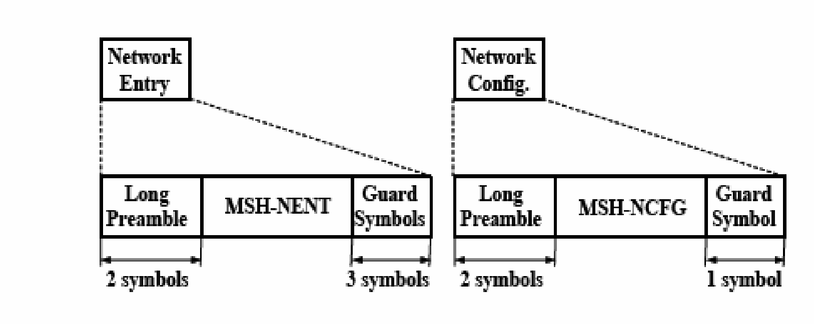


Fig. 4.10. Mesh network control messages.

- MSH_CTRL_LEN -1 sets of 7 OFDM symbols are allocated for network configuration.

The part for the network entry is reserved for new stations that want to enter the system. The portion for network configuration is used to broadcast network information to all nodes and provide a basic level of communication among nodes in different nearby network. The number of frames containing the Schedule Control sub-frame between two frames with Network Control sub-frames is defined by a 4 bits field (in multiple of 4 frames) in the MSH-NCFG message. A frame with the Network Control sub-frame can occur at most in 60 frames.

Schedule Control sub-frame

During the Schedule Control sub-frame the Mesh BS indicates how many distributed scheduling messages (MSH_DSCH_NUM in the MSH-NCFG message) may occur in the Control sub-frame. The first

7 . (MSH_CTRL_LEN – MSH_DSCH_NUM)

OFDM symbols are allocated to transmission bursts containing MSH-CSCH (Mesh Centralized Scheduling) and MSH-CSCF (Mesh Centralized Configuration) messages. The remainder is allocated to transmission burst containing MSH-DSCH (Mesh Distributed Scheduling) messages. MSH-CSCH and MSH-DSCH messages handle portion of the network where respectively the distributed and centralized scheduling is applied.

Data sub-frame

The Data sub-frame serves for the transmission of user data in variable length PHY BURSTs. The PHY BURST contains a number of fixed length FEC (Forward Error Correction) blocks in order to fill the allocated resources.

4.6 MAC PDU

Each standard has a different structure of messages. This structure is influenced greatly by the characteristics of the standard, as well as the standard depends in the features of the messages. Therefore it is mandatory start explaining the MAC PDU.

4.6.1 MAC PDU formats

Each PDU shall commence with a fixed-length Generic MAC header (fig. 4.11). As it is being studying the Standard in the Mesh Mode it can be already included the Mesh sub-header however as it is logic this sub-header is only necessary for Mesh Network. All the sub-header included the Mesh sub-header are within the payload but among the sub-headers, the Mesh sub-header shall be always the first. The implementation of CRC capability is mandatory for SCa, OFDM and OFDMA PHY layers. Therefore, as Mesh Mode is supported only over OFDM, CRC shall be included in the PDU format.

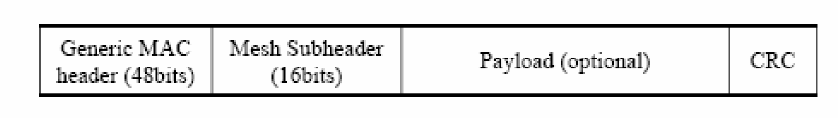


Fig. 4.11. MAC PDU format.

There are two different MAC header formats. The first and the most important heard format is the generic MAC starting each MAC PDU containing either MAC management messages or CS data. The second is used when requesting bandwidth (bandwidth request header). The generic MAC header is illustrated in Fig. 4.12.

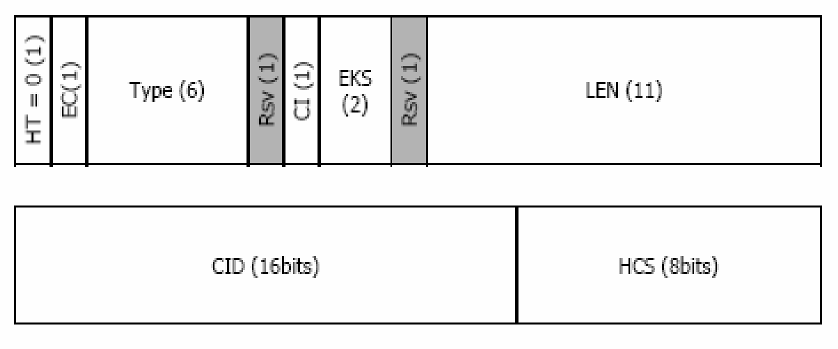


Fig. 4.12. Generic MAC header format.

HT : Header Type
Shall be set to zero. Otherwise (“1”) corresponds to a Bandwidth request header
EC : Encryption Control
Payload is encrypted (“1”) or no (“0”)

Type
This field indicates the sub-headers and special payload types present in the messages payload. It is organized by bits. Beginning from the most significant bit (MSB)#5:

- #5: Mesh sub-header present (“1”). In our case it shall set to 1.
- #4: ARQ Feedback Payload
- #3: Extended Type. Packing or Fragmentation sub-headers extended.
- #2: Fragmentation Sub-header
- #1: Packing Sub-header
- #0: FAST-FEEDBACK allocation sub-header (downlink) or Grant Management sub-header (uplink present)

CI : CRC Indicator
CRC is included (or no) in the PDU

EKS : Encryption Key Sequence
The index of the Traffic Encryption Key (TEK) and Initialization Vector used to encrypt the payload.

LEN : Length
The length in bytes of the MAC PDU including the MAC header and the CRC if present

CID : Connection Identifier
The CID construction is different in PMP and Mesh Mode. It shall be used a 8 bit link identifier (Link ID) for addressing nodes in the local neighborhood. One ID for each link. The Link ID shall be transmitted in each MAC generic header as part of the CID in unicast messages.

If it is a MAC Management broadcast Xmt Link ID shall be 0xFF and the CID shall constitute of Xmt Link ID (1byte = 0xFF) and Logical Network ID (1 byte), if not it shall be as follows:

Type: (2 bits) 0x0: MAC Management
0x1 : IP
Reliability: (2bits) 0x0: No retransmissions

0x1 : Up to 4 retransmissions

Priority/Class (3 bits)

Drop Precedence (2bits)

Xmt Link ID (8bits)

HCS : Header Check Sequence

An 8 bit field used to detect errors in the header

The Mesh Sub-header is only composed by the Xmt Node ID (16 bits).

4.6.2 Construction of MAC PDUs

In order to achieve a correct and efficient construction of a MAC PDU, many processes are used (as shown in Fig. 4.13). Fragmentation and Packing are the most important in the IEEE 802.16 but without forgetting the concatenation, which is related with PMP networks, therefore it will not be investigated. Fragmentation is the process by which a MAC PDU is divided into one or more fragments, in order to allow efficient use of available bandwidth relative to the QoS requirements of a connection's service flow. Fragmentation and reassembly capabilities are mandatory in the MAC layer.

When the connection is created by the MAC SAP the authority of the fragment traffic on a connection is defined. The fragments are labeled according to their position in their parent SDU. The different options can be observed in the Fragmentation sub-header format, shown in the Fig. 4.14). Note that with the **FC** field it can figure out that the fragments are tagged with their position in their parent SDU. The fragmentation process varies a little depending if the connection is ARQ-enabled or non-ARQ. In the first case fragments are formed for each transmission by linking sets of ARQ blocks with adjacent sequence number. The BSN value within the fragmentation sub-header is the BSN for the first ARQ block appearing in the segment. On the case of non-ARQ connections fragments are transmitted one time in sequence. With the sequence number assigned to each fragment the receiver is able to recreate the original payload and detect if some fragment failed in the transmission. After a loss of intermediate fragment the receiver shall discard all the MAC PDUs until a new first fragment or non-fragmented MAC PDU is detected.

The packing process provides the capability of packing multiple MAC SDUs into a single MAC PDU. This packing process can be realized with fixed-length or variable-length packets, always indicated. As in the fragmentation the construction of PDUs varies for the ARQ-enabled and non-ARQ connections (Fig. 4.14).

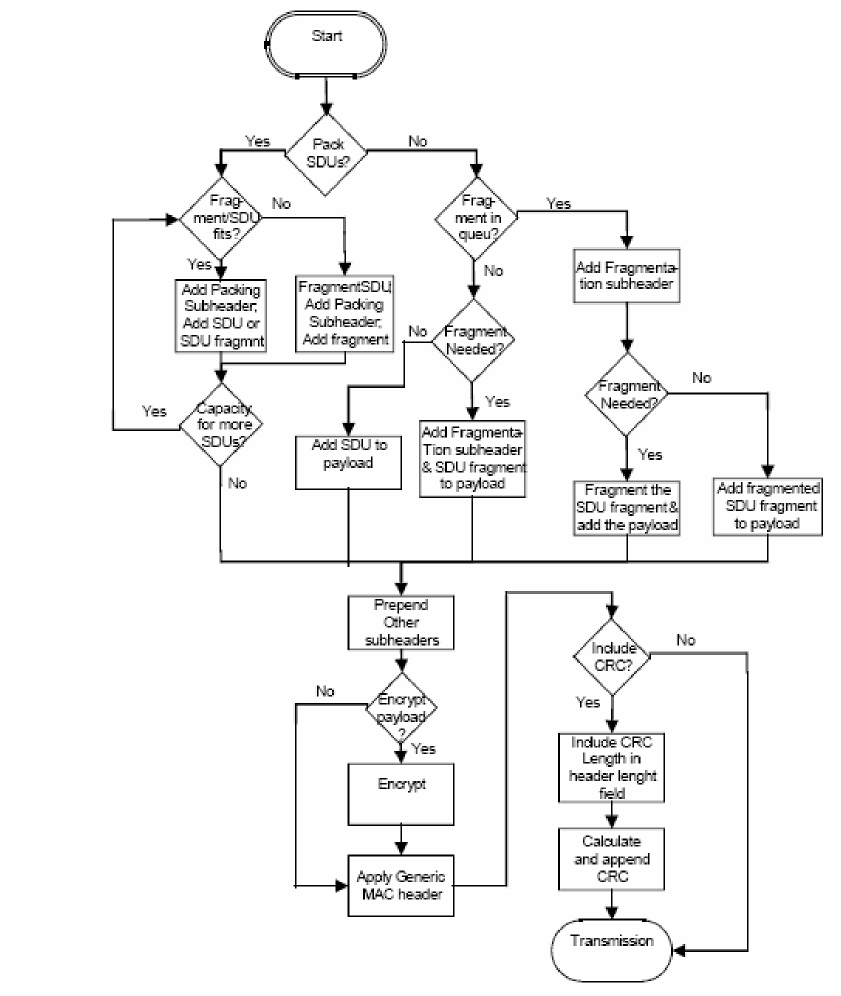
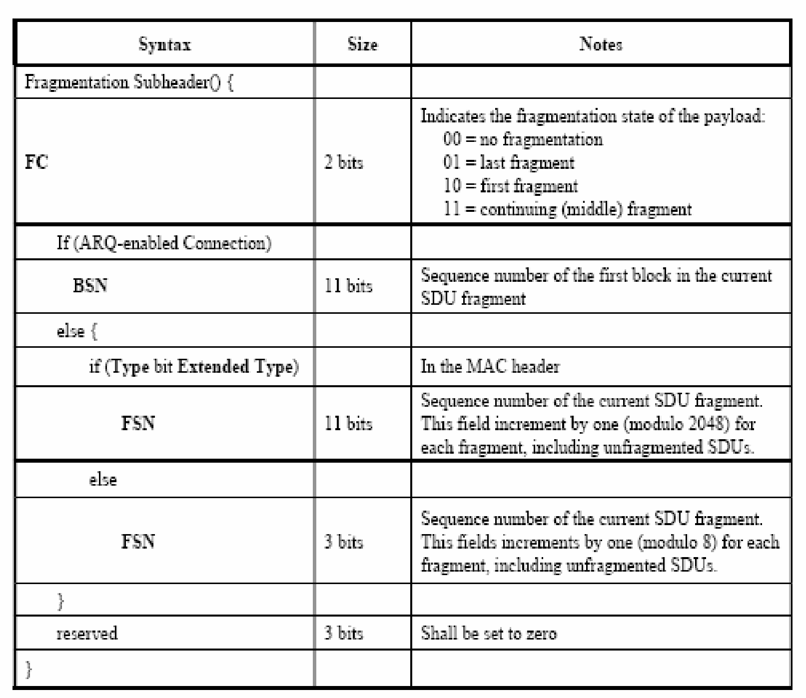


Fig. 4.13. Construction of a MAC PDU.



Syntax	Size	Notes
Fragmentation Subheader() {		
FC	2 bits	Indicates the fragmentation state of the payload: 00 = no fragmentation 01 = last fragment 10 = first fragment 11 = continuing (middle) fragment
If (ARQ-enabled Connection)		
BSN	11 bits	Sequence number of the first block in the current SDU fragment
else {		
if (Type bit **Extended Type**)		In the MAC header
FSN	11 bits	Sequence number of the current SDU fragment. This field increment by one (modulo 2048) for each fragment, including unfragmented SDUs.
else		
FSN	3 bits	Sequence number of the current SDU fragment. This fields increments by one (modulo 8) for each fragment, including unfragmented SDUs.
}		
reserved	3 bits	Shall be set to zero
}		

Fig. 4.14. Fragmentation Sub-header format.

4.6.3 Arq Mechanism

The implementation of the ARQ mechanism is optional. If the ARQ mechanism is implemented, it may be enabled on a per-connection basis. During connection creation the per-connection ARQ shall be specified and negotiated, because a connection can have ARQ or non-ARQ traffic, but not both at the same time. The reach of a specific instance of ARQ is limited to one unidirectional connection. In the case of ARQ-enabled connections, it may be used fragmentation or no. In both cases the fragment size shall be according to the ARQ_BLOCK_SIZE. ARQ feedback cannot be fragmented. However it may be packed. An ARQ feedback payload may consist in more than one ARQ feedback IE. This is possible on ARQ or non-ARQ connections. Only one ARQ Feedback payload can be presented within a MAC PDU. In the rest of the aspects, the ARQ Feedback payload is treated like any other payload.

4.7 Network Entry and Synchronization

Before explaining the procedure of the Network Entry it would be interesting to provide a brief introduction about the messages there are in the Mesh mode. All the messages in the Mesh mode have a Mesh Sub-header which includes only the node ID.

4.7.1 Management Messages

In the MAC layer a set of MAC Management messages are defined. There are many types of them. Some of these types shall neither be fragmented nor packed (with kind of connection: Basic, Broadcast and Initial Ranging). Within this last group the Management Messages of Mesh Mode are. Upon Mesh Mode there are five different MAC Management Messages:

- MSH-NCFG: Mesh Network Configuration
- MSH-NENT: Mesh Network Entry
- MSH-DSCH: Mesh Distributed Schedule
- MSH-CSCH: Mesh Centralized Schedule
- MSH-CSCF: Mesh Centralized Schedule Configuration

Within the Network Entry and Initialization in Mesh Mode only MSH-NCFG and MSH-NENTMAC Management Messages are used. Therefore it is easy to realize that this procedure is independent with the different topologies (Distributed or Centralized).
Firstly it would be important to describe a little of both MSH-NCFG and MSH-NENT messages.

MSH-NCFG : (Mesh Mode Configuration). This message provides a basic level of communication between nodes in close networks. There are two important flags:

- NetEntry MAC Address Flag: If this flag I "1" it is because the MAC Address is present
- Embedded Packet Flag: As the first case, a "1" means the MSH-CNFG embedded data is present, with a variable length. At the same time within this field it can be found:
    - **Type:** 0x1: Network Descriptor
      0x2: Network Entry Open
      0x3: Network Entry Reject
      0x4: Network Entry Ack (Embedded_data_IE() == NULL)
      0x5: Neighbor Link Establishment Protocol:

0x0 Challenge
0x1 Challenge response
0x2 Accept
0x3 Reject

- **Embedded _data_IE():** If in here ist is found that Channels is not null there are five different options for the MSH-NCFG_Channel_IE(): MSH-NCFG Channel IE (license-exempt), MSH-NCFG Channel IE (licensed), Network entry Open IE, Network entry Reject IE or Neighbor link Establishment IE.

MSH-NENT: (Mesh Mode Network Entry). The Management Message Type = 40. For a new node to gain synchronization and initial network entry into a Mesh Network. In this case the only field is worthy to distinguish is:

- **Type:** 0x1: NetEntry Ack
  0x2: NetEntry Requester (MSH-NENT Request IE with the MAC address)
  0x3: NetEntry Close

4.7.2 Procedure of Entry and Initialization

Node initialization and entry in Mesh mode are different in some aspects with Point-to-Multipoint Mode (PMP). It must match the procedure for this different mode which needs another kind of operation.

All the actions for this procedure in the correct order are shown below. As in the PMP mode the last three are optional.

- Scan for active network and establish coarse synchronization with the network
- Obtain network parameters
- Open Sponsor Channel
- Node Authorization
- Perform Registration
- Establish IP connectivity
- Establish time of day
- Transfer operational parameters

4.7.2.1 Scanning and Coarse synchronization to the Network

The first step is scan for active network and establishes synchrinization with the network. This is possible on the initialization or signal loss by receiving a MSH-

NCFG in the new node. The coarse synchronization is acquired from the timestamp field in the MSH-NCFG message.

4.7.2.2 *Obtain Network parameters*

Once it has been achieved the synchronization, the MAC shall try to acquire Network parameters (Fig.4.15). Without neglecting the construction of a physical neighbor list. While the node is receiving MSH-NCFG the new node is in synchronization, however it is not allowed to do anything more.
The new node shall accumulate all the MSH-NCFG messages. With all the valid messages it is receiving it shall build a physical neighbor list.
When the new node has received at least two MSH-NCFG messages from one node and one Network Descriptor (Embedded Packet Flag = 1 -> Network Descriptor IE), all from nodes with acceptable Operator IDs, it is not necessary any more to accumulate more MSH-NCFG.

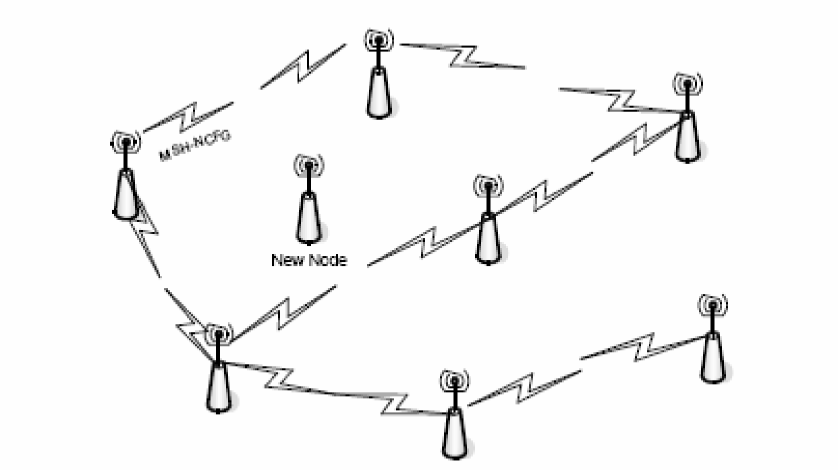


Fig. 4.15. New node is accumulating the MSH-NCFG from all the nodes.

From all the nodes in established physical neighbor list, the new node shall choose a possible sponsoring mode having the logical Network ID of the node. They have to get synchronized assuming null propagation delay.

4.7.2.3 *Open Sponsor Channel*

Once the new node has selected a possible sponsoring node it has to negotiate basic capabilities. Until the new node has been assigned a Node ID it will use the 0x0000 in the Mesh Sub-header. In this moment the new node shall call candidate node. The candidate node shall request the candidate sponsoring node to set up a temporary schedule that could be used during the candidate node initialization. The request is started by the candidate node transmitting a MSH-NENT: NetEntry Request message (MSH-NENT with Type: 0x2) to the candidate sponsoring node. After the reception of the MSH-NENT: NetEntry Request the candidate sponsoring node could either open the sponsor channel (MSH-NCFG embedded data with Network entry Open IE) or reject the request (MSH-NCFG embedded data with Network entry Reject IE).

Once the candidate node has received the NetEntry Open message from the candidate sponsoring node in the MSH-NCFG message, it shall confirm the schedule by transmitting a MSH-NENT: NetEntry Ack message (MSH-NENT with Type: 0x1) to the candidate sponsoring node.

When the candidate sponsoring node accepts the request and opens the Sponsor Channel, the channel is ready for use instantly after the transmission of the NetEntry Ack message. In this moment the candidate sponsoring code becomes the Sponsoring Node. After opening the Sponsor Channel new node can start upper MAC entry. This is Security sub-layer and basic capability exchange operations. In Mesh Mode the basic capabilities are negotiated as in the PMP, using the same messages. Once the logical link has been established the new node that requested the logical node shall act as the SS (Subscriber Station) and shall initiate the SBC-REQ (Basic Capability Request).

4.7.2.4 MAC Management message tunneling

In Mesh Networks during network entry, certain MAC message protocols, take place between entities in Stations separated by multiple hops. In these cases when the new node requires exchanging messages with any node farther than the Sponsor node this last shall relay the MAC messages from the new node to other performing the commitment of the PMP BS.

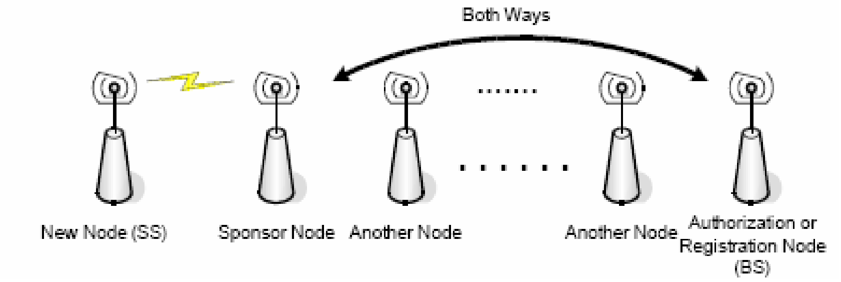


Fig. 4.16. Tunneling in Mesh mode.

The Sponsor node shall tunnel, as shown in Fig. 4.16, the MAC messages listed in the table shown below to the entity performing the BS part of the protocol. This transmission shall be implemented over UDP.

4.7.3 Frame Structure and Scheduling algorithm

In the Mesh Mode there are not a clearly separate downlink and uplink sub-frames. Each station is able to connect directly with others without obligation to pass through the BS. The communication in the links among different SS shall be controlled by a algorithm. However in Mesh Mode there shall be some nodes providing the functions of the BS in PMP mode (centralized mode). In Mesh Mode when a BS is mentioned is referred to the station that connects the Mesh Network to the backhaul links. It shall be distinguished two different schedules: Centralized and Distributed. In Mesh Centralized Mode the BS nodes (connected to the backhaul links) perform in a similar manner than BS in PMP mode, however the main difference is that in Mesh Mode not all of the SSs have to be directly connected to the BS. Because it is not desired for studying a topology where there are BS nodes performing as manager in the network, Mesh Distributed Mode is the objective of the investigation.

4.7.3.1 Frame Structure

The frames structure in Mesh Networks is highly different of the frame structure in PMP Networks, which has the frame divided in two sub-frames: Down-Link and Up-Link Subscriber Station. This is useless for Mesh mode since all the nodes has the same importance, each station can connect directly with others. In Mesh Networks, for the scheduling algorithm, control message and data packets are allocated in different time slots in a frame. At the same time there are two control sub-frame types in Mesh Mode. One is the *Network Control* sub-frame (Network entry and Network Configuration) that creates and maintains the cohesion between different systems. This sub-frame is the same for centralized and distributed systems however the other control sub-frame, *Schedule Control* sub-frame, depends in the Network Distribution. The sub-frame structure is shown in Fig. 4.17. The transmission of the *Network Control* sub-frame occurs periodically and the rest frames contain *Schedule Controls* sub-frames. Every control sub-frame consists of sixteen transmission opportunities and every transmission opportunity consists in seven OFDM symbols time. The data sub-frame is situated after the control sub-frame in a frame and is divided into minislots. The minislot is the basic unit for resource allocation. All of these measurements of the frame are explained in Fig. 4.18, with each sub-frame.

In Coordinated Distributed Scheduling all the stations shall indicate their own schedule by sending a MSH-DSCH regularly. As it has been seen MSH-DSCH messages are transmitted during the *Schedule Control* sub-frame. For controlling the proportion between *Schedule Control* and *Network Control* sub-frames the field Scheduling Frame (within MSH-NCFG: Network Descriptor) is used. This field indicates how many frames have a *Schedule Control* sub-frame between two frames with *Network Control* sub-frame. The number is multiple of four frames.

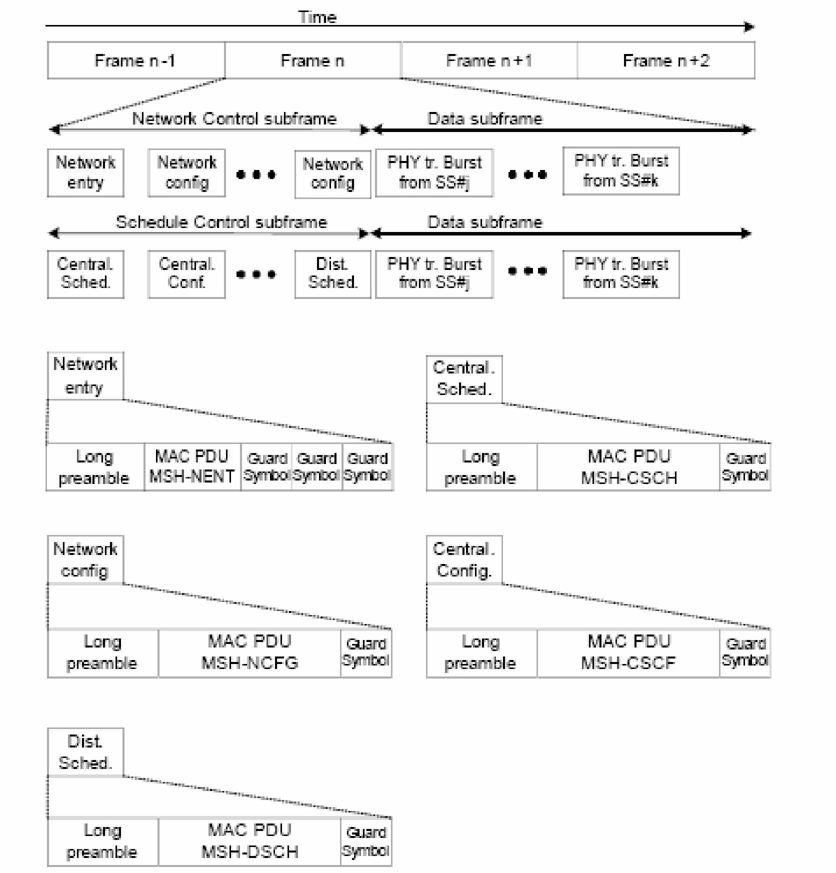


Fig. 4.17. Frame structure in Mesh Mode.

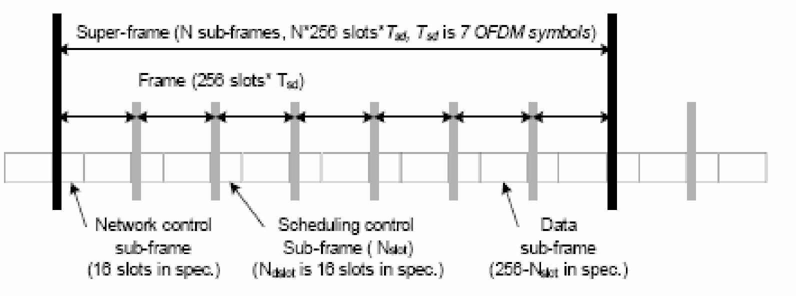


Fig. 4.18. Overall frame structure.

4.7.4 Parameters for Distributed Scheduling

There are two parameters used in Distributed Mesh Networks for scheduling: NextXmtMx and XmtHoldoffExponent. These two parameters are contained within MSH-NCFG and MSH-DSCH: Scheduling IE messages. Since in Distributed Scheduling there is not a Base Station which schedule and control the transmission of each node, it is necessary a distributed manner to schedule the transmissions.

The concept is based on communicating all nodes when any node is going to transmit (in the case of MSH-DSCH messages including the information of the neighbors) thus, every station has the knowledge of the scheduling of its two-hop neighborhood. As it has been seen before, MSH-NCFG messages are scheduled in the Network Control sub-frame and MSH-DSCH messages in the *Schedule Control* sub-frame. In Coordinated Distributed scheduling the MSH-DSCH messages are scheduled in a free manner, there are not collisions. In Mesh Mode eligibility and transmission opportunities are concepts commonly used to explain the scheduling. Here it is explicated the **NextXmtMx** and **XmtHoldoffExponent**.

- **XmtHoldoffExponent**: XmtHoldoffTime is the number of MSH-NCFG/MSH-DSCH transmit opportunities after **NextXmtTime** (there are **MSH-CTRL-**1 opportunities per *Network/Schedule Control* sub-frame, with MSH-CTRL-LEN indicated in the Network Descriptor) that this station is not eligible to transmit MSH-NCFG/MSH-DSCH packets.

$$XmtHoldoff\ Time = 2^{(XmtHoldoff\ Exponent\ +4)}$$

- **NextXmtMx:** NextXmtTime is the next MSH-NCFG/MSH-DSCH eligibility interval for this station

$$2^{XmtHoldoffExponent} * NextXmtMx < NextXmtTime \leq$$

$$2^{XmtHoldoffExponent} * (NextXmtMx + 1)$$

For example, if **NextXmtMx** = 2 and **XmtHodoffExponent** = 4 the station would be eligible between the 33 and 48 transmissions opportunities.

4.7.5 Distributed Election Algorithm

Every node calculates its **NextXmtTime** during the current transmission according the distributed election algorithm. In this algorithm one node sets the first transmission slot just after the **XmtHoldoffTime** as the temporary next transmission opportunity. In this instant this node shall compete with all the competing nodes in the two-hop neighborhood (this node is called Node A). There are different types of competing nodes (Fig. 4.19):

- **NextXmtTime** includes the temporary transmission slot (Node

B).

- **EarliestSubsequenceXmtTime** (equal to **NextXmtTime** + **XmtHoldoffTime**) is ≤ the temporary transmission slot (Node C)
- The Next Time is not known (Node D).

This algorithm is a pseudo-random function which uses the slot number and the Node’s ID as the inputs, this algorithm is executed in each node. It generates pseudo-random values depending in the input. The node wins when its result is the largest mixing value (Fig. 4.20).

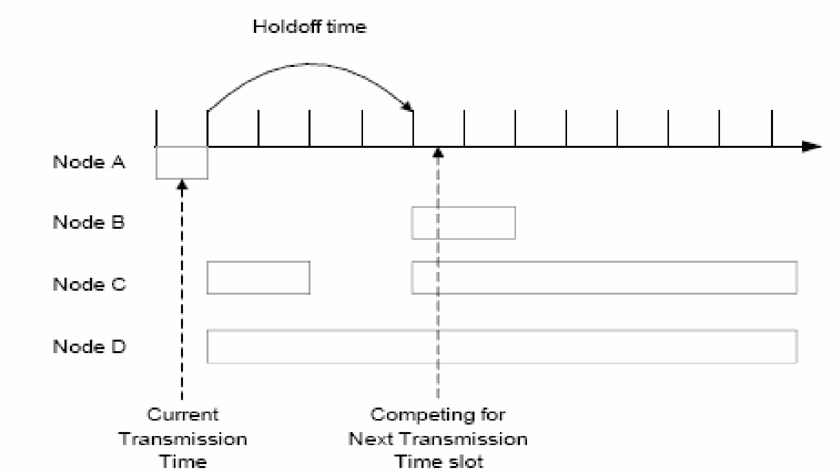


Fig. 4.19. Competing Nodes for Next Transmission time slot.

When any node wins, it sets the temporary transmission opportunity as its next transmission time and logically it shall communicate this information to all the neighbors by sending the corresponding packet.

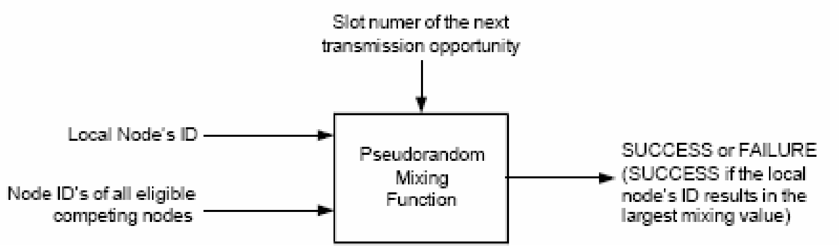


Fig. 4.20. Pseudorandom Mixing Function.

In the case a node has not won, it chooses the next transmission opportunity and repeat the algorithm as many times as it needs to win.

4.7.6 Uncoordinated Distributed Schedule

Unlike coordinated schedules (distributed or centralized) uncoordinated distributed scheduling can be used for fast transmissions, ad-hoc setup of schedules on a link-by-link basis. Uncoordinated distributed schedules are established by using a three-way handshake (requests and grants between two nodes). This exchange of messages shall be schedule to ensure that the resulting data transmission does not cause collisions with the data and control traffic scheduled by the coordinated distributed methods.

In both, coordinated and uncoordinated distributed Mesh Networks, a three-way handshaking procedure is used in order to set up connection with neighbors. This procedure is shown in Fig. 4.21.

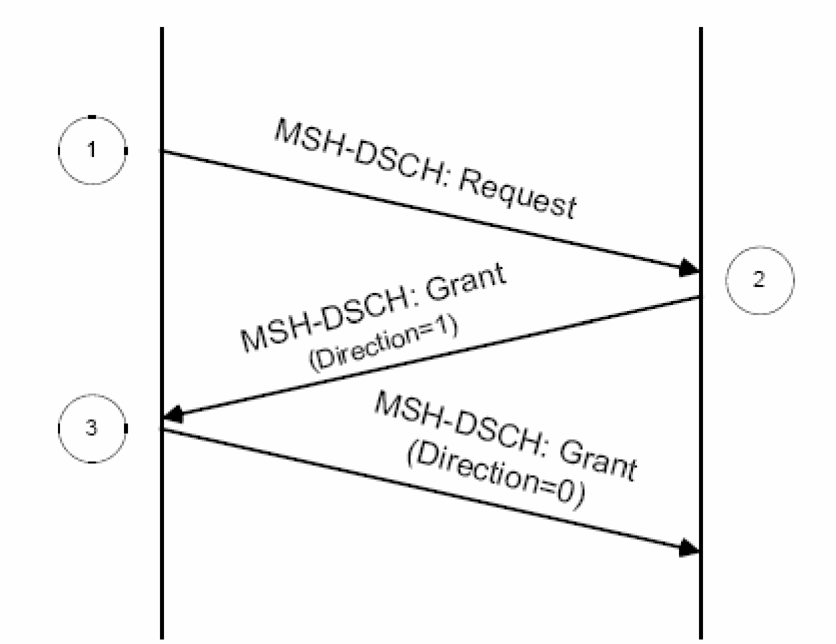


Fig. 4.21. Three-way handshaking.

First of all the requester sends the request information in the MSH-DSCH packet along with the data sub-frame availability information, which indicates potential slots for replies and actual schedule. After receiving the request, the receiver shall response with a grant message including all or a subset of the suggested availabilities. The MSH-DSCH packet transmission is always broadcasted among the neighborhood; therefore the neighbor nodes not included in the exchange assume the transmission takes place as granted. When the requester receives the grant messages, it replies with another grant message as confirmation message (containing a copy of the replies with another grant message as confirmation message (containing a copy of the grant from the other part. Also the neighbors of this node not involved in this schedule shall assume the transmission takes place as granted). Then all the neighbors of the requester cannot use allocated minislots anymore. With this mechanism, all the neighbors of the requester and the granter can have the up-to-date data sub-frame allocation information.

Once explained the procedure used for the set up connections with neighbors, it is very important to indicate that logically there are many differences between coordinated and uncoordinated distributed scheduling:

The MSH-DSCH messages in coordinated scheduling are scheduled in the control sub-frame in a collision free manner as it was seen above.

In the uncoordinated case MSH-DSCH messages may collide. They shall be sent during the data sub-frame.

In the uncoordinated case, nodes responding to a Request should wait enough number of minislots of the indicated availabilities before responding with a grant, in order to let other nodes, listed earlier in the Request, have an opportunity to respond. The Grant confirmation shall be sent in the minislots immediately following the first successful reception of an associated Grant packet.

4.7.7 Physical Neighborhood List

In Mesh Distributed Mode all the stations which have direct links shall constitute a neighborhood, being all of them neighbors. A two-hop extended neighborhood includes, in addition, all the neighbors of the neighborhood. This is possible by using the physical neighborhood list.

As it is mentioned in the Entry and Initialization, the basic functions are based on the information that each node in Mesh Mode has about all the neighbors in the neighborhood. This information is maintained in a Physical Neighborhood List wherein the fields are as follows:

- **MAC address:** 48-bit MAC address of the neighbor
- **Hop Count:** the distance in hops from the present node to this neighbor. If a packet has been successfully received from this neighbor the Hop Count is considered 1.
- **Node Identifier:** 16-bit number to identify this node in a more efficient way in MSH-NCFG messages.
- **XmtHoldoffExponent:** the minimum number of MSH-NCFG transmit opportunities that no MSH-NCFG message transmission is expected from this node after **NextXmtTime.**

- **NextXmtTime:** the MSH-NCFG transmit opportunity(ies) when the next MSH-NCFG message from this node is expected.
- **Reported Flag:** Set to TRUE if this **NextXmtTime** (NextXmtTime within the field **NetConfig schedule info** in MSH-NCFG message) has been reported by this node in a MSH-NCFG packet otherwise set to FALSE.
- **Synchronization hop count:** This counter is used to determine superiority between nodes when synchronizing the network. Nodes shall synchronize to nodes with lower synchronization hop count, and in the case counts are the same, to the node with lower Node ID.

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5

Chapter 5 MAC Protocols over WMN: problems and perspective

The wireless mesh networking has emerged as a promising technology for future broadband wireless access [1, 2]. Although the notion of mesh networking has been discussed extensively in wireline and optical networks [3, 4], the research mainly focuses on restoration of link failure and/or design of survivable and healing networks. When applying mesh networking techniques over shared wireless medium with limited radio spectrum, many new challenges are raised such as fading mitigation, effective and efficient medium access control (MAC), quality of service (QoS) routing, call admission control, etc. Wireless mesh networks (WMNs) consist of wireline gateways, mesh routers, and mesh clients, organized in a three-tier architecture [1, 5] as shown in Fig. 5.1. A mesh client network can be formed in an ad hoc manner, and connected to one or more mesh routers. The mesh routers in fixed sites comprise a wireless mesh backbone to provide relay service to the mesh client networks and other access networks such as cellular networks, wireless local area networks (LANs), etc. The wireless mesh backbone provides a platform to integrate the wireless local area networks, so that a multi-mode mobile station with multiple air interfaces can roam freely among the access networks and select desired services. For WMNs, due to the limited radio bandwidth, MAC is essential to coordinate the transmissions from/to the mesh routers and clients in an effective and efficient manner. MAC for wireless networks can be categorized into two groups: centralized and distributed MAC, according whether the access to the medium is coordinated in a centralized or distributed fashion. Centralized MAC is usually designed for infrastructure-based networks such as cellular networks. On the other hand, distributed MAC is suitable for infrastructure-less networks such as mobile ad hoc networks without a pre-existing central controller, where each node determines its own access to the medium according to its local observation of the channel [6]. Due to the self-organization nature of WMNs, it is desired to apply distributed MAC to achieve efficient resource utilization. Without central coordination, distributed MAC is more challenging than centralized MAC as contention and hence transmission collision are generally inevitable. There are extensive research results on distributed MAC over mobile ad hoc networks in the literature [7, 8]. Although organized in an ad hoc manner, the WMNs are quite different from traditional mobile ad hoc networks [14, 15, 16, 17, 18]. In fact, the wireless mesh backbone is with low (or no) mobility and has no power constraint, and the wireless clients may form a network attached to fixed mesh routers, thus with only limited mobility. The traffic volume in the wireless mesh backbone in a large-scale WMN can be very large and can vary from one mesh router to another, thus posing significant challenges on the MAC design. Therefore, it may not be effective or efficient to directly apply existing MAC protocols proposed for ad hoc networks (i.e., the Evolutionary-TDMA, E-TDMA [9], [19]) to the wireless mesh backbone and the mesh client networks. This paper is to provide a comprehensive overview on distributed MAC protocols, discuss their suitability for WMNs, and present new solutions while discussing further research issues in this area.

5.1 The Standard IEEE 802.11: Problems and Challenges in a WMN

5.1.1 The IEEE 802.11: some details

The IEEE 802.11 protocol covers the MAC and physical layers. The standard currently defines a single hop MAC which interacts with three PHYs (all of them running at 1 and 2 Mb/sec) as follows: frequency hopping spread spectrum in the 2.4 GHz band, direct sequence spread spectrum in the 2.4 GHz band, and infrared. The MAC layer defines two different access methods, the distributed coordination function (DCF) and point coordination function (PCF). The basic access mechanism, the DCF, is basically a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. A CSMA protocol works as follows. A station desiring to transmit senses the medium. If the medium is busy (i.e., some other station is transmitting), the station defers its transmission to a later time. If the medium is sensed as free, the station is allowed to transmit. These kinds of protocols are very effective when the medium is not heavily loaded, since it allows stations to transmit with minimum delay. But there is always a chance of stations simultaneously sensing the medium as free and transmitting at the same time, causing a collision. The latter case will cause significant delay. In order to overcome the collision problem, the 802.11 uses a CA mechanism coupled with a positive acknowledge scheme, as follows:

- A station wanting to transmit senses the medium. If the medium is busy, it defers. If the medium is free for a specified time, called the distributed inter-frame space (DIFS) in the standard, the station is allowed to transmit.

- The receiving station checks the cyclic redundancy check (CRC) of the received packet and sends an acknowledgement packet. Receipt of this ACK indicates to the transmitter that no collision occurred. If the sender does not receive the ACK packet, it retransmits the frame until it receives an ACK or throws it away after a given number of retransmissions. According to the standard, a maximum of seven retransmissions are allowed before the frame is dropped.

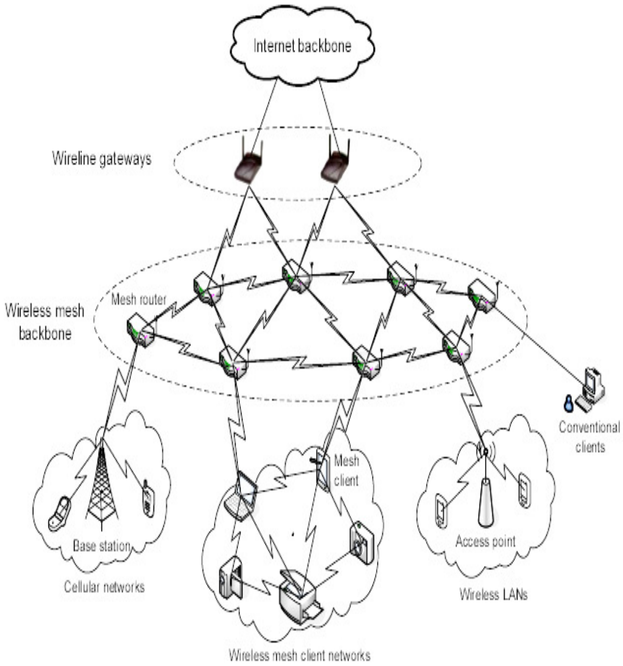


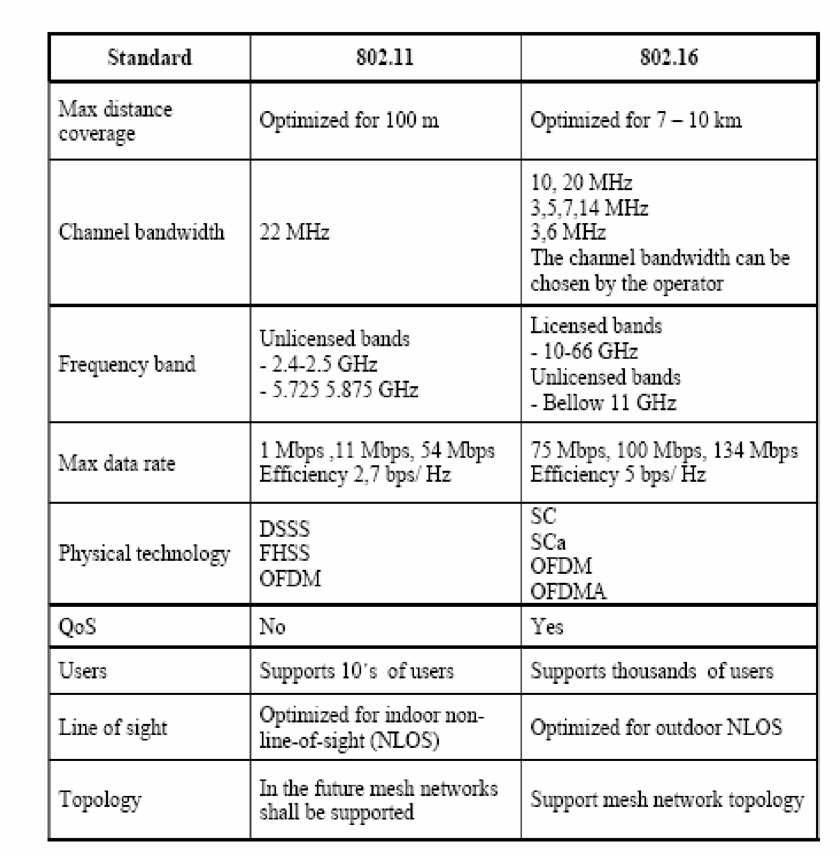
Fig.5.1. An illustration of Wireless Mesh Network.

In order to reduce the probability of two stations due not hearing each other, the well-known “hidden node problem”, the standard defines a virtual CS mechanism: a station wanting to transmit a packet first transmits a short control packet called request to send (RTS), which includes the source, destination, and duration of the intended packet and ACK transaction. The destination station responds, if the medium is free, with a response control Packet called clear to send (CTS), which includes the same duration information. All other stations receiving either RTS and/or the CTS set their virtual CS indicator, called a network allocation vector (NAV), for the given duration and use this information together with the physical CS when sensing the medium. This mechanism reduces the probability of the receiver area collision caused by a station that is "hidden" from the transmitter during RTS transmission, because the station overhears the CTS and "reserves" the medium as busy until the end of the transaction. A hidden node is one that is within the interfering range of the intended destination but out of the sensing range of the sender. Hidden nodes can cause collisions on data transmissions. Wireless packets networks also face the exposed node problem. Exposed nodes are complementary to hidden nodes. An exposed node is one that is within the sensing range of the sender but out of the interfering range of the destination. As consequence, the available bandwidth is underutilized. In the 802.11 MAC layer protocol, there is not scheme to deal with this problem. This might cause a serious problem when it is used in multi-hop wireless networks.

5.1.2 IEEE 802.11: Problems and Challenges in a WMN

A wireless mesh network is a dynamic collection of backhaul routers. It is similar to an ad hoc network, but the topology, composed of backhaul routers, is static. The backhaul router has more functionality than an AP. However the IEEE 802.11 MAC protocol, CSMA/CA, is originally designed for single-hop WLAN environment, not for multi-hop wireless networks. The backhaul networking of a wireless mesh network must have the following concerns: capacity, throughput, latency, and reach. Based on the analysis on previous works [10, 11], CSMA/CA can not meet the requirements of backhaul networking. In [10], the authors discovered that CSMA/CA did not function well in a wireless multi-hop environment. The results revealed that not only the instability problem of throughput occurred in the TCP connections, but also a serious unfairness existed among TCP connections. This is caused by the hidden terminal problem, the exposed terminal problem, and the binary exponential back-off scheme of the IEEE 802.11. In Section 5.2.2.2 we will show results that confirm results obtained in [10] and [11]. In Table 5.1 a comparison between standard 802.11 and standard 802.16, in general different aspects, is shown.

Table 5.1.General Comparison parameters of the two Standards



Standard	802.11	802.16
Max distance coverage	Optimized for 100 m	Optimized for 7 – 10 km
Channel bandwidth	22 MHz	10, 20 MHz 3,5,7,14 MHz 3,6 MHz The channel bandwidth can be chosen by the operator
Frequency band	Unlicensed bands - 2.4-2.5 GHz - 5.725 5.875 GHz	Licensed bands - 10-66 GHz Unlicensed bands - Bellow 11 GHz
Max data rate	1 Mbps ,11 Mbps, 54 Mbps Efficiency 2,7 bps/ Hz	75 Mbps, 100 Mbps, 134 Mbps Efficiency 5 bps/ Hz
Physical technology	DSSS FHSS OFDM	SC SCa OFDM OFDMA
QoS	No	Yes
Users	Supports 10's of users	Supports thousands of users
Line of sight	Optimized for indoor non-line-of-sight (NLOS)	Optimized for outdoor NLOS
Topology	In the future mesh networks shall be supported	Support mesh network topology

5.2 Two Topology-Independent Schemes: R-MAC and DSS

In this paragraph we describe some potential enhancements to mesh deployment of 802.16 that are well within reach. The proposed advances should increase the average throughput and the robustness of the Coordinated Distributed Scheduling scheme of 802.16. We do not modify the structure frame of the standard and we do not add complexity, so the hardware of the standard must not be changed.

5.2.1 Randomized-MAC: some more details

Randomized-MAC permits conflict-free schedules with high probability to be built. Based on information acquired from its neighborhood each node updates its schedule. The current schedule is the actual schedule used by node to transmit and to compute another *Perm-S*. The mechanism used to compute a new transmission time (*Perm-S*) is a RandomFunction(). After a new broadcast slot is computed a message will be sent to the neighbors with the updated data schedule based on the number of data slots a node needs. In Fig. 5.2 the frame structure of the distributed TDMA protocol is shown. A Control Re-Distribution Round is executed at the beginning of the frame in order to assign a new *Perm-S* to each node that looses the right to transmit in a slot computed in the previous frame. In this approach the reservation of data slots is realized from the sender based on the information it received in the previous frame. In practice, in each frame a node reserves data slots based on information of the current control schedule (computed in the previous frame) and computes a new control schedule (called here next control schedule). In the Control Re-Distribution stage each node that does not have a *Perm-S* tries to acquire this based on the current schedule. In fact, a node *i* selects a set of available slots and a slot s is available if in the current schedule the state of the node *i* in this slot s is Idle.

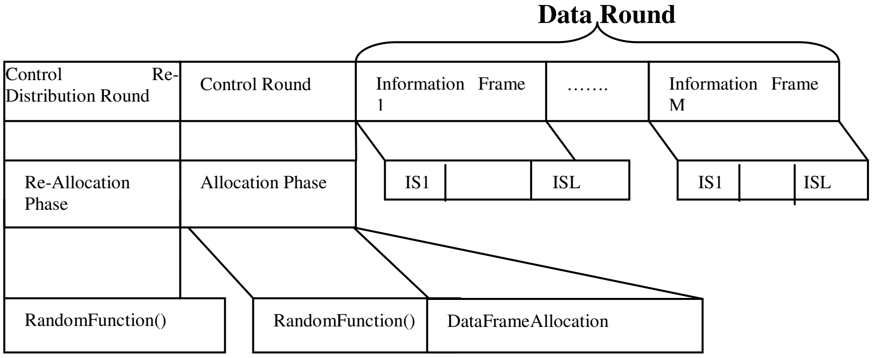


Fig. 5.2. Frame Structure. The control Re-Distribution Round is applied to all nodes that do not have an available Perm-S. In this way a "redistribution" of broadcast slots in which a node state is IDLE is realized.

In this stage two nodes that are in the same situation (that is, without a *Perm-S*) can set the same broadcast slot as *Perm-S* and in the current schedule there will be a collision, but the probability that two nodes that are without *Perm-S* and are neighbors (1 or 2 hop neighbor) and randomly select the same broadcast slot is sufficiently low and performance in terms of throughput and delay show as this aspect of the R-MAC protocol does not eliminate its efficiency. After this, each node will use the *Perm-S* assigned both, to reserve another *Perm-S* and to make data-reservation slots. In Fig. 5.3 the pseudo-code of the RandomFunction() to compute the next broadcast slot is reported. In Fig. 5.4 RandomFunction() applied to the current schedule at the beginning of a frame is reported. This latter is called only by the nodes that did not acquire an available *Perm-S* during the last frame. The randomness of the selection of the broadcast slot permits a fair scheduling scheme to be realized.

5.2.2 Performance Evaluation

5.2.2.1 Simulation Environment

The simulations are conducted using ns2 [……].

bool RandomFunction-NextSchedule()

```
for(int i := 0; i < #Perm-S; i++)
  int c = random(i);
 TDMA_Status NextSt Verify_MyNext_Status_of_Node(c);
   if(NextSt == Idle) {
   bool Avail_Next_Slot=(Verify_Next_Status_Neighbors(c));
         if(Avail_Next_Slot){
             //this slot can be reserved for the next available frame
             reserve_next_slot();
             reserve_data_slot();
             send-updated-schedule();
             exit();
          }
}
```

Fig. 5.3. Pseudo-code of the RandomFuntion(). A node runs this function in its actual Perm-S and tries to reserve a new Perm-S for the next schedule. Random(i) is a function that receives in input an integer and gives in output another integer representing a broadcast slot.

Different simulation campaigns have been conducted varying the speed to show the effectiveness of our approach under mobility conditions. The number of nodes considered is 30 nodes in the same simulation area for the different scenarios. Three different algorithms have been compared: 1) IEEE Std 802.11, 2) Evolutionary-TDMA and 3) R-MAC. Nodes are randomly placed over 1000x1000 sq. meter area. 20 nodes are randomly chosen to be CBR (constant bit rate) sources, with a time lag, each of which generates 64 bytes data packets to a randomly chosen destination. Sources rate vary between 4 and 500 pkts/sec. The transmission range of a node is constant and it is 250 m. Random movement of a node is modeled according to the Random Way Point model. In the beginning, the nodes are randomly placed in the area and each node remains stationary for a pause time. The node then chooses a random point in the area as its destination and starts to move towards it. After reaching a destination a node pauses again and starts to move towards another destination, as previously described. The speed of the movement follows a uniform distribution between 0 and the maximal speed v . Different network scenarios for $v = 0, 5, 10$ m/s are generated. This process is repeated for the duration of the simulation, which is 500 seconds. The set of parameters used is listed in Table 5.2.

bool RandomFunction-CurrentSchedule()

```
for(int i := 0; i < #Perm-S; i++)
  int c = random(i);
  TDMA_Status CurrSt Verify_MyCurr_Status_of_Node(c);
    if(CurrSt == Idle) {
    bool Avail_Curr_Slot=(Verify_Curr_Status_Neighbors(c));
          if(Avail_Curr_Slot){
              //this slot can be reserved for the next available frame
              reserve_curr_slot(c);
              exit();
          }
}
```

Fig. 5.4. Pseudo-code of the RandomFuntion(). A node that looses its *Perm-S* during the Control Round() tries to compute another *Perm-S* at the beginning of a frame for the current schedule.

5.2.2.2 Results

In Fig. 5.5 we evaluated the throughput as the percentage of delivered packets in respect of total sent packets. We evaluated this parameter vs the speed of the nodes in the network. Simulation results show as R-MAC permits better results, in terms of delivered packets, to be obtained. From the results shown in the Figs. 5.5 and 5.6 we can see the capability of the new MAC protocol, proposed in this work, to support well the mobility.

In fact, in the R-MAC protocol, at the beginning of each frame a new broadcast slot is reserved and this broadcast slot is used to communicate to the neighborhood the updated schedules and to make new data slots reservation. In R-MAC the phase introduced to compute this broadcast slot (*Perm-S*), used as a kind of permission, is smaller than the phase in the E-TDMA. In fact, in the E-TDMA when a node needs more data slots (a node has to make new reservation or some topological changes happened) must run a certain number of FPRP cycles and the latency introduced is higher than in the R-MAC.

Another drawback is represented to the MAC control overhead. In fact, more control packets are introduced to support this mechanism. If a node, in a certain frame, is not able to acquire the permission to make new reservation, its transmission will be deferred up to the acquisition of the broadcast slot will be done. In this way, conflict-free schedules are created with an higher latency and more control packets overhead. In fact, E-TDMA is extremely effective for static networks but it does work well under mobility conditions.

Table 5.2.Simulation Parameters

Input Parameters	
Simulation area	1000x1000
Traffic sources	CBR
Number of nodes	30
Sending rate	4, 10, 20, 100, 200, 500 packets/s
Size of data packets	64 bytes
Transmission range	250 m
Simulation Time	500 s
Mobility Model	
Mobility Model	Random Way Point
Pause time	10 s
Mobility average speed	0.5 ,5,10 m/s
Simulator	
Simulator	NS-2 (version 2.1b6a)
Medium Access Protocol	IEEE 802.11, E-TDMA, R-MAC
Link Bandwidth	1 Mbps
Confidence interval	95%

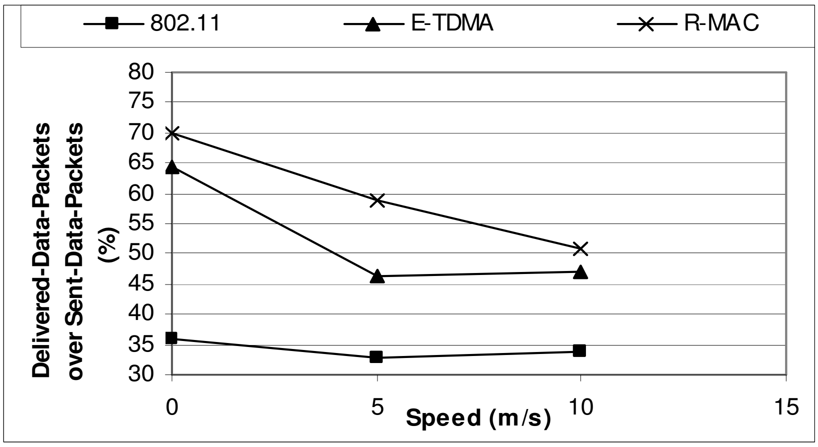


Fig. 5.5. Throughput (30 nodes in 1000x1000 area network): 20 sources.

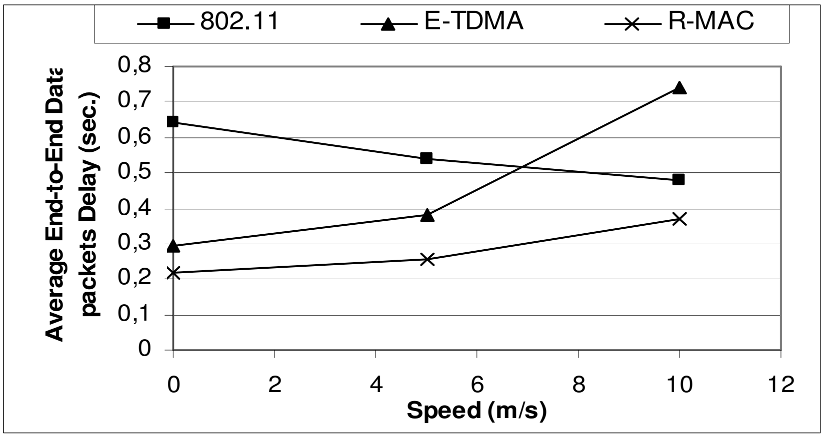


Fig. 5.6. Average end-to-end data packet delay (30 nodes in 1000x1000 grid network): 20 sources.

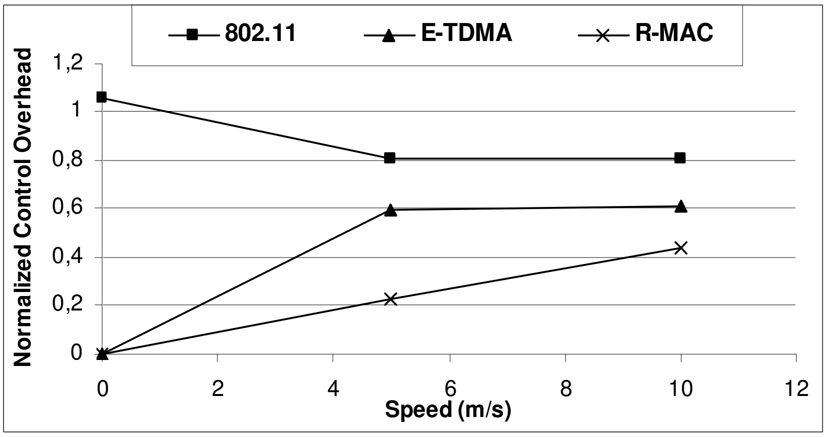


Fig. 5.7. Normalized Control Overhead. The overhead is normalized in respect of the number of delivered packets (30 nodes in 1000x1000 grid network): 20 sources.

Performance of the IEEE Std 802.11 degrade when an high load traffic is considered and speed of the nodes in the network increases. This is due to the fact that a node has to contend for the channel for each packet and when density and load traffic increase the number of collisions increase too. This behavior is reflected in the average end-to-end data packets delay (Fig. 5.6). When speed increases (10 m/sec.) E-TDMA does not work well because of latency introduced to update the schedules. In Fig. 5.7 we show the normalized overhead. This parameter is computed as the number of routing control packets over the number of delivered data packets. This parameter can be considered as a kind of measure of the stability of the paths in the network. In fact, each time a new path has to be re-built a certain number of control routing messages will be involved and inserted in the network. For this reason smaller values of this parameter reflect an higher stability in the network and have to be considered better. Smaller times in R-MAC permit the new bandwidth requests to be accommodated in smaller times than in the E-TDMA. In the Re-Distribution round of the R-MAC we introduced a mechanism that does not ensure the schedules are conflict-free, above all for higher network density but the probability two or more nodes randomly grab the same slot is small and this characteristic is not relevant to obtain good performance.

5.2.3 Details of the Distributed Scheduling Scheme (DSS)

The proposed scheme differs from the IEEE 802.16 CDS scheme in the selection of the new *XmtOp*. In fact, a node transmitting in the current *XmtOp* uses a Random Function instead of the hash function (the MeshElection function defined in the IEEE Std 802.16) to compute the next *XmtOp*. The frame structure is shown in Fig. 5.8. The DSS scheduling mechanism for Local Node (LN) is described in Fig. 5.9. In Fig. 5.9 RandomFunction() randomly picks-up an available slot. A slot is available if the state in the next frame of the Local Node is IDLE. The access is conflict-free because the Local Node uses the current *XmtOp* slot computed in a conflict-free fashion in the previous frame. Whether a node (Local Node, LN) did not find an available *XmtOp* slot in the previous frame or lost this slot for some reasons as show in Figure 4 it will apply a Redistribution Function. This function is an Hash Function in which a node, that needs a *XmtOp* for the current frame, analyzes a set of available slots (that is, the state of the Local Node is IDLE in this slot). The Hash Function will be applied to the 1-hop neighbours of the Local Node. In this way, all the neighbours that do not have a valid *XmtOp* slot in the current frame will apply the same function with the same information (slot number, neighbour ID and address of the node applying the function) and only one node will win the competition. The main advantage of the DSS mechanism is that no parameters must be set, and in this way the protocol is robust for different topologies and network scenarios. Each node considers a number of *XmtOp (opportunities)* that is 16 as well as in the IEEE 802.16 Std and this is the number of opportunities (in the control frame) to transmit updated schedule, send data slots reservation requests and reserve another *XmtOp*. Specifically, with constraints required by conflict-free TDMA transmissions, the activity of a node n_i in a slot s can be classified into the following states:

- TX: Transmits to a set of neighbors R: (*state(s) = Transmit, target(s) = R*)

- RX: Receive from a neighbour n_j: (*state(s)=Recv, target(s)* = n_j)

If a node is not transmitting or receiving in this slot, it is in one of the following (passive) states:

- Blocked from transmitting because at least one of its neighbors receives from another node, and none of its neighbors transmits: *(state(s) Block_TX)*,
- Blocked from receiving because at least one neighbour is transmitting to another node, and none of its neighbors receives: (*state(s) = Block_RX*)
- Both Blocked from transmitting because at least one neighbour is receiving, and blocked from receiving because at least another neighbour is transmitting: (state(s) = *Block_TX_RX*),
- Experiencing a collision when it is supposed to receive from a neighbour (*state(s) = Collision*),
- Idle, when none of its neighbours transmits or receives in this slot: (*state(s) = Idle*).

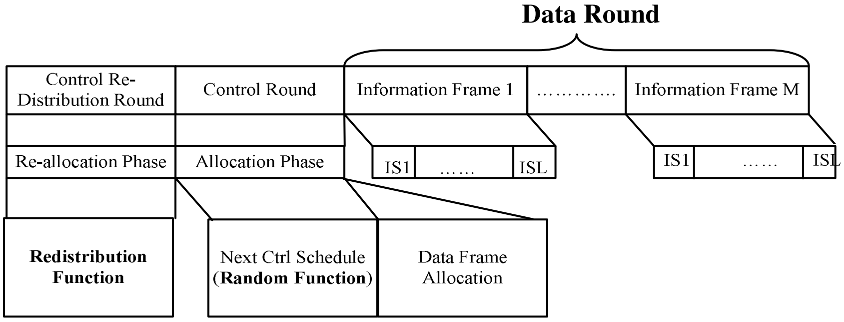


Fig. 5.8. Frame Structure of Distributed Scheduling Scheme (DSS). At the beginning of each control frame, a Control Re-Distribution Round is applied, it will be applied to the nodes that do not have a valid XmtOp in the current frame. The Redistribution Function considered in this work is the same Hash Function considered in the IEEE Std. 802.16e. In the Control Round each node applies a Random Function to compute the next XmtOp and sends updated information in the current XmtOp. Data slots allocation takes place in the Control Round. Each node in its current XmtOp can send data slots reservation requests.

Of course these states are mutually exclusive. The state of the slots in which a node transmits is called active state, state in which a node does not transmit is a passive state. The channel is partitioned in two sub-portions: a Control Round where the schedules are updated and Data Round where user data transmission takes place (Fig. 5.8). The state of the nodes in each slot is updated during the control round when each node in the current *XmtOp* computes the next *XmtOp* and sends the updated information to the neighbors. The data schedule will be updated at the beginning of each new frame; in this way different transmission requirements nodes can be accommodated. Two different information are considered in the Control Round: 1) current information (or current schedule) and 2) next information(or next schedule).

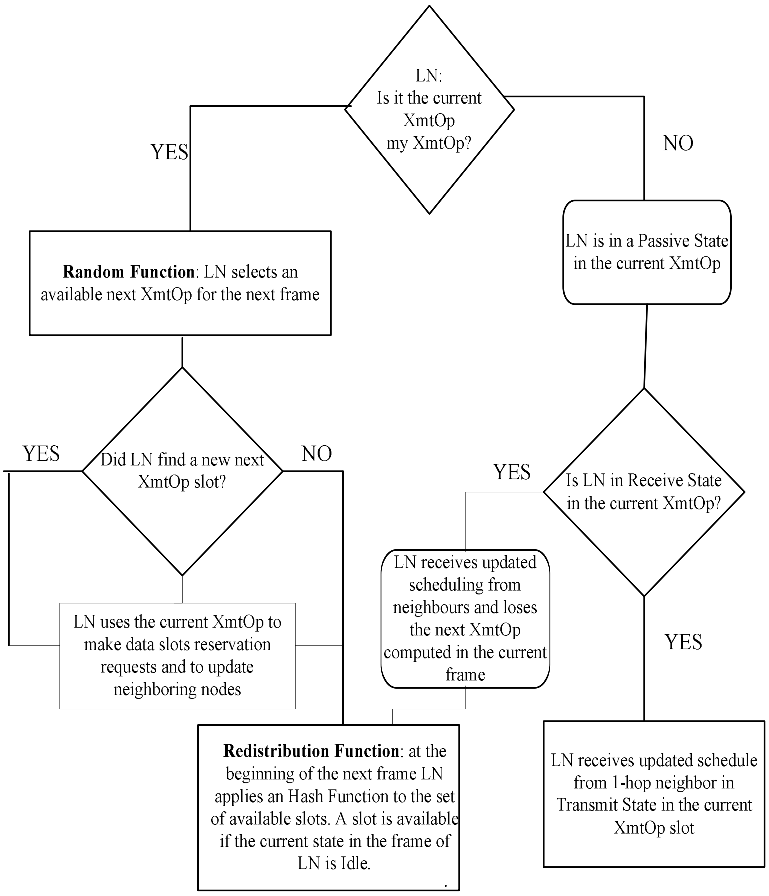


Fig. 5.9. Flow Chart of Local Node (LN) scheduling mechanism of DSS.

The current schedule is the actual schedule used by the node to transmit and to compute another *NextXmtTime* (in accordance with the IEEE 802.16 notation, that is the next *XmtOp*). The mechanism used to compute a new transmission time (*NextXmtTime*) will be the Random Function in DSS (Fig. 5.9). After the

Random Function is called and the *NextXmtTime* is computed a node updates its schedule and sends this (the updated schedule) to its neighborhood through the message (MSH-DSCH) where the request of a certain bandwidth is contained. In the mechanism described above, it can happen that a node acquired a conflict-free broadcast slot, loses it because it will receive some other information from some neighbors after it reserved the slot. When this latter situation occurs, a node will contend for an unassigned slot at the beginning of the next frame (the state of the node in the slot must be Idle). A typical situation that may occur is described in Fig. 5.10. and a node (node 5, in the specific case) will be not able to use the *XmtOp* computed in the next frame. For this reason at the beginning of each frame, where the partial schedule is ready and all the nodes acquired information from the neighborhood, each node that does not have a *XmtOp* will run a Redistribution Function to try to use the control broadcast slots unused. In order to ensure that no two neighbor nodes grab the same slot, an hash function based on the ID of the nodes and a timestamp (slot) is used. Of course, the Redistribution Function will be applied only for the broadcast slots in which the node state is Idle. This new scheduling mechanism ensures that the schedules are conflict-free and a node has not to wait for any particular order to reserve a new broadcast control slot.

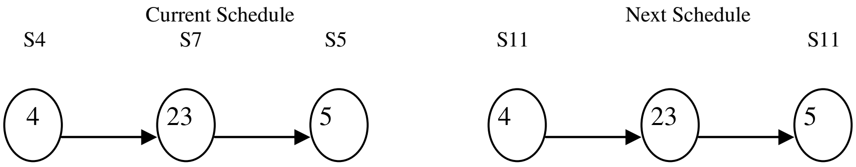


Fig. 5.10. Current Schedule: node 4 is transmitting in the slot S4, node 23 is transmitting in the slot S7 and node 5 is transmitting in the slot S5. Node 4 reserves the slot S11, in the current schedule for the next schedule, as XmtOp. This reservation takes place in the slot S4. Node 4 transmits the updated schedule to its neighborhood. Node 23 is notified with the updated schedule. In the next slot, S5, node 5 reserves the same slot S11 (selected randomly). Node 5 will be notified that this slot is already reserved by another neighbor node (node 4) in the slot S7 by node 23.

5.2.4 Delay Bound Computation

The performance metrics of interest in the MAC layer include the throughput and delay. In the IEEE 802.16 mesh mode, the details of the data sub-frame reservation are left un-standardized and to be implemented by the vendors; and the control sub-frame is independent of the data sub-frame. In this section we develop an analytical delay model that gives a lower bound. The following analysis aims at providing an approximation of the end-to-end data transmission delay. For the analysis we make the following assumptions:

- The wireless backbone network and the wireless access network operate on different channels. Therefore we assume that there is no interference between the data transmissions between the access points (APs) and the transmissions between the mobile nodes and the APs.
- The APs are uniformly distributed.
- All the APs have similar transmission capabilities. This assumption makes the analysis more tractable (and the same assumption is maintained in the simulation campaigns).
- Time is slotted and synchronization is maintained by the APs (i.e., through the periodic transmission of beacon messages).
- The medium access is performed in a conflict-free fashion through a TDMA protocol which operates in two different channels: a control channel and a data channel (this assumption is coherent with the Coordinated Distributed Scheduling of the 802.16 and the DSS introduced in this paper). The control channel is characterized by the same number (16 control slots) of control slots used in the Coordinated Distributed Scheduling scheme (CDS) and the Distributed Scheduling Scheme (DSS) introduced in this work. We assume that the TDMA protocol used for our analysis is optimal. To produce the optimal schedule (where optimality is measured in terms of bandwidth efficiency; i.e. we desire schedules with the minimum number of TDMA slots) is NP-complete [21, 22, 23]. With the term optimal we signify that the distribution both of the control slots and the data slots is realized in an optimal fashion, that is maximize the assignment of the slots maintaining the conflict-free property of the schedules.

The evaluation of the delay has been computed considering different components of the delay (propagation delay, transmission delay and queuing delay) and considering the delay introduced by the transmission of the packets between two Access Points (in a multi-hop environment). In order to conduct this analysis we assume that there is a total knowledge of the topology and some centralized coordinator is able to manage the distribution of slots in a TDMA fashion. In this way the distribution of the bandwidth resource is only constrained by the density of the network.

The end-to-end delay is computed considering the 1-hop transmission delay between access points. The parameters introduced in our evaluation are reported in Table 5.3.

In order to consider a more accurate model all kinds of delays have been taken into account, as said:

- **Propagation Delay**: it has been computed as the ratio of the distance between two nodes (Access Points) and the propagation speed *PropSpeed*. As the distance between two nodes may vary between $\epsilon > 0$ (we assume two nodes are not exactly at the same location) and r (transmission radius of a node), the average inter-nodes distance d_a can be computed as follows:

$$d_a = \sqrt{\frac{r^2 - \varepsilon}{2}} \text{, that is } d_a \approx \sqrt{2}\,\frac{r}{2} \qquad (1)$$

$$delay_{prop} = \frac{Dis\tan ce}{\text{PropSpeed}} = \frac{d_a}{3 \cdot 10^8 (m/\sec.)} \qquad (2)$$

Table 5.3.Parameters used for the analytical model

R	Range of the network
r	Transmission radius of an AP
N’	Number of 1 and 2 hop Neighbors
N	Number of nodes in the network
P	Network Density
PropSpeed	3×10^8 m/sec.
Bandwidth	1 Mb/sec.
Data Packet Dimension	64 bytes
Queuing Buffer Dimension	50 pkts (in the simulations)
T_{TS} (Slot Duration)	$1{,}54 \times 10^{-4}$sec.
T_{PS}	$1{,}2264 \times 10^{-2}$ (sec.)
$T_{data\text{-}frame}$	$9{,}8 \times 10^{-3}$(sec.)
$T_{ctrl\text{-}frame}$	$2{,}464 \times 10^{-3}$(sec.)

- **Transmission Delay**: it is related with the number of control slots and data slots used. When the number of control slots and data slots is higher than the number of nodes in the network the delay is related to the duration of the frame and the duration of the slot, otherwise the transmission delay is related with the density of nodes in the network.
- **Queuing Delay**: it is related with the number of packets that have to be sent from an Access Point.

The computation of the delay between access points follows a similar approach as in [12]. As represented in Table 5.3 r is the radius of an access point (for simplicity we assumed all the Access Points have the same radius) and N the number of the Access Points uniformly distributed over an area of diameter k. The data transmission process involves two different schedules: the control schedule and the data schedule. In the control schedule a node, with a certain probability p, acquires a control slot. This control slot is used to update the schedule, to send the updated schedule to the neighbors and to reserve data slots.

Data slots are allocated in the control schedule. Two different states are associated with each node (in a simplified version): ***Passive (PS)*** state and a ***Transmitting (TX)*** state (Fig. 5.11). In the ***Passive*** state a node can be blocked to transmit in a certain slot because another neighbor is transmitting in the same slot or can be Idle or can be in a receiving state. To the scope of our analysis it is not important the particular passive state associated with a node but it is only important whether a node grab a slot to transmit or not. A packet transmission is complete when two data slots are assigned, because each slot is 32 bytes and a data packet is 64 bytes. In the ideal case we assume do not have any overhead. In the simulation campaigns we take into account an overhead of 20 byte and the real dimension of a data packet is 84 bytes. We are assuming backlogged sources. Let p the probability that a saturated Access Point transmits a packet in a frame (control-frame + data-frame).

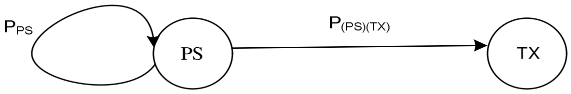


Fig. 5.11. Two states associated with each node for a generic slot S. PS is the Passive State and TX is the Transmitting State.

In an ideal TDMA paradigm this probability is related with the total number of neighbors (1 and 2-hop neighbors) and can be written as:

$$\begin{cases} p = \frac{NCS}{N^{'}-1} * \frac{NDS}{2(N^{'}-1)} & \text{if NCS} < (\mathrm{N}^{'}-1) \text{ and NDS} < 2(\mathrm{N}^{'}-1) \\ p = \frac{\mathrm{NDS}}{2(N^{'}-1)} & \text{if NCS} \geq (\mathrm{N}^{'}-1) \text{ and NDS} < 2(\mathrm{N}^{'}-1) \\ p = \frac{\mathrm{NCS}}{(N^{'}-1)} & \text{if NCS} < (\mathrm{N}^{'}-1) \text{ and NDS} \geq 2(\mathrm{N}^{'}-1) \\ p = 1 & \text{otherwise} \end{cases} \qquad (3)$$

Where *NCS* is the number of control slots and *NDS* is the number of data slots. Let N1 the number of 1-hop neighbors (it is the number of nodes in the coverage area of an Access Point). N1 can be expressed as $\mathrm{N1} = \rho \pi r^2$ where ρ is the network density and can be expressed as $\rho = \frac{N}{\pi R^2}$. N' is the number of 1 and 2-hop neighbors and can be computed as $N^{'} = 4N\frac{r^2}{R^2}$. By considering the equilibrium state, each transition can be straightforwardly computed as follows:

$$\begin{cases} P_{(PS)(PS)} = (1-p)^{N'} & \\ P_{(PS)(TX)} = 1 & \text{if } p = 1 \\ P_{(PS)(TX)} = p\,[(1-p)^{\rho B(d)}]^{\frac{(T_{data-frame}+T_{ctrl-frame})}{(T_{TS})}} & otherwise \end{cases} \quad (4)$$

Where T_{TS} is the duration of a slot, $T_{ctrl\text{-}frame}$ is the duration of the control frame and $T_{data\text{-}frame}$ is the duration of the data frame. For a given transmission, the area B(d) where nodes may potentially interfere with the transmitting node can be computed as (d is the inter-nodes distance) [13]:

$$B(d) = \pi r^2 - 2r^2 \arccos\left(\frac{d}{2r} - \frac{d}{2r}\sqrt{1-\left(\frac{d}{2r}\right)^2}\right) \quad (5)$$

$$delay_{AP-AP} = \left(\frac{1-\dfrac{P_{(PS)(TX)}(T_{ctrl-frame}+T_{data-frame})}{P_{(PS)(TX)}(T_{ctrl-frame}+T_{data-frame})+T_{PS}}}{\dfrac{P_{(PS)(TX)}(T_{ctrl-frame}+T_{data-frame})}{P_{(PS)(TX)}(T_{ctrl-frame}+T_{data-frame})+T_{PS}}}\right) * (T_{ctrl-frame}+T_{data-frame}) \quad (6)$$

Where d is the same as d_a computed in (1). The delay can be derived as in (6). T_{PS} is the time a node is in a Passive State. Let us remember that a Passive State is the state in a generic slot in which a node is not transmitting, that is a node can be in Receiving State, Blocked to Transmit, Blocked to Receive, Blocked to Transmit and Receive, Collision or Idle. We are evaluating the end-to-end data transmission delay and for this reason the T_{PS} is evaluated considering the average time a node spends in a passive state before to acquire the right to transmit in a data slot time.

Let's assume that the distribution of the Access Points is uniform, the transmissions are scheduled in a round robin fashion and the transmissions are multi-hop transmissions, that means that each intermediate Access Point would have to transmit its traffic as well as the traffic of its children. With these assumptions, the average number of node n_i at each hop level i can be expressed as:

$$n_i = \frac{N}{\pi R^2} \int_{(i-1)r}^{ir} 2\pi x dx \quad (7)$$

$$p_k = \frac{\sum_{k+1}^{R} \frac{Nr^2}{R^2}(k^2-(k-1)^2)}{\frac{Nr^2}{R^2}((k^2-(k-1)^2))} \quad (8)$$

$$n_i = \frac{N}{R^2}(i^2-(i-1)^2)r^2 \quad (9)$$

Let k_{max} the maximum number of hops and p_k the number of packets that an Access Point has to forward. Then, if we consider $k < k_{max,}$, p_k can be expressed as:

$$p_k = \frac{\sum_{k+1}^{k_{avg}} (k^2 - (k-1)^2)}{((k^2 - (k-1)^2))} \tag{10}$$

$$q_k = p_k * delay_{AP-AP} \tag{11}$$

$$delay_{TOT} = q_k + delay_{AP-AP} + delay_{PROP} \tag{12}$$

k_{avg} in (10) is the average number of hops that a packet has to traverse in order to be delivered to the destination. We evaluated the parameter k_{avg} considering different scenarios generated with ns. It is interesting to observe that increasing the number of nodes in the network (considering the same dimension of the area), the parameter k_{avg} decreases because higher is the number of nodes that link a source to the destination. Of course, when the number of nodes increases the possibility of conflicts in the network increases too and the latency to acquire a slot increases. So, the queuing delay q_k can therefore be approximated by (11). The total average delay can be written as (12).

5.3 Performance Results

In this section results pertaining to the performance of an 802.16 system in a distributed mesh deployment are presented in comparison with the new totally Distributed Scheduling Scheme (DSS) presented in section IV and the IEEE Std 802.11. Results about IEEE 802.11 are shown in order to confirm simulation results obtained in other works [10, 11]. Furthermore, the analytical approach developed in section V has been used to compute a delay lower bound. In the current MAC modules for ns-2 no 802.16 MAC module is available yet, so we implement a new MAC module for the IEEE 802.16 mesh mode. The module consists of the scheduling controller that handles the signaling channel contention and in the current transmission slot contends the next transmission time using the election mechanism defined in the standard based on the collected neighbors' information. Another fundamental component of this module is the data channel that receives and transmits data packets in the allocated time slots. Identical *XmtHoldoffExponent* and *NextXmtXm* have been used for all scenarios as far as the IEEE 802.16 is concerned. Specifically, different simulation campaigns have been conducted with the same traffic load and the same topology and different *XmtHoldoffExponent* and *NextXmtXm* values and the better values, in terms of delay and throughput, have been selected. The parameters evaluated in this section are:

- Throughput: is the percentage of delivered packets over the total packets sent in the networks.
- Delay: intuitively, the delay of a packet in a network is the time it takes the packet to reach the destination after it leaves the source. We take into account queuing delay at the source because we consider multihop transmissions and a node can be involved in different simultaneous transmissions. Moreover, the delay has been computed considering the different components of the delays, that is propagation delay, transmission delay and queuing delay.
- Unused Slot: this parameter has been introduced as a kind of measure of the effectiveness of the scheduling scheme used. In fact, we will show how the CDS manages the bandwidth resources in a fashion the conflict-free property of the schedules created to be guaranteed, but a certain amount of slots in each frame is unassigned. In this way, the efficiency of the network decreases.

In this dissertation, we evaluated performance of wireless mesh networks in tree-based architectures. The node 1 works as a gateway and the others nodes work as Access Points. We simulated traffic of terminal users with varying traffic load among the Access Points. In all the plots 802.16 is the Coordinated Distributed Scheme (CDS) of the IEEE 802.16, DSS is the Distributed Scheduling Scheme developed in this work, 802_11 is the IEEE Std 802.11 and Analytical Scheme is the ideal, analytical scheme developed in section 5.2.4. Comparisons of CDS scheme, DSS and IEEE 802.11 in terms of average throughput and average end-to-end data packets delay in different density network conditions are done, considering a different number of nodes in the network. Specifically, we varied the number of nodes in a grid of 1000x1000, between 25 and 70. In order to estimate the system performance of 802.16 CDS, DSS and 802.11, results were obtained using a well-known simulator, the ns2 [20]. Parameters used in the simulation campaigns are shown in Table 5.4. In Fig. 5.12 the average throughput for different network densities (varying the number of nodes between 25, 30, 40, 50, 60 and 70 in the same area network) is shown. Concerning the 802.16 CDS we had to set the parameters, the better values of *NextXmtTime* and *XmtHoldoffExponent* in order to obtain the better throughput and the minimum delay. This represents a drawback of the CDS scheme, because by changing the network density and the topological characteristics of the network we need to set up the values of these parameters and for this reason we defined our scheme Topological-Free scheme. In fact, in DSS we do not have to set any parameters to select the next *XmtOp*. In Figure 5.12 we show the delivery ratio of data packets. As we expected [10, 11], the performance of IEEE 802.11 MAC protocol is not satisfactory in a wireless multihop environment. Concerning the performance comparisons between the CDS of the IEEE Std 802.16 and the DSS, we can see how our scheme permits more data packets to be delivered to the destination. Above all with a higher density of the network (50, 60 and 70 nodes in the same area), our scheme delivers a higher percentage (10%) of data packets than the CDS.

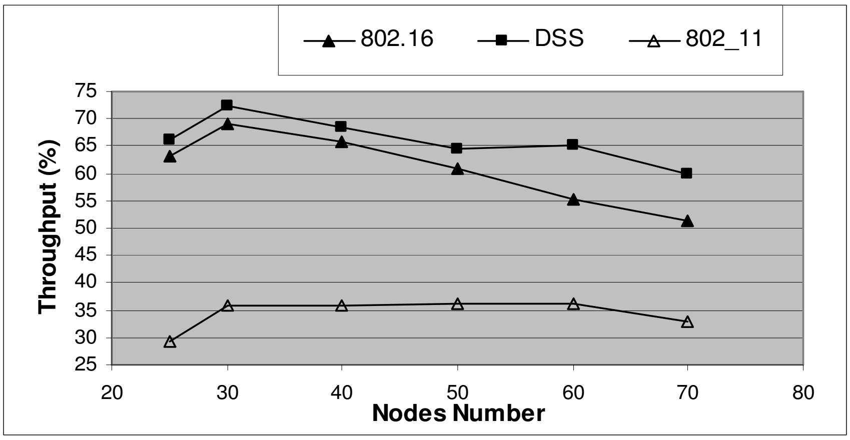


Fig. 5.12. Percentage of packets delivered over packets sent.

In order to understand why we obtain better results in terms of throughput (Fig. 5.12) and delay (Fig. 5.13), by using our scheme, we can observe the parameter in Fig. 5.14, Unused Control Slots. This latter represents the degree of utilization of the control broadcast slots (Opportunity to Transmit *XmtOp*) in the network. In practice, with this parameter we tried to measure the capability , in both of the schemes, the *XmtOp* to be assigned. Of course, we assumed that each node tries to acquire a *XmtOp* in each frame but there is a higher number of unassigned slots in the CDS scheme. This is due to the mechanism used by the CDS scheme. In fact, it is based on a hash function, the MeshElection, that permits both randomness and predictability to be guaranteed but, on the other hand, this mechanism does not guarantee that each *XmtOp* in each frame will be assigned, that is, although some node require a *XmtOp* in a certain frame and there are some *XmtOp* “free”, available to be assigned, the *XmtOp* will be unassigned.

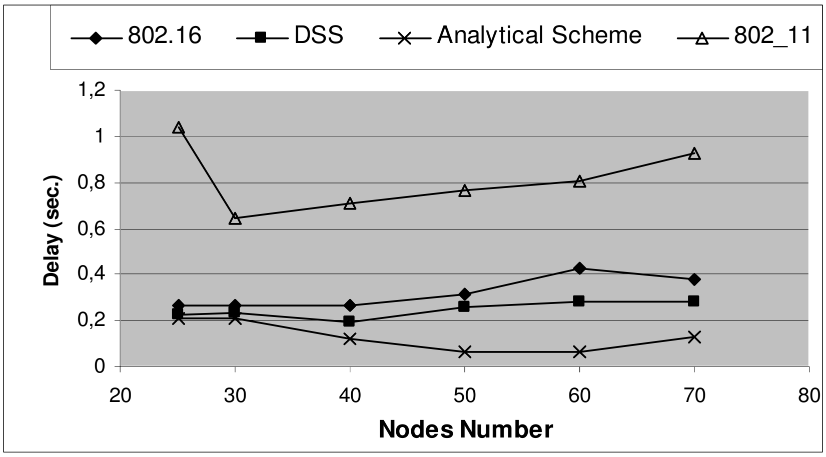


Fig. 5.13. Average end-to-end data packets delay.

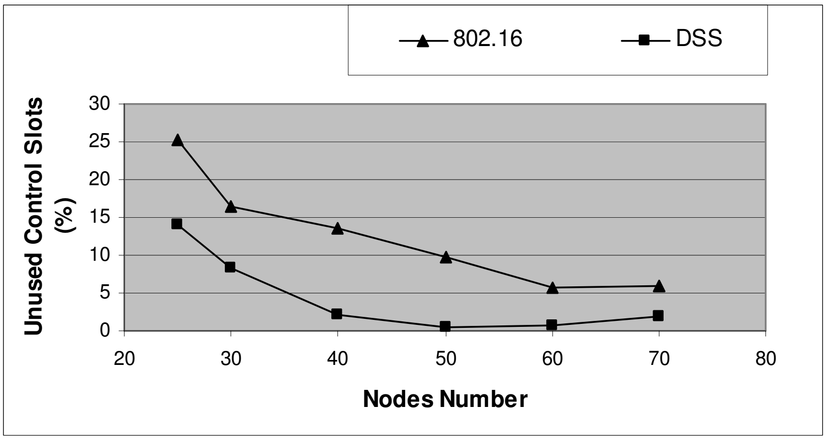


Fig. 5.14. Percentage of control slots unassigned vs the number of nodes in the network.

Concerning scenarios where a smaller number of nodes in the network is considered (25, 30 and 40 nodes) we can see that the degree of under-utilization in both the schemes is higher, but this is due to the fact that not all the *XmtOp* have to be used. In fact, the number of neighbors (1 and 2-hop neighbors) in the networks is much smaller than the number of *XmtOp* (that are 16), in the simulated scenarios and in the analytical model (see Table 5.5). Considering that we can re-use some *XmtOp*, in this case the parameter does not reflect exactly the under-utilization in the network. The under-utilization of the *XmtOp* is well reflected when the number of nodes in the network increases. In fact, considering 50, 60 and 70 the number of neighbors in the simulated scenarios is higher than the number of opportunity to transmit considered, so in this case in each frame each node tries, in average, to acquire a different *XmtOp*. Obviously, in this latter case is very important that for each frame we reduce the number of unassigned slots and we realized this in our scheme. In fact, in our scheme, the degree of under-utilization is almost close to zero. On the contrary, in the CDS we have an under-utilization degree of 10 and 5 % for 50, 60 and 70 nodes respectively. This behavior is reflected in the throughput and delay plots. In fact, DSS works well also when the density of the network increases. Also in this case, the latency introduced is smaller than those introduced with the CDS scheme. Smaller latency also increases the reactivity of the network and decreases the average end-to-end delay. Remember that we show the under-utilization of the control slots in Fig. 5.14 and the delay of data packets in Fig. 5.13, but these two parameters are strictly related. In fact, a node (i.e., Local Node, LN) that has to reserve data slots needs a *XmtOp* to make new reservations and to exchange updated schedules. When the latency of the scheme that manages the "distribution" of the *XmtOp* increases as in the case of the CDS scheme, LN will be able to reserve data slots in more time (with a more amount of delay) and performance of the network degrade. This is due to the fact that the network is much more reactive when we distribute in a more efficient fashion the *XmtOp*, that is, the under-utilization degree in the network concerning the broadcast control slots is smaller. Concerning the analytical scheme we show the delay of this in Fig. 5.13 and we based the estimation of the number of the neighbors on the formula $N' = 4N\frac{r^2}{R^2}$, used in section V. Actually, an under-estimation is obtained in this way when the number of nodes in the network increases. In fact, as shown in Table 5.5, for 50, 60 and 70 nodes the number of neighbors is higher than the number of *XmtOp* used. We used these values and not the values obtained considering the simulation scenarios because the scope of the evaluation of the analytical delay was to establish a lower bound in terms of delay and how much the schemes that have been analyzed in this work are close to these analytical results. In this way for 50 and 60 nodes our evaluation does not take into account the interference area and the number of neighbors. In fact, the probability p a broadcast control slot to be acquired is 1 and the $P_{(PS)(TX)}$ that is the transition from a Passive State (PS) to an Active State (TX) is 1. In this way the delay is only related with the duration of the slot and the duration of the frame (control frame and data frame). The better distribution of control slots permits the latency of our scheme to be reduced in comparison of the latency introduced by the CDS. For this reason the average end-to-end data packets delay is smaller in our scheme, because the reactivity of the network is higher when the degree of under-utilization (of control slots in this case) is smaller.

Table 5.4.Simulation Parameters

Input Parameters	
Simulation area	1000x1000
Traffic sources	CBR
Number of nodes	25, 30, 40, 50, 60, 70
Sending rate	4, 40, 400 packets/s
Size of data packets	64 bytes
Transmission range	250 m
Simulation Time	500 s
Mobility Model	
Mobility Model	Random Way Point
Pause time	10 s
Mobility average speed	Static Network
Simulator	
Simulator	NS-2 (version 2.1b6a)
Medium Access Protocol	802.16 (CDS), DSS
Routing Protocol	AODV
Link Bandwidth	1 Mbps
Confidence interval	95%

Table 5.5.Number of Neighbors (1 and 2-hop) for different number of nodes in the network.

# Nodes in the Network	N' (Analytical)	N' (Simulation)
25	6,25	8,2
30	7,5	7,6
40	10	11,3
50	12,5	17
60	15	20
70	17,5	22

Moreover, we introduced more robustness in our scheme because the behavior of our scheme does not depend on the particular network conditions, as the density of the network or the topological characteristics of the network.

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Chapter 6 Conclusions

In this work we have analyzed different types of wireless networks and we have investigated the behavior of different MAC and routing protocols and different protocol architectures. Specifically, we have analyzed a TDMA MAC protocol for Mobile Ad hoc NETworks called Evolutionary-TDMA (E-TDMA). Based on this protocol we have developed a cross-layer approach that uses multiple link-disjoint paths for a pair *source-destination* supporting a soft QoS. For this latter point we have developed a Multipath Forward Algorithm to manage and assign the slots. We have developed two different schemes: QoS scheme 1 and QoS scheme 2 and compared these schemes in terms of throughput, delay and overhead with a well-known multipath protocol routing, the AOMDV over 802.11 MAC protocol and AOMDV over E-TDMA. We have obtained good performance exploiting advantages of a TDMA MAC protocol and a Multipath routing protocol. Simulation results have shown as a cross-layer approach permits good performance in terms of throughput, end-to-end data packets delay and overhead to be obtained. In fact, multipath routing protocols for wireless ad hoc networks have been investigated because the use of alternate paths permits a greater fault-tolerance to be obtained. As far as multipath routing protocol is concerned we have developed and analyzed a multipath routing protocol based on geographic positions of the nodes in the network, Geographic Multipath Protocol (GMP). Results, in terms of throughput and delay, show that the multiple paths with minimum interference are better. We have investigated the cross-layer approach also for Wireless Sensor Networks. Although, this kind of networks could be considered an extension of Ad hoc networks, characteristics of WSNs are so different that protocols explicitly developed for MANETs cannot be directly applied for sensors networks. After analyzed some protocols we have proposed some solutions to increase the lifetime of the sensor networks considering other important parameters as throughput and latency. Finally, our analysis of wireless networks finishes with the analysis of Wireless Mesh Networks. We have investigated multi-hop wireless networks based on the IEEE 802.16 technology. Specifically, we have analyzed the Coordinated Distributed Scheme (CDS) of the IEEE Std. 802.16 and we have developed a MAC module supporting the CDS in ns2. Moreover, we have developed two different totally distributed schemes that do not require any changes of the structure of the hardware used in the 802.16. The two schemes proposed manage the assignment of the control slots (Transmit Opportunity *XmtOP*), in a different fashion. We have developed the two scheme in ns2 in order to compare them with the CDS of the 802.16. Our approaches permit good performance in terms of throughput and delay to be obtained. Our approaches are independent from parameters of the network as density or topology. On the other hand, the CDS is not robust for different network conditions because the behavior of the scheme depends from the setting of particular parameters.

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