Collision Avoidance, Contention Control and Power Saving in IEEE 802.11 Wireless LANs

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1 Introduction

For decades Ethernet has been the predominant network technology for supporting local area network (LAN) communication. In recent years the proliferation of portable and laptop computers has led to LAN technology being required to support wireless connectivity [25, 27, 44]. Mobile and Wireless solutions for communication have been studied for many years to make it possible for mobile users to access information anywhere and at anytime [44]. The Wireless Internet services (e.g. Web, e-mail) are considered the most promising killer applications pushing for wireless technologies, services and infrastructures deployment on behalf of network service providers and private customers. The integration of the wired internet communication with the innovative and challenging last-mile wireless connectivity will require to support full services and protocols' integration among the two worlds.

1.1 The role of protocols in the wireless scenario

A variety of networking solutions, services, protocols, standards, technologies, and new applications have been proposed in recent years to meet the goal of the Wireless Internet and wireless last-mile connectivity. Wireless medium problems and resource restrictions in wireless systems made the "anywhere and at anytime connectivity" goal difficult to obtain. Some of the problems to be solved include environment obstacles and interference, user mobility and dynamic network topologies, variable user density, variable load, low channel bandwidth, frequent link failures, limited battery energy, overheads reduction. Under the protocol design viewpoint, these problems have been dealt with at many layers in the OSI protocol stack. At the physical layer, suitable technologies for transmission, reception and coding are required. At upper layers, protocols' design plays an important role: protocols define the way resources are used, shared, and also protocols define the way the information is coded, fragmented, re-ordered, assembled, checked and validated. Protocols also determine which services the system can support and the Quality of Service (QoS) guaranteed to the users' applications.

It results a great area of investigation of the role of protocols and distributed algorithms for network systems' management. New limiting constraints given by the wireless scenarios have caused a consistent research in order to realize optimal tuning of the protocols and algorithms derived from protocols and algorithms adopted in wired networks. One of the challenging tasks for researchers in recent years has been (and still is) the need to overcome the wireless system weaknesses by maintaining the *inertial* definition of management protocols and architectures for the inter-communication of wireless systems with the wired counterparts. The need to maintain system and service architectures, and protocols definitions derived from the wired networks counterpart, has brought to adaptive solutions on the wireless side, instead of a complete re-design of the wireless protocols. By designing *adaptive protocols* the system integration should be as much transparent as possible to the final users, devices and service providers, both on the wired and on the wireless side.

1.2 Adaptive protocols and cross layering

It is widely recognized that the dynamic nature of the wireless link demands fast and low-cost adaptation on the part of protocols [7, 13, 14, 27]. As an example, mobility of the users and frequent parameters' fluctuations due to wireless channels characteristics stress the adaptive behavior of protocols. Therefore, the study of tuning knobs of adaptive protocols is an important issue already in the protocol design. It is also necessary to understand the problems one might encounter with adaptive protocols, such as excessive overheads, stability and fairness problems.

All the network layers will require ability to adapt to changing channel conditions, perhaps implemented through some form of channel state estimation and tracking. What is required is an appropriate suite of adaptive, event-driven protocols that pass state-information across layers in an effort to cope with this variability. Little is known about this new approach in the protocol design, and considerable research is required here, although a large payoff potential is expected [12, 14]. As an example, dealing with the new assumptions of the wireless scenarios and the effects of such new assumptions on the *Medium Access Control (MAC)* protocol design, this chapter will illustrate the evolutionary design perspective of the class of distributed random-access MAC protocols. A distributed, random-access MAC protocol is the basic access scheme in today's IEEE 802.11 MAC definition.

Recently, the need for adaptive behavior of protocols, based on the information exchange between the OSI protocol layers, has evolved to the idea of a collapse of the OSI layering structure for the wireless world (i.e. *cross-layering*). Emerging motivations and criticisms consider two-edged the *cross-layering* principle in the design of protocols: it is quite clear and consolidated the need for adaptive behavior of protocols based on the exchange of information among the protocol layers. On the other hand, a warning on the risk of unstructured and "spaghetti-design" principles for wireless scenarios and the correlated risk for cyclic design solutions and unstable protocols was recently discussed in [48].

1.3 WLANs and MANETs

Wireless LAN technology (WLAN) is going to integrate and replace wired LANs at a fast rate because the technology solutions are becoming less expensive and with acceptable performances. The WLAN infrastructure is based on static Access Points (APs) serving and managing local (mobile) nodes. If nodes leave the WLAN area they should register to a new AP, if any.

On the other hand, new classes of wireless networks, such as the *mobile ad hoc networks (MANETs)* or infrastructureless networks have no counterpart in today's networks. MANETs are composed of a set of mobile hosts (MHs), possibly connected to each other in a best-effort way, through one (single-hop) or more (multi-hop) communication links. The transmission range of a MH is limited and the topology of the network is dynamic, so that multi-hop communication is necessary for nodes to communicate with each other. Basic assumptions in current wired networks, including the notions of a quasi-permanent fixed topology and stable links, might not apply to such new networks. The dynamic nature and topology of the MANETs challenges current MAC and routing techniques, and requires a more-autonomous style of *Peer-to-Peer* (P2P) network management than one finds in today's centralized, stationary systems.

The problem of how such a network self-organizes and responds to node mobility, channel interference and contention requires solutions. Moreover, the rapidly variable number of nodes that one might find in such a network underscores the need for a level of scalability not commonly present in most of the approaches to network management. Let us think, for example, to a burst of users with mobile devices that moves, at a given time instant, in the same meeting room thus generating a sharp increase in the traffic of the corresponding WLAN. While the number of hosts that can be connected to a WLAN may be large, wireless links will continue to have significantly lower capacity than wired links and hence congestion is more problematic. The protocol scalability influences the QoS perceived by the users, and the resources' utilization (mainly battery-energy and channel bandwidth). Since energy and bandwidth are such precious resources in wireless networks, there should be a focus on protocols that support the minimization of their use.

At the Medium Access Control (MAC) layer, the objective is to make the most effective use of the limited energy and spectrum available while supporting the distributed services that adequately meet the QoS requirements of the users' applications accessing the communication network. Accordingly, researchers will have to gain a better understanding of how to design the MAC, data link, network, and transport protocols, and their interactions, for these networks [3]. Furthermore, the multiple access technique in use on any wireless subnetwork should allow flexible and efficient internetworking with both WLANs and MANETs. In this way MANETs could be adopted to extend the WLAN coverage areas (e.g. WLAN hotspots) [25]. At the upper layers, protocols should allow heterogeneous systems communication, and wireless integration with the wired backbone network.

The success of WLANs is connected to the development of networking products that can provide wireless network access at a competitive price. A major factor in achieving this goal is the availability of appropriate networking standards. Wireless Local Area Networks (WLANs) experienced an explosive growth and user demand in recent years. The IEEE 802.11 Standard (Wi-Fi) technology has become a *de-facto* standard for the Medium Access Control (MAC) layer in such networks. This fact led the research in the field of WLANs and MANETs to be mainly focused on IEEE 802.11-based MAC solutions.

1.3.1 The MAC level perspective

Mobile hosts access a shared channel with their wireless transmissions, which may be detected by all neighbor hosts within a given range, given the broadcast nature of the wireless transmissions. In WLANs and MANETs, the medium access control (MAC) protocol is the main management component that determines the efficiency in sharing the limited communication bandwidth of the wireless channel and, at the same time, manages the congestion situations that may occur inside the network. MAC definition and tuning is essential in providing an efficient resource allocation, and power saving, among competing nodes.

Centralized protocols are based on the support of a centralized coordinator, e.g. a base station or Access Point (AP) coordinating the channel accesses. The centralized scheme can support quality of service, priority schemes, asymmetric channel scheduling among coordinated nodes, but suffers the system dynamics like mobility, load changes, and can result in complex management and resource waste. The need for the central coordinator is a strong assumption that can be acceptable in infrastructure-based and WLAN systems, but it is not a reliable choice in infrastructureless and mobile ad hoc networks.

Distributed MAC protocols realize less critical implementations, defined to work under peer-to-peer management conditions, resulting in easy implementation and no need for coordinating nodes. For this reason, common choices for Wireless LANs (WLANs) and Mobile Ad Hoc Networks (MANETs) are based and realized by distributed MAC protocols. On the other hand, distributed random-access MAC protocols have been demonstrated to suffer scalability, efficiency and QoS problems under high loads. Among the distributed MAC protocols, two classes of protocols can be identified: reservation-based schemes and contention-based (random-access) schemes. Reservation-based schemes are realized on the assumption that nodes should agree on the order and duration of their respective channel accesses before to try any access. In centralized schemes this policy can be easily demanded to the central coordinator, which collects requests by the wireless nodes, and generates a schedule of the channel accesses. Channel access is governed by the central coordinator by means of a polling-authorization mechanism. In distributed schemes, this policy is much more difficult to realize due to the absence of the central coordinator. Two common approaches that can be adopted to realize the reservation-based access in a distributed way are: explicit reservation (i.e. the static list approach) and implicit reservation (i.e. token-based approach). The explicit reservation approach is based on the creation of a static ordered list of nodes and duration of their respective accesses, and it can be adopted when the number of nodes and the traffic requirements are stable. Such an approach is really unpractical in wireless and mobile systems, because it cannot adapt to the system dynamics, and it may result in a waste of resources. In the token-based approach, a message called *token* circulates in mutually exclusive way between nodes organized in a cyclic sequence. The node receiving the token owns the right to transmit for a given time, then it must pass the token to the next node in the list. This scheme has been considered for wireless systems, but the risk to lose the token, distributed failure-tolerance and management issues made the implementation quite complex and unpractical for wireless networks.

The distributed, random-access or contention-based MAC protocols have been considered as the good compromise between ease of system management, resources' utilization and performances in many wireless systems. The idea behind such MAC protocols is to define distributed protocols as event-based algorithms, randomly spreading the accesses of nodes in an effort to reach system stability, acceptable resource utilization and performances, as the aggregate behavior of nodes. The events governing the distributed contention-based MAC protocols are represented by the limited feedback information perceived by the network interface of every node. In the next sections we will provide an historical perspective of proposals based on different assumptions about the feedback information that could be exploited by nodes. The efficient implementation of distributed MAC management in MANETs would require every MH to obtain the maximum information regarding the neighbor nodes, if any. This information could be adopted in clustering and routing layers, and in MAC contention control as well. As we will see in the next sections, information gathering is a complex activity in WLANs and MANETs, and it is subject to many biasing effects. The increase in the confidence level of the information obtained at the MAC layer, is subject to inverse trade-offs with resources' utilization, power control and power saving principles.

A complete taxonomy of the possible Medium Access Control protocols and management techniques proposed in recent years for the wireless scenario is out of the scope of this chapter. In this chapter, we will provide the reader with an historical perspective and a state-of-the-art illustration of examples and solutions (sometimes milestones) that have been proposed in the field of the distributed Medium Access Control (MAC) layer protocols for wireless and mobile ad hoc networks.

The chapter emphasis will be on the protocols and distributed algorithms at the basis of historical and recent developments in the collision avoidance, contention control, and power saving issues of the MAC design in IEEE 802.11 WLANs and MANETs. The MAC layer definitions play an important role also in other problems studied in the context of wireless networks, e.g. Quality of service and real-time, unicast and multicast delivery, load distribution, fairness and prioritized access. In this chapter we will analyze solutions for increasing both the MAC protocol efficiency and the protocol ability to react to congestion conditions. In addition, we also investigate the protocol robustness to wireless vulnerabilities (hidden/exposed terminals and channel errors) and the power saving potential of the class of IEEE 802.11 based MAC protocols.

2 The IEEE 802.11 Standard

In this section we present the essential information, related to the IEEE 802.11 Standard for Wireless LANs (WLAN), which is required for the analysis of some problems in the congestion reaction and power saving mechanisms implemented with the Standard definition. IEEE Std 802.11-1997 and successive releases specify a single Medium Access Control (MAC) sublayer and 3 Physical Layer Specifications: Frequency Hopping

Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and Infrared (IR) [31]. The physical layer is out of the scope of this chapter. Two projects are currently ongoing to develop higher-speed PHY extensions to 802.11 operating in the 2.4 GHz band (project 802.11b, handled by TGb) and in the 5 GHz band (project 802.11a handled by TGa), see [32].

The IEEE 802.11 WLAN is a single-hop infrastructure network. In addition, it is emerging as one of the most promising technologies for constructing multi-hop mobile ad hoc networks (MANETs). The current definition of the IEEE 802.11 MAC is not ideal under this viewpoint: next sections will illustrate that further analysis and enhancements are required to capture more system characteristics for optimized protocols design at the MAC and Logical Link Control (LLC) layers. Specifically, support for multi-hop communication, flow synchronization, power control and power saving, and enhancements at the MAC layer require additional work [86]. Anyway, IEEE 802.11 Standard can be considered the prototype standard definition, and the basis for prototype implementation of MANETs. It has become a reference both for practical implementations and for the research in this field. In the following section, we will first provide an overview of distributed contention control management in IEEE 802.11 networks (specifically the Distributed Coordination Function, DCF);

2.1 Distributed Foundation Wireless Medium Access Control (DFWMAC)

In the IEEE 802.11 systems considered in this chapter, the *Distributed Foundation Wireless Medium Access Control protocol (DFWMAC)* includes the definition of two access schemes, co-existing in a time-interleaving super frame structure [31]. The *Distributed Coordination Function (DCF)* is the basic access scheme and it is a distributed, random-access MAC protocol for asynchronous, contention-based, distributed accesses to the channel. On top of the DCF, an optional *Point Coordination Function (PCF)* is defined as the access scheme to support infrastructure-based systems based on a central coordinator (i.e. Access Point) for centralized, contention-free accesses.

Stations can operate in both configurations, based on the different coordination functions:

- Distributed Coordination Function (ad hoc network): the Mobile Hosts (MHs) exchange data like in peer-to-peer (P2P) communication, and there is no need for infrastructures to be installed. The DCF is completely distributed, and the channel access is contention-based. Stations in such a configuration realize an Independent Basic Service Set (IBSS). Two or more IBSS communicating wireless via an intermediate station realize the multi-hop communication between different IBSS which is made possible in IEEE 802.11 networks.
- Point Coordination Function (infrastructure configuration): the MHs communicate to Access Points (APs) which are part of a Distribution System (DS). An Access point serves the stations in a Basic Service Set (BSS) implementing a centralized control of the system. The access method is similar to a reservation-based polling system and uses a coordinator to determine the transmission scheduling of MHs.

The basic access method in the IEEE 802.11 MAC protocol is the *Distributed Coordination Function* (DCF) which is a *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) MAC protocol. In few words, this means that a station listen the channel before to transmit. Since this protocol is the main focus of this work, it will be separately considered in detail in next sections.

Before taking control of the channel and transmitting, each station in the IBSS (including the AP, if any) is associated with an amount of idle time (i.e. the IFS) that the station must wait, while performing a carrier sensing of the channel state. If a station senses another stations' transmission on the channel during its IFS, it defers its own transmission. It results that the station with the shortest IFS is allowed to take control of the channel. It is worth noting that the fundamental hypothesis of this access scheme is that the state of the channel is consistent for all stations sharing the channel. As we will show in next sections, this is not always guaranteed due to hidden terminals. Three possible levels of priority are considered, related to three IFS intervals: in increasing order, Short interframe Space (SIFS), PCF Interframe Space (PIFS) and DCF Interframe Space (DIFS).

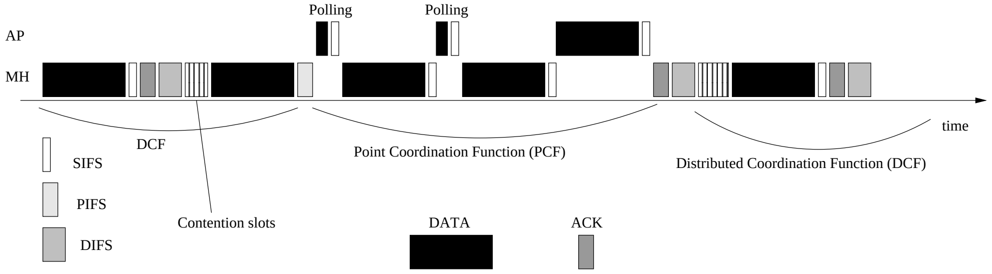
The SIFS is the shortest interframe space, and it is implicitly assigned to a station which is expected to transmit immediately by the context of the communication process: e.g. to send an acknowledgement for a received frame, or to send a frame after a polling signal from the AP.

The PCF is supported on the top of the DCF by exploiting a super-frame structure and PCF Inter Frame Spaces (PIFS). The PIFS is the intermediate IFS ($SIFS < PIFS < DIFS$), and it is related with the Access Point (AP) only. Whenever the AP wants to take control of the channel, it waits up until the first idle PIFS time on the channel, and immediately transmits to take control of the channel. The AP gain the control of the channel and maintains it up until it leaves a DIFS of idle time to elapse on the channel (see figure 1).

The DIFS is the longest interframe space, and it is the enabler IFS to start the DCF phase. After every transmission, stations under DCF control must wait for an idle time on the channel at least equal to the DIFS before to start the contention for the channel (see figure 1). Contention based access is performed by peer-MHs by adopting Collision Avoidance and Contention Control schemes. This short description of interframe spaces is sufficient for the considerations that will be presented in this chapter, but it is not exhaustive. Interested readers should address to [31] for further details.

In the next sections we will concentrate our analysis over the DCF Collision Avoidance and Contention Control which, due to distributed random-access characteristics, may be affected in significant way by the congestion problem. The Point Coordination Function may be affected by the contention problem as well, in an indirect way. The transmission requests from the MHs to the AP are performed in DCF frames and are subject to contention-based accesses. In other words, the DCF access scheme is considered the Basic Access scheme in IEEE 802.11 networks, hence its optimization is a relevant research activity for both DCF and PCF access schemes.

Figure 1: IEEE 802.11 DFWMAC Superframe structure



3 Background and wireless assumptions for MAC protocols

In this section, we will briefly summarize some of the assumptions and characteristics that have been considered for the design, tuning and implementation of distributed, random-access MAC protocols in wireless scenarios. Most of the following assumptions can be considered the new MAC protocol design problems, which made most of the successful solutions for the wired scenarios to become unpractical for the wireless scenarios.

3.1 Wireless signals

Wireless signals can be used to code the information being transmitted in many ways. Coding techniques are out of the scope of this chapter, and more information on this topic can be found in [61]. From a physical viewpoint, wireless signals are electromagnetic waves that propagate away, all around from their sources (i.e. like the light around a lamp). This phenomenon is usually denoted as the physical "broadcast nature" of the wireless transmissions, i.e. signals cannot be restricted on a wire, but they diffuse over the area around the transmitter. It is quite clear how this assumption is to be considered in the MAC design, which is devoted to manage the channel capture. The way the wireless signals propagate can be described in many ways by adopting *propagation models*. Propagation models describe the combined effects of the medium characteristics, the environment obstacles, and the transmission power of the signal source (i.e. the wireless transmitter). In every medium, the transmission power of wireless signals (Ptx) is subject to a natural decay: the more the distance d from the transmitter, the lower the residual power for the signal being detected by a receiver (in the order of Ptx/d^k, $k \geq 2$) (see figure 2). If the residual signal power to the receiving network interface is above the *reception threshold* Rth then a communication is possible between sender and receiver. Otherwise, to allow a communication (i.e. link establishment) between the sender and receiver it would be necessary to increase the transmission power of the sender, and/or to reduce their relative distance d. In order to obtain a bi-directional link, i.e. the required condition for most of the MAC and LLC protocols proposed, the communication must be possible on both directions, from sender to receiver and vice versa. This assumption must be considered when heterogeneous devices with different sensitivity thresholds and different transmission power levels co-exist in the same scenario. In general, network interfaces can be managed to transmit signals with a variable transmission power Ptx. In the receiving phase, network

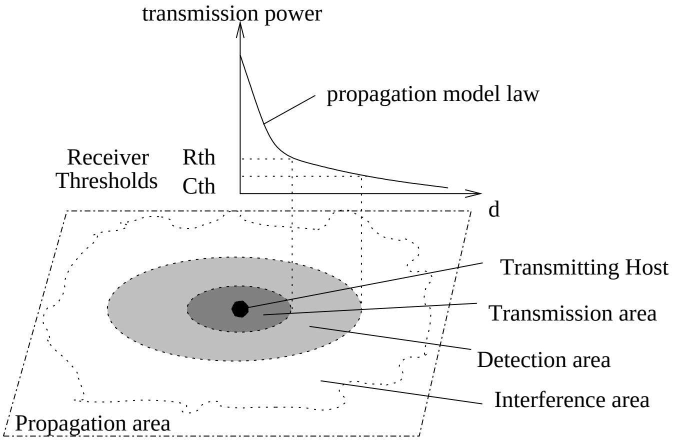


Figure 2: **Transmission power, propagation and coverage areas**

interfaces can be summarily described by means of the *receiving threshold Rth* and a *carrier-sense threshold* Cth [61] (see figure 2). For every transmitter-receiver pair, if the receiving power perceived for the ongoing transmission is greater than Rth then it would be sufficient for reception, if it is greater than Cth it would be sufficient for detection and carrier-sensing, otherwise it would be simple interference. Reception and carrier sensing events can be detected by the device components and made available to Medium Access Control protocols to locally manage the transmissions.

The *transmission (coverage) area* of a wireless transmitter (see figure 2) is the area where the wireless signal propagates and can be correctly detected and decoded (i.e. transmission is possible with few/no errors are due to interference). It should be noted that this area depends on the transmission power of the transmitter, on the propagation characteristics of the medium, on the reception threshold (sensitivity) of the receiving network interface (Rth), and on the amount of interference (noise) caused by other transmissions and by environment factors [61]. Only the receiver (i.e. not the sender) knows if the transmission has been received or detected, hence the transmission area cannot be completely determined by the transmitter's properties only.

The *detection area* (see figure 2) of a wireless transmission-device is the area where the signal propagates, and where it can be detected by a carrier sensing mechanism (see below), without being necessarily decoded (i.e. $Cth \leq Received\_Signal\_Power \leq Rth$). This means that a mobile receiver can sense the wireless medium as busy, without being able to decode the received signals. The existence of this area in the system, for each transmitter, may be relevant for the evaluation of detailed carrier sensing and MAC level effects, such as exposed terminals, hidden terminals, capture effects (described in the following).

The *Carrier Sensing (CS)* mechanism is shortly described as the physical capability of the network interface to detect transmissions, and to send a signal to the MAC layer indicating the event: "some signal is being detected on this channel".

The *interference area* of a wireless transmission-device is defined as the area where the wireless signal

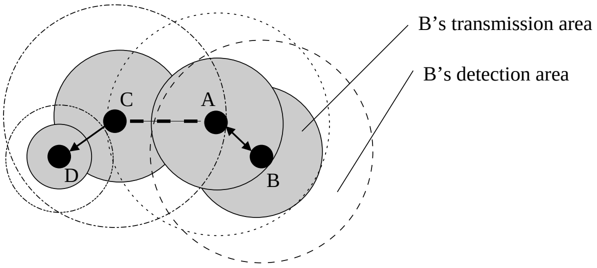


Figure 3: **Example of a collision domain**

propagates, without being detected or decoded by any receiver. Interference adds noise to any possible ongoing transmission for intended receivers within the interference range. The cumulative effect of multiple interferences might add errors to the bits of information transmitted to receivers.

3.2 Collision domains, capture effect

A *collision domain* can be defined as the union of the coverage areas of a set of nodes, mutually connected by a single shared communication channel. Given the collision domain example shown in figure 3, D can only receive C, C and B can detect each other but cannot receive respective transmissions, and A and B can receive (and detect) each other. Interference areas ar not shown in the figure: it could be assumed that every node is in the interference range of each other. A collision happens on a given receiver when two or more portions of concurrent transmissions superimpose each other in the time and space domains, by causing decoding errors for the information received. If the received signal power of one of the colliding signals is much more greater than others, it may happen that the receiver is able to capture such transmission anyway (e.g. A could capture B's data while C transmits). In this case a *capture effect* of signals can be exploited. Otherwise, collision of concurrent signals transmitted on the same collision domain may cause a destructive interference for detected signals on the receiver. The main goal of a MAC protocol policy is to avoid such collisions, and to adapt the density of transmissions, i.e. the contention level. The contention level can be thought as the risk to cause a collision if a transmission is performed. In the next sections, we will illustrate other problems and issues for the MAC design.

3.3 Half Duplex channels

Once the link existence is established at the physical transmission level, the MAC protocol should manage the MAC level link properties inherited from the physical layer.

A single wireless communication device, i.e. a wireless network interface (NI), can transmit and receive data in separate time windows, but cannot transmit and receive at the same time on the same wireless channel. One of the characteristics of a single wireless communication channel between any two nodes A and B is that a single channel can be used only in *half-duplex mode* for communications. This means that a single channel can be used to send data from A to B or vice versa, but not both ways on the same time (see figure 3). In other words, a network interface cannot "listen" to receive communications while it is transmitting on the same channel. Even if this behavior could be technically possible at the hardware level (e.g. by using two NIs), the result would be nullified because the transmitted signal would be in most cases much more powerful in the proximity of the device than every other received signal. This is due to the physical propagation laws for wireless signals.

3.4 Collision Detection (CD)

The half-duplex characteristic of wireless channels is one of the most critical and limiting assumptions to be considered in the design of MAC protocols for the wireless scenario. As a consequence, collision detection (CD) techniques adopted in wired LANs MAC protocols (e.g. IEEE 802.3 and Ethernet) cannot be implemented on a single wireless channel. The only way to obtain a similar function in wireless scenarios could be given by adopting a couple of network interfaces and a couple of channels: while A sends data to B on the DATA channel, if a collision is detected, B may send a jamming signal to A on the CD channel, to cause an early stop of the DATA transmission.

3.5 Full Duplex links

A bi-directional (Full Duplex) link can be obtained by adopting duplexing techniques, like Time Division Duplex (TDD), or Frequency Division Duplex (FDD). TDD creates a logical abstraction of a full duplex link by splitting the transmission and reception phases over consecutive, non-overlapped time intervals, on a single half-duplex (physical) channel. FDD consists in adopting two physical channels: one for transmission and one for reception. In most WLANs and MANETs, logical (bi-directional) links are commonly defined as time division duplex channels. All data transmissions and receptions have to be in the same frequency band, since there are no "bridge" nodes (maybe excepted Base Stations) to translate the transmissions from one physical channel to another one. This usually requires strict time-synchronization in the system, and Medium Access Control (MAC) protocols' defined accordingly [16].

In the following we will describe the main distributed MAC protocol proposals for WLAN scenarios. It is worth noting that three important and leading factors determine the MAC protocol definition: time, space and power (energy). In few words, a distributed MAC protocol should locally manage the time-schedule of transmissions, depending on the variable traffic load requirements, in such a way to avoid collisions on the receivers, and to exploit the maximum degree of spatial-reuse of the limited channel resource. On the other hand, any reduction of energy consumed for transmission and reception phases is another critical point for battery-based devices at the MAC layer. To the wireless scenario characteristics and problems described, it must be added the effect of mobility of users, resulting in highly dynamic and variable collision domains and contention levels.

4 Evolutionary perspective of distributed contention-based MAC

This section describes the evolution of proposals in the field of distributed contention-based multiple-access MAC protocols for the wireless scenario. The list of proposals is not exhaustive, due to space reasons, but it is an incremental illustration of the milestones and the evolution of the protocols, leading to IEEE 802.11. Specifically, given the focus of the chapter, this perspective is oriented to the contention control and power saving issues in the distributed contention-based MAC protocol design.

4.1 Distributed contention-based MAC protocols

The following MAC protocols deal with the reduction of the vulnerability of contention-based transmissions over the same wireless collision domain.

4.1.1 The Aloha MAC protocol

The first MAC protocol defined for distributed, multiple-access wireless transmission of data frames (called packets) was the *Aloha* protocol [1]. In this protocol the *Carrier Sensing (CS)* concept was still not included, i.e. every node was not assumed to "listen" to the channel before transmitting. The MAC protocol policy was straight-forward: every node transmits any data in the buffer queues immediately, whenever it is ready. During the transmission, Collision Detection (CD) is not possible, and the transmission attempt is performed, up to the end of the data frame, over half-duplex channels. After the transmission is performed, some form of *Acknowledgment (Ack)* was provided (e.g. on a separate channel), to ascertain a successful transmission. The transmitter waits for the Ack up to a maximum amount of time (ack timeout). In case of unsuccessful transmission (i.e. missing acknowledgment after the timeout) a new transmission attempt is required. The simple bi-directional "Data + Ack" structure of the frame transmission realizes the prototype definition of a reliable Logical Link Layer. In order to avoid synchronization of re-transmission attempts among multiple contending nodes, resulting in a sequence of collisions, every re-transmission is scheduled after a pseudo-random waiting time.

The *vulnerability* of a frame being transmitted is defined as the size of the maximum time window containing the frame transmission, during which another frame may be transmitted by originating a collision on the receiver. In [50] it was demonstrated that the vulnerability period for each frame (by assuming constant size) in the Aloha access scheme is twice the average frame size expressed in time units. In the same paper it was demonstrated that, by assuming independent Poisson-distributed arrivals of frames' transmissions (with constant size), and collisions as the only source of transmission errors, the expected channel utilization was upper bounded by only 18% of the channel capacity (i.e. the maximum channel throughput). In other words, by increasing the load offered by independent nodes (load G is defined as the frame size multiplied by the Poisson inter-arrival rate), the probability of a collision increases, and the MAC policy would not be able to support channel utilization greater than 18% (see figure 4). This is a theory result that well describes the scalability limits of this MAC policy under the contention control viewpoint.

4.1.2 The Slotted-Aloha MAC protocol

The *Slotted Aloha* protocol, was introduced to limit the vulnerability of each frame. The time is assumed to be divided in *frame-slots* (with fixed frame size), each one able to contain a frame transmission. This protocol is similar to Aloha, but a quantized synchronization of nodes is assumed, such that every transmission starts only at the beginning of a *frame slot*. In this way, the relevant advantage is that the vulnerability period is limited by the single frame slot where the transmission is performed. Analytical models demonstrate that the expected channel utilization was upper bounded by 36% of the channel capacity, i.e. twice the Aloha value (see figure 4). This theory result shows that the scalability of this MAC policy is better than Aloha, but is still far from the optimality.

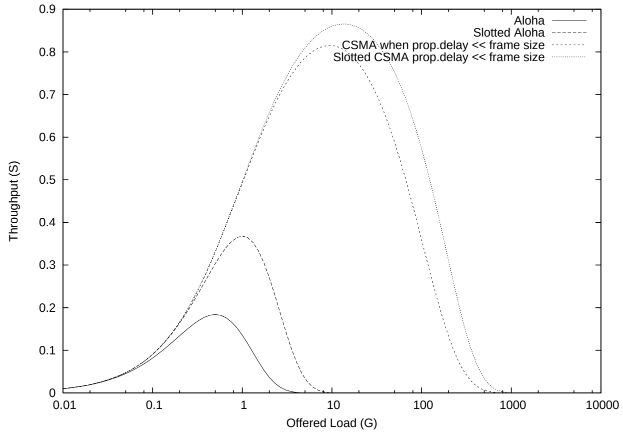
4.1.3 The pure CSMA MAC protocol

Previous studies motivated for designing and introducing the Carrier Sense Multiple Access (CSMA) concept [50]. In the CSMA MAC, every node "listen" the channel before transmitting, and if the channel is found to be busy it defers the transmission to later time (i.e. non-persistent carrier sensing), otherwise it transmits immediately. The advantage of this policy is that ongoing transmissions can be detected and the next candidate transmitter would nicely avoid to collide with them. Unfortunately, if the propagation delays are significant with respect to the frame size, the performance of CSMA would be negatively affected. The propagation delay temporarily hides the ongoing transmission to other potential transmitters, whose transmissions may cause a collision to the intended receivers. In such a way, the vulnerability of the frame was demonstrated to be reduced to only two times the maximum propagation delay ($2 * \tau$) of wireless signals, among any two distant transmitters. As an example, the transmission of a transmitter X starting at time t_x is exposed to the risk of collision with possible transmissions started at time $t_y \geq (t_x - \tau)$ by any transmitter Y (whose transmission has not still been detected by X). The transmission from X is also exposed to the risk of collision with any possible transmitter Z whose transmission will start at time $t_z \leq (t_x + \tau)$ (i.e. before Z can detect the ongoing transmission from X). The propagation delay τ is usually considered orders of magnitude lower than the size of the typical frames [50]. This is specifically more probable for common WLAN and MANET scenarios. The CSMA throughput was modeled and was defined as high as 80% of the channel capacity (see figure 4).

4.1.4 The Slotted-CSMA MAC protocol

By applying the slot-based concept to CSMA, the *Slotted-CSMA* protocol was proposed as a further enhancement of CSMA [50]. A *minislot* is defined as the upper bound of the propagation delay between different transmitters in the system (τ). In the Slotted-CSMA protocol, every node with a frame to transmit "listen" the channel at the beginning of the next *minislot*, and if the channel is found to be busy it defers the transmission to later time (i.e. non-persistent carrier sensing), otherwise it transmits immediately at the beginning of the current minislot. The advantage of this policy is that the beginning of possible transmissions are synchronized up to a minislot-quantized time. Transmissions are guaranteed to be detected at worst at the beginning of the next minislot by all the transmitters in the system. In such a way, the vulnerability of the frame was demonstrated to be reduced to the minislot time (τ). If the propagation delays are significant with respect to the framesize, the performance of Slotted-CSMA would degrade. The attainable Slotted-CSMA throughput was modeled and was giving better values than the CSMA channel capacity, for the same scenarios (see figure 4).

Figure 4: Analytical investigation of contention-based MAC throughput



4.2 Collision Detection in Wireless systems

All previous MAC policies were assumed to receive an Acknowledgment-based (Ack) feedback indication of the successful transmission from the intended receiver. The Ack is usually provided as a short reply frame, and can be exploited to realize the Link Layer concept of "reliable link" between transmitter and receiver. In some systems, and in early wireless MAC proposals, Acks were sent on separate control channels. Nowadays, the Ack transmission is usually piggybacked by the Data receiver immediately after the end of the Data reception, on the single, shared, half-duplex communication channel. In this way, at the MAC/LLC layer, the receiver could immediately exploit the contention won by the transmitter for sending the ack frame (i.e. a new contention is not required since the shared channel has been successfully captured by the sender).

Different policies and definitions of the MAC and LLC layers can be defined by assuming the explicit indication of the motivation for unsuccessful transmissions (e.g. if a frame was received with errors, if it was subject to collision, etc.). Anyway, the LLC layer is out of the scope in this chapter. The knowledge of the reasons for the unsuccessful transmissions has been considered in the literature, and analysis shown that the more information feedback is provided on the cause of a contention failure (i.e. collision, number of colliding nodes, bit error due to interference, etc.) the more performance and adaptive behavior can be obtained by the MAC protocol. Unfortunately, in most scenarios, the only feedback information provided after a transmission attempt is the existence of Ack frames within a timeout period.

In early wired LANs, researchers considered solutions based on CSMA techniques and transmitters with

Collision Detection (CD) capabilities [56], i.e. the nodes were listening to the channel while they were transmitting. As mentioned before, in wireless systems, CSMA and slotting techniques can be exploited to reduce the vulnerability of frames being transmitted. Anyway, when the frame transmission starts, there is no way to early detect if a collision is occurring at the receiver node. Under this hypothesis, CSMA/CD schemes like Ethernet and IEEE 802.3 cannot be exploited in wireless MAC protocols. The implementation of collision detection in wireless scenarios has been investigated in some research works, e.g. [54, 63, 67]. Given the characteristics of wireless systems, the only practical way to obtain something equivalent to CD is the adoption of separate signalling channels and multiple Network Interfaces (NIs). This would require twice the channel bandwidth, power and network interfaces than other mechanisms. We will see in the following how researchers defined new MAC policies for the wireless world that could be considered quite equivalent to the collision detection schemes under the channel reservation and channel utilization viewpoint.

4.3 Collision Avoidance

The Aloha and CSMA MAC protocols illustrated in the previous section were thought for the reduction of the vulnerability period of the contention-based frame transmissions. The Collision Avoidance (CA) techniques have been designed in order to preventively create the same conditions provided by collision detection, by using a single shared channel and a single network interface. If the contention-based transmission evolves in a collision to the intended receiver, then the amount of energy wasted and channel occupancy by the colliding transmission should be as much limited as possible.

Collision avoidance can be thought as a preliminary spatial reservation of the collision domain between sender and receiver, in order to preserve the whole data transmission. The spatial reservation can be performed by resolving the channel contention among multiple transmitters in the neighborhood of both the sender and the receiver. Before of illustrating the proposals for collision avoidance, we are going to define the most representative problems to be considered at the MAC layer under this viewpoint.

4.3.1 The Hidden and Exposed Terminals

The dynamic topology of wireless ad hoc networks, the adoption of shared channels for transmissions, and a carrier-sensing based policy for the MAC protocol implementation may bring some nodes to experience the *Hidden Terminal* and the *Exposed Terminal* problems. These problems happen for a node receiving the concurrent transmissions of at least two other neighbor nodes, respectively hidden to each other. In such scenarios, any time-overlapping of concurrent transmissions on the receiver may result in a *collision* which has a destructive effect. Given the collision definition, this phenomenon happens only on the receivers and it is dependent on the threshold levels (sensitivity) for the residual energy perceived by the receiver's network interface (for reception, detection and interference, respectively).

As an example, let us suppose A is within the *detection area* of C and vice versa, B is within the *transmission area* of A and vice versa, and C is outside the *detection area* of B (see figure 5). In this scenario

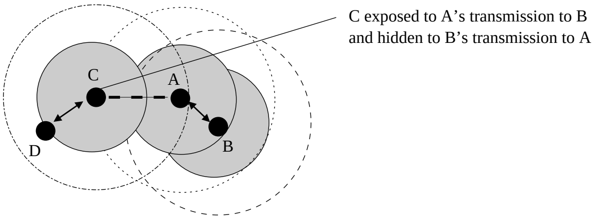


Figure 5: **Example of hidden and exposed terminal**

C senses the transmission of A, i.e., it senses the channel as busy, but it cannot decode the transmission. This condition illustrate the *exposed terminal* condition for C with respect to A [16]. Exposed terminals are terminals, (e.g., C) whose transmission is not allowed, (e.g., by a MAC policy over a collision domain) due to exposure to irrelevant transmissions, (e.g., from A to B). The exposed terminals problem is the cause of a limitation of the possible channel reuse.

Another problem is given by *hidden terminals*: due to shadowing effects and limited transmission ranges, a given terminal B could start a transmission towards another terminal A (B and A are within each other's transmission area, see figure 5), while A is receiving signals from a hidden (with respect to B) terminal C. This means that A cannot complete any reception, due to the destructive collision of signals from B and C. It may happen also that A can detect and isolates one of the colliding transmissions, (e.g., from B to A): in this case, we obtain a *capture effect* of transmission from B to A, despite C's interference and collision. A discussion of details for hidden and exposed terminals and capture effect can be found in [16, 59]. Being the CSMA-based solution proposed in [50] implemented by transmitters, it is not guaranteed that CSMA is sufficient for transmitters to detect each other before their respective transmissions. In such a scenario, the throughput of CSMA and ALOHA would fall again to less than 18% the channel capacity. This is the reason why the hidden terminal problem was discussed quite early in 1975, by Tobagi and Kleinrock [73].

The solution proposed in [73] was the Busy Tone Multiple Access (BTMA) protocol, where a separated channel was used to send a busy tone whenever a node would be detecting a transmission on the data channel. In this way the information about the (local) occupancy of the channel at each receiver is forwarded by the busy tone signal to neighbor nodes, and every node should perform a Carrier Sense on the busy-tone channel before sending a frame. The major drawback of BTMA is that it would require a separate channel and a couple of network interfaces to perform carrier sensing on the busy-tone channel while transmitting on the data channel.

4.3.2 The Request-to-Send (RTS) and Clear-to-Send (CTS) scheme

Another more affordable way to contrast the hidden terminal problem among wired terminals connected to a centralized server was suggested in Split-channel Reservation Multiple Access protocol (SRMA) in 1976 [74]. The solution was based on the handshake of short messages Request-to-send/Clear-to-send (RTS/CTS) between senders (i.e. terminals) and receivers (i.e. the server), over three separated channels (RTS, CTS and DATA channels). The RTS/CTS scheme was originally designed to manage the efficient transmission scheduling between senders and receivers, without originating interferences among hidden terminals on the server [74].

Some time later, the RTS/CTS scheme was interpreted and adopted in quite a different way with respect to SRMA, and it was performed on a single transmission channel as originally proposed, for wired LANs, in the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme by Colvin in 1983 [23]. The idea is to send a short request-to-send (RTS) frame (by applying the CSMA MAC channel access scheme) to the intended receiver, before a data transmission. If the receiver correctly receives the RTS, then it immediately responds with a clear-to-send (CTS), back to the transmitter. In this way the double successful transmission of both RTS and CTS, should reserve the channel (i.e. the collision domain) between sender and receiver against hidden transmitters.

The principle of this solution, modified in opportune way, has been successively adopted in the next years in many protocols and standards. Collision avoidance based on RTS/CTS is an optional function included in current IEEE 802.11 DCF implementation.

4.3.3 Multiple Access Collision Avoidance (MACA)

RTS/CTS was first introduced in wireless systems in the Multiple Access Collision Avoidance (MACA) protocol [47]. MACA is a random-access MAC protocol, trying to solve the hidden terminal problem by making a step back with respect to the carrier-sensing approach. In MACA, it was observed that the relevant contention is at the receiver side, not at the sender's, suggesting that the carrier sensing approach at the transmitter is not fully appropriate for the purpose of collision avoidance. Carrier sensing at the sender would provide information about potential collisions at the sender, but not at the receiver. Since the carrier sensing mechanism implemented on the transmitter-side cannot ensure against hidden terminals, and leads to exposed terminals, the radical proposal is to ignore carrier sensing before transmissions. The idea is to bet on the contention of two really short frames, request-to-send (RTS) and clear-to-send (CTS), adopted to reserve the coverage area (i.e. the collision domain) between sender and receiver before to send the DATA frame. Both RTS and CTS are 30 Bytes long, and contain the information about the expected duration of the channel occupancy for the following Data transmission. The main critical assumption in this definition is the perfect symmetry of links, i.e. (A detects B) $\Leftrightarrow$ (B detects A). The transmitting node sends the RTS to the receiver as a broadcast message. If the receiver receives the RTS, and it is not deferring due to a previous reservation, it immediately responds with the CTS, which also contains the information about the expected duration of the channel occupancy. If a node different from the sender receives the CTS (that is meaning that node is in the critical range for the receiver), then it would be informed about the transmission duration and it would nicely enter the deferring phase for that interval. If the sender receives the CTS it knows that the receiver is within the transmission range, and the channel should have been reserved successfully. This indicates that the Data transmission could start with a good probability to be successful. All nodes receiving the RTS, different from the intended receiver, could listen to hear the CTS reply. If they are not receiving the CTS, they could assume they are not in the critical range of the receiver (i.e. receiver is not exposed), hence they could start their own transmissions, increasing in this way the spatial reuse of the channel [1]. This could be considered a first solution for terminals "exposed" with respect to the sender's RTS. In this scheme, the acknowledgment based confirmation (CTS) of the success in the channel capture is based on a lower risk to waste channel bandwidth, if a collision occurs, than the risk given by collisions of two or more long Data frames. If CTS is not received within a timeout period, the sender assumes a collision occurred, and re-schedule a new RTS transmission by adopting a contention control scheme (Backoff protocol), see section 4.3.4) to select the "slot time" for the new RTS transmission. RTS and CTS are 30 Bytes long and their time duration defines the "slot time" for quantizing transmissions.

Other solutions for collision avoidance are based on the reversing of the RTS/CTS handshake. In MACA By Invitation (MACA-BI) [72] and in many Receiver Initiated Multiple Access (RIMA) versions [77], the RTS/CTS scheme is initiated by candidate receivers sending Ready-to-Receive (RTR) frames to the neighbors. In this way the collision avoidance scheme reduces the overhead required in some scenarios.

4.3.4 The Backoff protocol

The Backoff protocol is a *contention control* protocol that is frequently associated with contention-based, collision avoidance, slotted access schemes. We anticipate here its presentation, even if collision resolution and contention control protocols will be described in next sections. Whenever a collision is detected by the sender (e.g. missing Ack or missing CTS) this event can be considered an indication of a high contention level in the channel. A time-spreading and randomization of re-transmission attempts is required to reduce the contention, and to avoid new collisions due to the choice of the same slot. The Backoff scheme realizes the adaptive contention reduction based on the experience of collisions for a frame transmission. For every new frame transmission, the Backoff scheme is re-started. The first transmission attempt is performed in one of the next slots selected with pseudo-random uniform distribution in the interval $[0..CW\_Size\_min-1]$, where CW_Size_min is an integer value. The CW_Size is increased after each collision, up to a maximum value CW_Size_MAX, and reduced to the minimum CW_Size_min after a successful transmission. In the Backoff protocol that was defined in MACA, the CW_Size is doubled after every collision (i.e. a Binary Exponential Backoff, BEB), $CW\_Size\_min = 2$ and $CW\_Size\_max = 64$.

4.3.5 MACA for Wireless

MACA for Wireless (MACAW) [5] is a modified version of MACA, where the new wireless scenario's assumptions still play an important role. Note that MAC protocols should deliver high network utilization together with fair access to every node (i.e. no "one node takes all" solution). In [5] the unfairness problem of BEB was described: local experience of collisions from one sender could make it reaching high CW_Size, while

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[1] Note that final acknowledgments after the Data transmission are not expected on the sender in this protocol

other senders could keep winning the contention within CW_Size_min slots. The suggested solution to this problem was to insert in the frame header the CW_Size information: every node receiving the packet would copy locally the CW_Size value, by obtaining a more fair access distribution. Multiplicative increase and linear decrease (MILD) algorithm was applied to CW_Size and was suggested to avoid wild fluctuations. Also, the concept of "stream-oriented" fairness, instead of station-oriented fairness, was taken into account in [5]. Imagine two contending stations: the first one with a single frame queue, and the second one with many frame queues coming from many different running applications. The "contention pressure" given by the MAC protocols of the two stations is the same, even if the "flows pressure" is not fair. The idea was to adopt one backoff queue per stream with local scheduling and resolution of virtual collision of frames within the local station. In this way the density of accesses on the channel is not the same for all the stations, but is a function of virtual contention among flows inside each station. Recently, this idea has been considered in the IEEE 802.11e definition, leading to a distributed implementation of differentiated accesses to the channel for flows with different priority levels. New special frames DS and RRTS were defined in MACAW to propose solutions for the synchronization problems and for making the receiver able to contend for bandwidth even in the presence of congestion [5]. Some optimizations of the Binary Exponential Backoff (BEB) and CW_Size-copying algorithm have been proposed: *i)* based on the observation that the "copying" algorithm works well only in uniform contention scenarios, and *ii)* based on the assumption to know the motivation for RTS and CTS problems, if any. This protocol introduced for the first time the assumption that channel contention in wireless scenarios is location dependent, and some kind of "collective enterprise" should be adopted in order to allocate the media access fairly. The MAC protocol should propagate contention information, instead of assuming every node is able to discover such information on a local basis. Finally, the MAC protocol should propagate synchronization information about contention periods, in order to allow every device to contend in effective way, e.g. by exploiting contention initiated on the receiver side (RRTS).

In MACAW, by following the suggestion coming by Tobagi and Kleinrock [75], Appletalk [67] and the early IEEE 802.11 working groups, immediate acknowledgment is introduced after the RTS-CTS-DATA exchange of information at the MAC-Logical Link Control sub-layer. In this way, if RTS-CTS-DATA-ACK fails, immediate retransmission at the link layer can be performed if the frame was not correctly received for some reason. This condition is assumed by the sender if the ACK is not received, even if the CTS was received. This improves many network and user performance indices with respect to a transport-layer re-transmission management, due to the characteristics of the wireless scenario (mainly the high risk of bit error and interference). The immediate ACK from the receiver to complete the transmission sequence makes the sender acting as receiver during the RTS-CTS-DATA-ACK transmission scheme. The solution proposed in MACA for eliminating exposed terminals is now a drawback for MACAW, because concurrent transmitters could interfere with the reception of ACKs. This limits the spatial reuse of the channel that was obtained by the RTS/CTS policy in MACA (i.e. a sender transmits anyway, if it was receiving another sender's RTS but not the corresponding CTS). MACA and MACAW are not based on the carrier sensing activity at the transmitter before the transmission of the RTS. Also, at least a double propagation-delay time of idle-channel space should be required between the channel becoming idle and the RTS transmission, in order to allow for the full reception of ACKs [5].

4.3.6 Floor Acquisition Multiple Access (FAMA)

Floor Acquisition Multiple Access (FAMA) [30, 29] is a refinement of MACA and MACAW with the introduction of *i)* carrier sensing on both senders and receivers, before and after every transmission, in order to acquire additional information on the channel capture, *ii)* non-persistence in the CSMA access scheme (if the channel is found to be busy, a random wait is performed before a new carrier sensing), *iii)* lower bound of the size for RTSs and CTSs based on worst case assumptions on the propagation delays and processing time, *iv)* RTS size shorter than CTS (CTS dominance) to avoid hidden collisions among RTS and CTS. It is worth noting that, from MACAW on, the frame transmission is considered complete when the RTS-CTS-DATA-ACK is completed. The need for ACK reception on the sender to complete the handshake imply that both receiver *and* sender must be protected against hidden terminals (as mentioned before, the main drawback of hidden terminals is the collision that may happen on a terminal acting as a receiver).

Since collision detection is not practical in (single channel) wireless scenarios, in FAMA the carrier sensing approach is extended to both sender (for RTS) and receiver (for CTS). Sender and receiver aim to reserve the "floor" around them, in order to protect the DATA reception on the receiver, and the ACK reception on the sender, against their respective hidden terminals. This conservative approach may give a reduction of long collisions and link layer transmission delays, hence a better utilization of scarce resources like channel bandwidth and battery energy. In [29] the demonstration of sufficient conditions to lead RTS/CTS exchange a "floor" acquisition strategy is provided (with and without carrier sensing).

4.3.7 Analysis of Collision Avoidance schemes

To summarize, the RTS/CTS mechanism has many interesting features and a couple of drawbacks.

Let us describe first the RTS/CTS interesting features: its adoption guarantees in most cases the transmission will be worthwhile because a successful RTS/CTS handshake ensures: *i)* the sender successfully captured the channel in its local range of connectivity, *ii)* the receiver is active, *iii)* the receiver reserved the channel in its local range of connectivity (not necessarily the same area of the sender) and it is ready and able to receive data from the sender, *iv)* the RTS/CTS exchange would allow the sender and receiver to tune their transmission power in adaptive way (hence, by saving energy and reducing interference). Recent studies shown that the RTS/CTS problem would be not so heavy as the amount of work on this topic would let people think [83]. On the other hand, as a conservative approach, the RTS/CTS solution is the basis for many research proposals. Specifically, RTS/CTS exchange could be considered as a milestone for MAC in wireless multi-hop scenarios, like MANETs. Ongoing activities are based on the adoption of directional antennas to implement directional collision avoidance schemes. The idea is to adopt directional antenna beams to reserve the channel over small area sectors between sender and receiver. In this way, less energy can be used and more spatial reuse of channel can be obtained. Directional MAC protocols and directional collision avoidance schemes are ongoing research activities.

Turning our attention to RTS/CTS drawbacks, the first drawback is that in ideal conditions (i.e. when the contention and interference scenario is trivial), the additional transmissions of RTS and CTS frames for any data frame to be sent, would require additional bandwidth and energy than the strictly sufficient amount. One possible solution to this drawback, adopted in IEEE 802.11 networks, is to set a *RTS/CTS_threshold* defining the lower size of frames that require the adoption of RTS/CTS exchange. If at least one transmitter needs to send a long frame, whose size exceeds the RTS/CTS_threshold, then a RTS message would be adopted to avoid a long-collision risk. If RTS/CTS overhead is not considered worthwhile, then the possible collision would not be exceeding the pre-defined threshold. With this scheme, the RTS/CTS goal is twofold: *i)* a channel reservation is performed to contrast hidden terminals, and *ii)* long collisions can be avoided.

The second drawback is given by a set of worst case scenarios where the adoption of RTS/CTS would not guarantee the successful transmission, due to collisions among RTSs and CTSs, and due to the characteristics of interference and propagation of wireless signals [83]. For a description of such worst case scenarios, see e.g. [68, 30, 5, 83]. In [83], the analytical and simulation-based evaluation of the RTS/CTS solution for ad hoc networks has been performed, by assuming IEEE 802.11 DCF MAC protocol. The relevant contribution in this work is given by the analytical investigation of transmission ranges, detection ranges and interference ranges (in open space) by assuming a two-way ground reflection propagation model [61]. Another important issue being considered is the difference existing between the reception (or detection) thresholds and the interference threshold in current wireless network interfaces [83]. The analysis shown that RTS/CTS handshake would leave a consistent area around the receivers where potential transmitters may not receive any RTS or CTS. Such potential transmitters would not activate their "deferring phases" (i.e. Virtual Carrier Sensing). The interference generated by such transmitters would be sufficient to generate collisions on the receivers despite they successfully exchanged RTS/CTS [83]. The proposed solution to enhance the RTS/CTS scheme was the Conservative CTS-Reply (CCR) scheme: a quite simple modification of the standard RTS/CTS solution. A conservative *RTS_threshold* power level is defined that should be reached by the RTS signal on the receiver side, in order to allow the receiver to send the CTS back [83]. With this assumption, data exchange is activated only if the transmitter is received with high power, and capture effect is probable despite interferences.

4.4 Collision Resolution protocols

The IEEE 802.11 DCF taken as a reference in this chapter is based on a slotted CSMA/CA MAC protocol. The slot size is kept as low as possible, and it is defined as a function of *i)* the maximum propagation delay in the collision domain, and *ii)* the time required to switch the Network Interface from carrier sensing to transmission phases. While the Collision Avoidance scheme tries to reduce the risk of a collision caused by hidden terminals, the contention control and collision resolution schemes (which may be considered as secondary components of the collision avoidance) are defined in order to reduce the risk of a new collision after a previous one.

In the following we will consider only collisions caused by the selection of the same transmission slot on behalf of more than one transmitter in the range of the receiver. We assume that Collision Avoidance (RTS-CTS) was performed in background.

The collisions become more probable if the number of users waiting for transmission on a given collision domain is high, i.e. if the channel contention is high. The collision resolution protocols can be defined, similarly to the contention control protocols, to reduce the probability of collision as low as possible, in adaptive way, with respect to the variable load in the collision domain.

Tree based collision resolution mechanisms have been suggested in [15, 76]. A good survey of such protocols can be found in [45, 34], and in the related bibliography. The set of k contending nodes is assumed to belong to the initial set $S0$: every node randomly selects one slot for transmission among the next R slots (with fixed integer R), called a "round" or a "contention frame". Whenever the feedback information indicating a collision is perceived, all the colliding nodes randomly split in two or more subsets. Every subset will try a new re-transmission in a separate subset of R slots (i.e. separate rounds), hence reducing the contention. Further splitting is performed after every new collision, originating a tree-like structure of subsets, giving the name to this mechanism. The main problem with tree based schemes is to adapt parameters like the number of slots R in each round, and the number of splitted subsets, in order to maximize the channel utilization, and to minimize the energy consumption and the collision resolution delay. Different assumptions about the amount of information perceived by the collisions were used to define many tree based schemes. As an example, by assuming to detect the number of colliding nodes by the residual energy detected, the round length R could be tuned in adaptive way [49, 36]. In Neighborhood-Aware Contention Resolution protocol (NCR) [4], some contention resolution protocols were based on the assumption that every node knows the IDs of neighbors within two-hops. Such assumptions are quite strong, and in general, collision resolution schemes have not been considered as a practical choice in IEEE 802.11 WLANs and MANETs, based on the CSMA/CA with contention control protocol.

Under light load conditions, collision avoidance and collision resolution protocols achieve the same average throughput of FAMA protocols [34]. A good description and comparison of collision avoidance and collision resolution schemes like ICRMA, RAMA, TRAMA, DQRUMA, DQRAP and CARMA can be found in [34].

4.5 Contention control in IEEE 802.11 DCF

In previous sections, the reader should have reached a sufficient background to begin the analysis of the IEEE 802.11 DCF contention control and collision reaction.

The DCF access method is based on a CSMA/CA MAC protocol. This protocol requires that every station, before transmitting, performs a Carrier Sensing activity to determine the state of the channel (idle or busy). This allows each station to evaluate the opportunity to start a transmission without interfering with any other ongoing transmission. If the medium is found to be idle for an interval that exceeds the *Distributed InterFrame Space* (DIFS), the station continues with its Collision Avoidance access scheme. If the medium is busy, the transmission is deferred until the ongoing transmission terminates, then after the DIFS, a Collision Avoidance mechanism is adopted.

The IEEE 802.11 Collision Avoidance mechanism is based on the (optional) RTS/CTS exchange.

Positive acknowledgements are employed to ascertain a successful transmission. This is accomplished by the receiver (immediately following the reception of the data frame) which initiates the transmission of an acknowledgement frame (ACK) after a time interval *Short Inter Frame Space* (SIFS), which is less than the DIFS (see figure 1).

When a collision occurs, this event is considered as an indication of a high level of contention for the channel access in backoff protocols. The reaction to the high contention level that caused the collision is obtained with a variable time-spreading of the scheduling of next accesses. Hence, a contention based MAC protocol is subject to a channel waste caused both from collisions and from the idle periods introduced by the time-spreading of accesses (i.e. idle slots). As the reduction of the idle periods generally produces an increase in the number of collisions, to maximize the channel and energy utilization the MAC protocol should balance these two conflicting costs [11, 10, 14, 33]. Since these costs change dynamically, depending on the network load, and on the number of mobile users, the MAC protocol should be made adaptive to the contention level of the collision domain [19, 33, 41].

The distributed collision reaction in IEEE 802.11 CSMA/CA is based on a *contention control* scheme realized by the *Binary Exponential Backoff* protocol [31, 39, 41]. The contention control can be defined as the problem to make the probability of collision as low as possible, in adaptive way, with respect to the variable load in the collision domain. Backoff protocols have been already sketched with the description of the backoff protocol introduced by MACA in section 4.3.4.

4.5.1 The Binary Exponential Backoff (BEB) protocol

By assuming that a collision occurred due to the selection of the same slot by at least two contending MHs, a backoff protocol is adopted to control the contention level, by exploiting the frame history regarding successes or collisions [41]. Specifically, given the system assumptions, each user is not assumed to have any knowledge about other users' successes or collisions, or even about the number of users in the system.

The objectives of the backoff scheme are: *i)* a distribution (the most uniform as possible) of the transmission attempts over a variable-sized time window, and *ii)* small access delay under light load conditions. According to this mechanism, a station selects a random interval, named *backoff interval*, that is used to initialize a *backoff counter*. When, the channel is idle the time is measured in constant-length units ($Slot\_Time$) indicated as "slots" in the following. The backoff counter is decreased as long as the channel is sensed idle for a $Slot\_Time$, stopped when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. A station transmits as soon as its backoff counter reaches the value zero. The backoff interval is an integer number of slots and its value is uniformly chosen in the interval $(0, CW\_Size - 1)$, where CW_Size is, in each station, a local parameter that defines the current *Contention Window* size. Specifically, the backoff value is defined by the following expression [31]:

$$Backoff\_Counter(CW\_Size) = int(Rnd() * CW\_Size) \ ,$$

where $Rnd()$ is a function which returns pseudo-random numbers uniformly distributed in [0..1]. The Binary Exponential Backoff is characterized by the expression that gives the dependency of the CW_Size parameter by the number of *unsuccessful transmission attempts* (Num_Att) already performed for a given frame. In [31] it is defined that the first transmission attempt for a given frame is performed by adopting CW_Size equal to the minimum value CW_Size_min (assuming low contention). After each unsuccessful (re)transmission of the same frame, the station doubles CW_Size until it reaches the maximal value fixed by the standard, i.e. CW_Size_MAX, as follows:

$$\begin{aligned} &CW\_Size(Num\_Att) = \\ &\quad \min(CW\_Size\_MAX, CW\_Size\_min * 2^{Num\_Att-1}). \end{aligned}$$

where Num_Att (starting from the value 1) is the counter of the transmission attempts. When the transmission of a given frame is successful, then the mechanism is re-started by assigning $Num\_Att = 1$, even if a new frame is ready for transmission. In this way there is no a "memory effect" of the contention level perceived for a given frame, in successive transmissions. The $CW\_Size\_min = [16, 32]$ and $CW\_Size\_MAX = 1024$ in IEEE 802.11 DCF [31]. If the fixed maximum number of transmission attempts is reached, for a given frame, a "link failure" is indicated to the upper layers.

Analytical investigation of stability and characteristics of various Backoff schemes have been presented in [33, 35, 39, 41].

4.5.2 Analysis of IEEE 802.11 contention control

The increase of the CW_Size parameter value after a collision is the reaction that the 802.11 standard DCF provides to make the access mechanism adaptive to channel conditions. By analysing via simulation the behavior of the 802.11 DCF mechanism, under various contention levels (i.e. the number of active stations with continuous transmission requirements), some problems could be identified. Figure 6 shows simulation data regarding the channel utilization of a standard 802.11 system running in DCF mode, with respect to the contention level, i.e. the number of active stations with continuous transmission requirements. The parameters adopted in the simulation, presented in Table 1, refer to the Frequency Hopping Spread Spectrum implementation [2] [31]. The RTS/CTS mechanism is off, and a single static collision domain is assumed to capture the contention effect.

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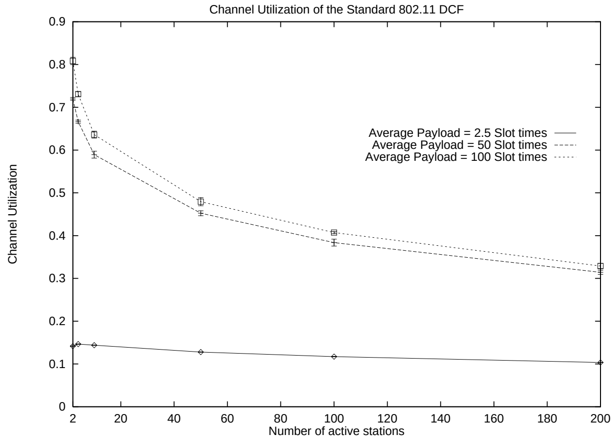
[2] The payload-size parameter is a simulation factor with average values 2.5 slots ($\approx$ 32 Bytes), 50 slots ($\approx$ 600 Bytes) and 100 slots ($\approx$ 1250 Bytes)

Table 1: System's physical parameters (FHSS implementation)

Parameter	Value
Number of Stations (M)	variable from 2 to 200
CW_Size_min	16
CW_Size_MAX	1024
Channel transmission rate	2 Mb/s
Payload size	Geometric distribution (variable)
Acknowledgement size	200μSec (50 Bytes)
Header size	136μSec (34 Bytes)
SlotTime	50μSec
SIFS	28μSec
DIFS	128μSec
Propagation time	$< 1\mu$Sec

Figure 6: Channel utilization of the IEEE 802.11 DCF with variable contention level



Specifically, the figure 6 shows that the channel utilization is negatively affected by the increase in the contention level. These results can be explained as, in the IEEE 802.11 backoff algorithm, a station selects the initial size of the Contention Window by assuming a low level of contention in the system. This choice avoids long access delays when the load is light. Unfortunately, this choice causes efficiency problems in burst-arrival scenarios, and in congested systems, because it concentrates the accesses in a small time window, hence causing a high collision probability. In high-contention conditions each station reacts to the contention on the basis of the collisions so far experienced while transmitting a given frame. Every station performs its attempts blindly, with respect to the contention level, with a late collision reaction performed (by increasing CW_Size). The number of collisions so far experienced is reflected in the size of the CW_Size, and can be considered a local estimate of the contention level. Each increase of the CW_Size is obtained by paying the cost of a collision. It is worth noting that, as a collision detection mechanism is not implemented in the IEEE 802.11, a collision implies that the channel is not available for the time required to transmit the longest colliding frame. The carrier sensing protects the vulnerability of frames, but does not give any preliminary indication about the contention level. Furthermore, after a successful transmission the CW_Size is set again to the minimum value without maintaining any knowledge of the current contention level estimate. To summarize the IEEE 802.11 backoff mechanism has two main drawbacks: *i)* the increase of the CW_Size is obtained by paying the cost of many collisions, *ii)* each collision does not provide a significant indication of the actual contention level, due to stochastic variability in the slot selection[3], and *iii)* after a successful transmission no state information indicating the actual contention level is maintained.

Several authors have investigated the enhancement of the IEEE 802.11 DCF MAC protocol to increase its performance when it is used in WLANs (i.e. a typical single collision domain) and MANETs (i.e. multi-hop collision domains) [86]. Unfortunately, in a real scenario, a station does not have an exact knowledge of the network and load configurations but, at most, can estimate it. In [20, 26], via a performance analysis, it has been studied the tuning of the Standard's parameters. In [7, 81], solutions have been proposed for achieving a more uniform distribution of the accesses in the *Binary Exponential Backoff* scheme. The most promising direction for improving backoff protocols is to obtain the network status through channel observation [37, 40, 9]. A great amount of work has been done to study the information that can be obtained by observing the system's parameters [35, 62, 79]. For the IEEE 802.11 MAC protocol, some authors have proposed an adaptive control of the network congestion by investigating the number of users in the system [7, 13, 14]. This investigation would be time-expensive, hence difficult to obtain and subject to significant errors, especially in high contention situations [13].

In [9] a simple mechanism, named Distributed Contention Control (DCC) was proposed to exploit the information obtained by the carrier sensing mechanism as a preliminary contention level estimation, to be adopted in the contention control mechanism. The *slot utilization* observed during the carrier sensing phases (i.e. the ratio of non-empty slots observed during the backoff) has been demonstrated to be a better indicator of the contention level than the single collision events. In [9], the slot utilization estimate was proposed to be adopted in a probabilistic mechanism (DCC) extending the backoff protocol. The DCC mechanism defers scheduled transmissions in adaptive way, on the basis of the local contention level estimate and local priority parameters (with no need for priority-negotiations). Implementation details of DCC, stability analysis and performance results can be found in [9].

The Asymptotically Optimal Backoff (AOB) mechanism proposed in [11] tunes the backoff parameters to the network contention level by using two simple and low-cost estimates (as they are obtained by the information provided by the carrier sensing mechanism): the *slot utilization*, and the *average size of transmitted frames*. AOB is based on the results derived by exploiting the analytical model of the IEEE 802.11 protocol presented in [14], and the enhancement of the Distributed Contention Control (DCC) mechanism presented in [9]. In [11] it was shown that, for any average length of the transmitted frames, it exists a value for the *slot utilization* that maximizes the protocol capacity, indicated as *optimal slot utilization*. In addition, in [11] the analytical model presented in [14] has been extended to show that the optimal value for the slot utilization is almost independent on the contention level and the network configuration (i.e. the number

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[3] Collisions could occur even with few stations, so the contention indication obtained could be overestimated.

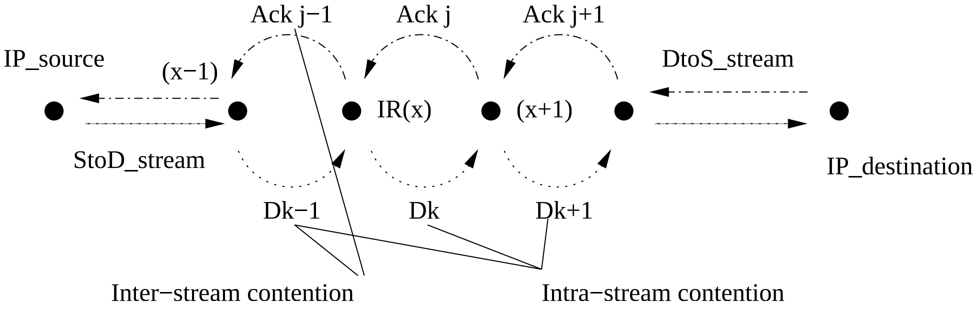
of active stations). This fact is really important because it would relax the need to estimate the number of users in the system, by simply estimating the slot utilization. Moreover, a simple definition of a tuning function that is adopted in the AOB mechanism to control the channel contention in congested scenarios is defined in [11]. AOB, by exploiting a rough and low cost estimate of the average size of transmitted frames, guarantees that the channel utilization converges to the optimal value when the network is congested, and no overheads are introduced in a low contention scenario. To achieve this goal, AOB schedules the frames' transmission according to the IEEE 802.11 backoff algorithm but adds an additional level of control before a transmission is enabled. Specifically, a transmission already enabled by the standard backoff algorithm is postponed by AOB in a probabilistic way. The probability to postpone a transmission depends on the network congestion level, and it is equal to one if the channel utilization tends to exceed the optimal value for the slot utilization. The postponed transmission is rescheduled as in the case of a collision, i.e., the transmission is delayed of a further backoff interval, as if a virtual collision occurred. This simple feedback mechanism could be implemented to extend the Standard IEEE 802.11 contention control without any additional hardware required, and converges to the near-to-optimal channel utilization. Additional interesting features of the AOB mechanism are given by the definition of a priority-based contention control without negotiations required, good stability, and good tolerance to estimation errors. More details about these points can be found in [9] and in [11].

4.6 Contention and CA of multi-hop flows at the MAC layer

Another MAC contention problem is the "Self-Contention" problem arising in IEEE 802.11 MANETs between multi-hop flows of frames sharing a common area of transmission (i.e. the same collision domain). This problem has been marginally addressed at the MAC layer in the literature [87], while some proposals are documented at the higher layers, e.g. inter-stream contention in transport [57] and routing layers [24], intra-stream contention at the link layer [28] and transport layer [71]. The problem is due to the unawareness of the generalized MAC protocols (e.g. like in IEEE 802.11) with respect to the transport layer session, and multi-hop flows, a MAC frame belongs to. As a result, MAC frames related to IP packets belonging to the same transport flows (both IPsender-to-IPreceiver and vice versa) may contend for the local channel resource without any synchronization, increasing the risk of collision and end-to-end delay. This problem may result in low goodput at the transport layer, when multi-hop communication is given at the MAC layer (like in MANETs).

Accordingly with [87], we define a *TCP stream* as a sequence of IP packets routed from the transport layer *IP_source* to *IP_destination*. A TCP connection typically consists of a couple of streams: the Data packets from the source to destination (StoD_stream), and the Ack packets from the destination to the source (DtoS_stream). Every MAC frame (e.g. D_k) encapsulating a (portion of) IP packet which belongs to a TCP stream is forwarded in the chain of intermediate receivers by using the RTS-CTS-DATA-ACK double handshake (the handshake is not shown for any D_k and Ack_j in figure 7 for readability). MAC

Figure 7: Self-contention of MAC frames



frames are subject to two types of self-contention at the MAC layer: *intra-stream* and *inter-stream* self-contention. Intra-stream self-contention is determined by MAC frames belonging to the same TCP stream: if an intermediate receiver $IR(x)$ (i.e. the x-th node in the multi-hop chain at the MAC layer) receives a MAC frame D_{k-1} by the $IR(x-1)$, it would need to forward that frame to the next intermediate receiver $IR(x+1)$ by contending for a new channel access. This new channel access for D_k by $IR(x)$ would contend for the local channel with any frame D_{k-1} and D_{k+1} belonging to the same TCP stream (intra-stream) to be sent by neighbor IRs (see figure 7). In most cases, the transport layer implements reliable end-to-end connection (e.g. as it happens with TCP, R-TCP, R-UDP). This implies that a DtoS_stream of acknowledgments would be usually transmitted on a reverse routing path of the StoD_stream of Data frames (see figure 7). Inter-stream self-contention at the node x is thus determined by the local contention of the Ack frames coming from $IR(x+1)$ to $IR(x)$ (Ack_j in the DtoS_stream), with the Data frames going from $IR(x-1)$ to $IR(x)$ (D_{k-1} in the StoD_stream). The lack of any synchronization mechanism at the MAC layer for the (many) opposite streams is the cause for contention problems in multi-hop communication, resulting in the increasing end-to-end delays and collision rates. Any synchronization scheme would be required to adopt dynamic scheduling policies, given the highly variable set of parameters in such scenarios (node mobility, variable transmission power, node topology and routing, variable loads). On the other hand, self-contention is a MAC layer problem, and a distributed access scheme like IEEE 802.11 DCF would be devoted to solve this kind of problem, by leaving untouched the upper layers, if possible [87]. In [87], two solutions have been sketched: *quick-exchange* and *fast-forward*. The quick-exchange solution is designed to alleviate the inter-stream self-contention: the idea is to exploit the channel capture obtained by a StoD_stream frame D_k from $IR(x)$ to $IR(x+1)$, to piggyback also possible DtoS_stream Ack_j frames from $IR(x+1)$ to $IR(x)$. In this way a new channel capture is not required and once the channel is captured by the sender and/or the receiver, the channel is not released since both streams' transmissions have been performed. The fast-forward solution works in the direction of favouring the multi-hop transmission of intra-stream frames: the idea is to create a hybrid MAC-layer acknowledgment frame for MAC Data frames (not to be confused with transport layer Acks shown in the figure). Hybrid-Acks transmitted by $IR(x)$ to $IR(x-1)$ would work as implicit RTS towards the $IR(x+1)$ for the current MAC Data frame. The hybrid-ACK sent by $IR(x)$ would be a broadcast frame (like RTS) with additional information to identify the intended receiver of its “acknowledgement” interpretation $IR(x-1)$, and the intended receiver of its “RTS” interpretation $IR(x+1)$. Nodes receiving the hybrid-ACK would interpret it as a RTS request coming from $IR(x)$, and they would set their virtual carrier sensing accordingly. Investigation of such mechanisms and proposals are currently ongoing activities.

5 Power saving protocols

Wireless networks are typically viewed as bandwidth-constrained relative to wired networks. However, for the portion of a wireless network consisting of battery-powered mobile nodes, a finite energy capacity may be the most significant bottleneck, and its utilization should be viewed as a primary network control parameter [3, 44, 51, 55, 64, 82]. Moreover, projections on the expected progress in battery technology shown that only a 20% improvement in the battery capacity is likely to occur over the next 10 years [66]. If the battery capacity cannot be improved, it is vital that energy utilization is managed efficiently by identifying any way to use less power preferably with no impact on the applications, on the management efficiency and on the resources' utilization.

Base stations may typically be assumed to be power-rich, whereas the mobiles they serve may be power-constrained. Thus, this asymmetry should be accounted for in the network protocol design at all levels, offloading complexity from the mobiles to the base stations as much as possible. Again, the problem may be more difficult in MANETs as the entire network may be energy-constrained: protocol complexity must be uniformly distributed throughout the network, and kept as low as possible.

Minimizing energy usage impacts protocol design at all levels of network control, including the MAC layer [3, 55, 82]. Due to the characteristics of wireless transmissions and wireless devices, the radio and network interface activities are among some of the most power consuming operations to perform [55, 70]. To save energy, most naturally one thinks of minimizing the ”on” time of network interfaces, i.e. switching the NI in *sleep mode* [70]. On the other hand, in WLAN and MANET scenarios, portable devices often need to transmit and receive data, required both by applications and by distributed and cooperative management. Techniques based on *synchronized sleep periods* are relatively easy to employ in systems where the system coverage area is ”centrally” controlled by a given base station, as in infrastructure WLANs. However, in systems relying on *asynchronous, distributed control algorithms* at all network layers (including MAC) such as in MANETs, participation in the control algorithms prohibits usage of simple static schedules, and more sophisticated methods are required.

Several studies have been carried out in order to define mechanisms, system architectures and software strategies useful for Power Saving (PS) and energy conservation in wireless LANs [3, 55]. Transmitter Power Control strategies to minimize power consumption, mitigating interference and increasing the cell capacity have been proposed, and the design aspects of power-sensitive wireless network architectures have been investigated [3, 64, 88]. The impact of network technologies and interfaces on power consumption has been investigated in depth in [70, 17]. The power saving features of the emerging standards for wireless LANs have been analysed in [82, 17].

Multidimensional tradeoffs between energy usage and various performance criteria exist. One may choose to burn more energy to decrease latency, increase throughput, achieve a higher level of QoS support, or to save energy by mitigating interference, or some combination thereof [10, 11, 12, 14]. From an energy-usage perspective, it may be better to be less spectrally efficient, e.g. by adopting separate signalling channels.

The adaptive behavior of the MAC protocol can best be accomplished by integrating the multiple access function with information provided by lower and higher levels in the protocol stack (e.g. user profile information, battery level indication, channel tracking information). Again, the MANETs and the multi-hop scenario is considered one of the most challenging scenarios under these viewpoints.

In infrastructure network and in reservation-based access scheme the power saving topic is still considered an hot topic by researchers, even if many assumptions are less critical. For this reason we will mainly illustrate the distributed contention based approach, and proposed solutions that may be applied to IEEE 802.11 DCF systems. In this section we present some of the power saving strategies at the MAC level. Specifically, we focus on the distributed, contention based access for WLANs and MANETs, and on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access mechanism adopted in the IEEE 802.11 DCF Standard [31].

6 Power Saving solutions at the MAC layer

Three categories of solutions for power saving and energy conservation have been considered at the MAC layer in MANETs and WLANs: transmission power control, low-power sleep management, power aware contention control.

Transmission power control: the idea behind power control is to use the minimum transmission power required for correct reception on the destination. Given the positive acknowledgment required to complete a frame transmission in CSMA/CA schemes, the transmission power control must be considered on both sides: sender-to-receiver and vice versa. Transmission power control strongly impacts factors like bit error rates, transmission bitrate, network topology and node connectivity (i.e. node density related to the contention level). Solutions have been proposed to deal with power control and its influence at the link layer to determine network topology properties [42, 60, 80, 43]. Also, network throughput can be influenced by power control, because of the differences in the frequency re-use, and in the spatial re-use of channels [52]. When transmitters use less power to reach the destination node, the collision domains are limited, and multiple transmissions could be performed in parallel, whose collision domains have no intersection [43, 52]. Limited collision domains would allow the same channel (i.e. frequency band) to be used among multiple disjoint collision domains. This is an important result in multi-hop wireless networks [52]. On the other hand, a high transmission power may also contribute to maintain high Signal-to-Noise Ratio (SNR) resulting in high bitrate coding techniques exploited on a wide-range area. The drawback is that high transmission power would also contribute to increase the in-band interference among signals, resulting in low Signal-to-

Interference-and-Noise ratio (SINR), low bit-rates coding techniques and high bit error rate (BER).

Low-Power sleep mode: many wireless devices support a low-power *sleep* or *doze* mode, as the opposite of *active* mode. The sleep mode is considered also in the IEEE 802.11 standard as a way to reduce the energy drain of network interfaces (NIs). Many investigations of the wireless network interface consumption shown that a significant amount of energy consumed in a wireless node is due to the wireless network interface activity . Many levels of power consumption can be identified, depending on the NI's state [17]. The active mode for NIs includes the transmission, reception and carrier sensing phases. When the NI is in the transmission phases, the amount of energy consumed is significant (in the order of mW). In carrier sensing and in reception phases, the amount of energy consumed is lower than in the transmission phases, but it is still significant. In many current devices, the transmission phases can be considered at least twice more power-consuming than the reception (and carrier sensing) phases [70, 17]. In doze or sleep phases the NI's energy consumption is limited to the minimum (both carrier sensing and radio components are switched off), and the energy drain is orders of magnitude lower than in active states [17]. These observations indicate that in order to reduce the energy consumption by the NI, it would be useful to reduce the whole time the NI is in active state, i.e. in Carrier Sensing, reception or transmission phases. When communication is not expected from/to a given node, it could switch the NI in sleep mode to save energy. Unfortunately, most NIs require a significant time (many microseconds) and a burst of energy to switch back from sleep to active state. This is the reason why it would not be always convenient to switch the NI in idle state as soon as the channel is idle for a short time. The sleep time management has been considered in many research proposals. The main challenges are given by the need for continuous carrier sensing to realize the MAC protocol functions, and the need to receive asynchronous frames, which could be sent while the receiver's NI is sleeping. Keeping the NI in the doze state also limits the neighbors' discovery and neighbors' information maintenance on the basis of many protocols. In infrastructure networks, the NIs wake up periodically to check for buffered packets on the AP, or to receive beacon frames [78, 82, 68, 22, 55]. This centralized scheme gives also the advantage that many transmissions and receptions can be clustered as contiguous, by increasing the average duration of sleep phases, and by reducing the rate of state switches [17]. Many MAC protocols for infrastructure networks have been compared under the power saving viewpoint in [17]. The sleep-synchronization scheme may be quite complicated in multi-hop networks, as we will see below. Recently, solutions have been proposed to switch off the network interface of wireless devices by exploiting dynamic, cluster-based infrastructures among peer nodes. Other solutions exploit information derived from the application layer (e.g. user think times in interactive applications [2]).

Power aware Collision Avoidance and Contention Control: previous discussion about these topics has illustrated the need to adapt access delays and the risk of collisions. Advantages obtained by the optimal tuning of the contention control and collision avoidance under the channel utilization viewpoint could be reflected also in the reduction of energy wasted on collisions and carrier sensing, e.g. [10, 17].

The *Power Aware Routing* topic is out of the scope of this chapter, being located at the Network layer.

The main solutions considered at this level are based on the filtering of forwarding nodes on the basis of the remaining energy and transmission power reduction [38]. This approach is cited in this context since it may be considered as a power saving policy to be considered for possible multi-hop forwarding techniques at the MAC layer, and in cross-layer hybrid solutions for routing at the MAC layer. Many other solutions, e.g. SPAN [18], GAF [84], AFECA [85], to guarantee a substantial degree of network connectivity (at the network layer) are based on the dynamic election of coordinator nodes, based on local and global information like energy, GPS position, mobility and degree information (i.e. node density). Such choices have effect on the MAC and Physical layers since only coordinator nodes never sleep and try to adjust their transmission power in order to maintain a fully connected network. In this way the contention for channel access can be controlled because a reduced number of hosts try to forward frames in the high density areas. The problem of the "broadcast storm" in the flooding-based solutions for routing is similar to the "self-contention" problem of multi-hop frame-flows in wireless broadcast channels, considered in previous sections.

6.1 The MAC contention under the power saving viewpoint

For contention-based MACs like the CSMA/CA protocols, the amount of power consumed by transmissions is negatively affected by the congestion level of the network. By increasing the congestion level, a considerable power is wasted due to the collisions. To reduce the collision probability, the stations perform a variable time-spreading of accesses (e.g. by exploiting backoff protocols), which results in additional power consumption, due to Carrier Sensing performed over additional idle periods. Hence, CSMA/CA and contention control protocols suffer a power waste caused both from transmissions resulting in a collision and from the amount of Carrier Sensing (active detection time) introduced by the time-spreading of the accesses. It is worth noting that collisions may cause a power waste in the transmission phase involving more than one transmitter. Some kind of transmission policy optimization could be performed by evaluating the risk (i.e. the cost/benefit ratio) of transmission attempts being performed, given current congestion conditions and the power-consumption parameters of the system. As an example, the power saving criterion adopted in [10] is based on balancing the power consumed by the network interface in the transmission (including collisions) and reception (or idle) phases (e.g. Physical Carrier Sensing). Since these costs change dynamically, depending on the network load, a power-saving contention control protocol must be adaptive to the congestion variations in the system. Accurate tuning of the adaptive contention-based access was designed by considering different (parameter-based) levels of energy required by the network interface's transmission, reception and idle (doze) states in [10]. The model and tuning information were adopted to implement the Power-Save Distributed Contention Control (PS-DCC) mechanism in [10]. PS-DCC can be adopted on top of IEEE 802.11 DCF contention control, and leads the contention control to converge to the near-to-optimal network-interface power consumption. In addition, the PS-DCC power saving strategy balances the need for high battery lifetime with the need to maximize the channel utilization and the QoS perceived by the network users [10, 55].

6.2 Sleep-based solutions

Given the open broadcast nature of the wireless medium, any ongoing transmission is potentially overheard by all the neighbor nodes within the communication range. Thus all active neighbor nodes consume power by receiving frames even though the frame transmission was not direct to them. The latter point has been faced in some cases; for example, IEEE 802.11 networks try to reduce the amount of physical carrier sensing activity (called Clear Channel Assessment, CCA), by exploiting Virtual carrier sensing based on Network Allocation Vectors (NAVs) [31]. NAVs are local timers counting the time to the expected end of the ongoing transmission. If any ongoing transmission is not addressed to the receiving node, its NAV can be initialized to the duration of the ongoing transmission. If the transmission duration is long enough to make worthwhile the transition to the sleep state, then the NI is switched off, and reactivated when the NAV expires to resume the monitoring of the channel status. The information to set the NAV timers can be obtained by introducing it in frame headers and in preliminary RTS and CTS messages adopted for Collision Avoidance. During the virtual carrier sensing, the CCA is not performed and the NI is sleeping.

Many designs of power saving protocols have been proposed for MANETs and WLANs to allow mobile hosts to switch to sleep mode, depending on the role of nodes and energy availability (e.g. chord or battery based). In infrastructure based networks, like IEEE 802.11 PCF, the sleep mode can be exploited based on the transmission scheduling indication of the Base Station (assumed to be power rich). The problem here can be considered quite easy to solve, because the Base Station can act as a central coordinator for nodes. The Base Station may buffer the frames sent to sleeping nodes, and periodically sends beacon frames at fixed intervals containing the information about the timeline of scheduled pending transmissions. Administrated (slave) nodes sleep most of the time, and wake up just in time to receive and send their information to the Base Station. This management approach based on the master-slave role of nodes has been introduced also in Bluetooth piconets, and in cluster-based architectures for MANETs, by exploiting the nodes asymmetry, and by demanding administration roles to the best candidates. Many more problems arise in the distributed sleep coordination schemes required for MANETs and multi-hop wireless networks. Usually, proposed solutions for power saving assume fully connected networks (i.e. not multi-hop) and overall synchronization of clocks. This is the case for IEEE 802.11 Timing Synchronization Function (TSF) in the PCF scheme, and its DCF version, that will be presented in the next section. Another critical issue related to the wireless scenario is the mobility of nodes resulting in variable network topology, variable contention level and variable traffic loads. The node asymmetry and heterogeneous characteristics of nodes in MANETs are other problems that should be considered in the design of power saving mechanisms at the MAC layer. To sum up, unpredictable mobility, multi-hop communication, no clock-synchronization mechanisms, heterogeneous power supplies (power chord vs. battery based) are some of the most critical design assumptions to be considered in power saving schemes for MANETs [68]. The absence of clock-synchronization mechanisms is the main problem in distributed scenarios, because it would be hard to predict if and when the receiver host would be ready to receive. A sleeping node can be considered a missing node. Nonetheless, neighbor discovery in highly dynamic scenarios with mobility is critical. The need for asynchronous protocols and solutions has been discussed in [78].

Other solutions have been proposed for MANETs in distributed and multi-hop scenarios. In [68] PAMAS (Power Aware Multi-Access protocol with Signalling) a separate signalling channel is adopted to discover and to manage the state of neighbor hosts. PAMAS is based on the MACA definition: Collision Avoidance based on RTS/CTS messages on the signalling channel is considered as a power saving solution. PAMAS was designed by assuming fully connected scenarios, and busy tones were thought in order to allow neighbor hosts not involved in ongoing transmissions to power-off their network interfaces to save energy. Power saving in PAMAS design was mainly conceived on the consideration that energy drain by the network interface is due to both transmission and reception activities. Every node was required to solve locally the problem of the NI activation, in order to be able to receive frames. The proposal was to adopt a sequence of channel probes on a separate control channel, to determine properly the re-activation time.

In [22] different sleep patterns can be defined to differentiate between hosts sleeping periods based on residual energy and QoS needs. A technological solution called Remote Activated Switch (RAS) is required to wake-up sleeping hosts, by sending them a wake-up signal. In this scheme, the sleep management is passive, i.e. it is controlled by senders, instead of active, i.e. managed by NAVs.

6.3 Power Control solutions

Dealing with power control, many similar solutions appear in the literature, like SmartNode [58], Power Controlled Multiple Access (PCMA) MAC protocol [52] and many others cited in [46]. The common idea adopted in such schemes was called the *basic power control* scheme. The idea is to exploit dynamic power adjustment between sender and receivers, by exploiting the RTS/CTS handshake as a common reference. The RTS and CTS frames are sent with the maximum nominal transmission power, and the adjustment is performed for the data transmission, relative to the residual power detected by the counterpart. This approach becomes quite critical with heterogeneous devices with different nominal power levels. In [46] a modification of the basic power adjustment schemes was proposed, based on periodic pulses of the transmission power during the data transmission. This scheme was thought as a way to contrast the throughput degradation due to the risk of hidden terminals during the data transmission, that cannot be avoided by the RTS/CTS handshake.

In [53], the COMPOW protocol was proposed as a distributed policy to find the minimum COMmon POWer for transmissions leading to a sustainable degree of node connectivity and bi-directional links.

6.4 IEEE 802.11 Power Saving

The IEEE 802.11 Standard supports two power modes for mobile hosts (MHs): *active* MHs can transmit and receive at any time, and *power-saving* MHs may be sleeping and wake up from time to time to check for incoming packets.

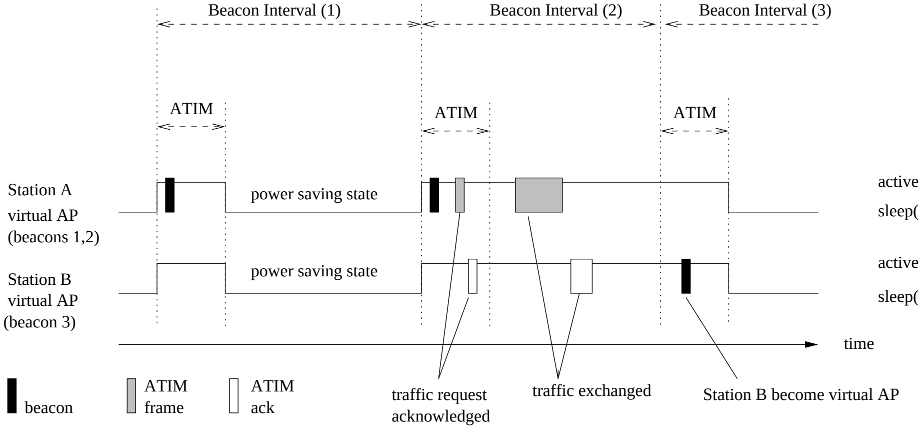
All the power saving schemes denoted below are based on the Point Coordination Function (PCF) access scheme defined for infrastructure systems based on Access Points, and Distributed Coordination Function (DCF) access scheme, referred to as the basic access scheme for ad hoc networks.

In infrastructure networks, indicated as a *Basic Service Set* of nodes, it is assumed the existence of the Access Point (AP) station managing the Point Coordinated channel access (Point Coordination Function, PCF). The AP is in charge of monitoring the state of each mobile host (MH), and a MH should always refer to the AP for any registration request, transmission requests, and state changes. The AP is also in charge of the synchronization of sleep an active periods between the stations. The synchronization is achieved by means of the Timing Synchronization Function (TSF), i.e. every mobile host (MH) would get synchronized by the clock indicated by the AP in special frames, called *beacon frames*. Periodically, the AP sends beacon frames to start a *beacon interval*. Beacon frames should be monitored by MHs, i.e. they should wake up in time to receive beacons. Every beacon contains a Traffic Indication Map (TIM) indicating the list of MH's IDs with buffered traffic on the AP: such MHs should stay active in order to receive the buffered traffic in the current beacon interval. For buffered broadcast frames, the AP sends a Delivery TIM (DTIM) message (indicating that every MH should stay active) and immediately starts with the broadcast frames' transmission.

In ad hoc networks, supported by the *Independent Basic Service Set* structure of nodes, the existence of the AP cannot be assumed as a centralized coordinator. This requires the power saving management to be implemented as a distributed policy. The MH initiating the IBSS assumes the role of the synchronization coordinator, and the sycnhronization approach is still based on beacon frames. How the IBSS is started and initialized is out of the scope of this chapter, see [31] for details. Every station in the IBSS assumes to receive a beacon message within a nominal amount of time, i.e. the *Beacon Period* proposed by the IBSS initiator. Local TSF timers are used to obtain a weak synchronization of distributed beacon intervals. At the beginning of a beacon interval, every MH listen for beacon frames while decrementing a randomly initialized backoff counter. If the backoff counter expires before to hear any beacon frame, the MH itself sends a beacon frame indicating its local TSF timer value. In this way, if any problem occurred, the IBSS initiator can be replaced on the fly (see station B in figure 8). Every MH receiving a beacon frame will compare the TSF indicated in the beacon with its local TSF timer. If the beacon-TSF value is later than the local TSF, the MH initializes its TSF timer to the beacon-TSF value. In this way, a weak synchronization scheme similar to the scheme adopted in infrastructure systems can be maintained, and local time is guaranteed to advance on every MHs.

During the DCF a MH can send a *PS-poll* to the AP when it is ready to receive buffered frames (contending for the channel). If the PS-poll is correctly received, the AP transmits the respective unicast buffered frames. MHs can sleep most of the time and periodically wake-up during short Ad hoc TIM (ATIM) time-windows, located at the beginning of each beacon interval (see figure 8). Here the assumption is that all MHs in the ad hoc network have synchronized ATIM windows where they can exchange *ATIM frames*,

Figure 8: IEEE 802.11 Timing Synchronization Function and power save



notifying each other about buffered frames (see figure 8). ATIM frames in ad hoc scenarios have the purpose to inform neighbor nodes about the pending traffic. ATIM and data frames are sent, within the ATIM window and after the ATIM window, respectively, and subject to contention rules (ie. the DCF CSMA/CA and BEB rules). A MH receiving an unicast ATIM frame will immediately acknowledge the ATIM frame and will wait for the transmission of buffered packets after the end of the ATIM window. If the ATIM sender does not receive the ACK it will try again later in the next ATIM window. Broadcast ATIM frames need no acknowledgment, and can be sent under DCF contention rules at the end of the ATIM window. During the ATIM window, only RTS/CTS, Ack, Beacon and ATIM frames can be sent.

Such a distributed Power Saving mode is designed for single-hop networks. In multi-hop scenarios, the global ATIM window synchronization can become a problem, because of the increasing propagation delays, clock drifts among multiple hosts, and temporary network partitions. This is even worst when the network scales to many nodes [78]. The discovery of neighbor hosts under Power Saving mode is not trivial because of the host mobility would change the neighbors set of every host, and during the sleeping time every host cannot receive nor transmit any beacon message. On the other hand, beacon messages concentrated on small time windows have a high collision probability (which may cause destructive transmission effect on the receivers).

In [82], the simulation analysis of the MAC layer IEEE 802.11 power saving mechanism has been performed. In [78] the proposal was to insert more beacons in every ATIM window, suggesting that beacons should be adopted not only for clock synchronization, but also for discovering neighbors and for self-advertising. Another proposal was to design the ATIM windows such that overlapping awake intervals are guaranteed even with maximum clock drift and worst scenario assumptions [78]. A definition and analysis of three power-saving-oriented beaconing algorithms for IEEE 802.11 MAC have been proposed in [78]: dominating-awake-interval, periodically-full-awake-interval, and quorum-based protocols. The relations between beaconing process, neighbors discovery delay, and power saving characteristics have been investigated. Some of the proposed solutions are more appropriate for highly mobile and low mobility scenarios, respectively. In general, solutions should be adaptive, dealing with system mobility (both predictable and un-predictable), multi-hop communication, variable traffic loads, and weak clock synchronization.

7 Conclusion

In WLANs and MANETs the MAC protocol is the candidate to manage the limited shared channel among mobile hosts in a highly dynamic scenario. The MAC protocols also influences the scarce resources' utilization, like channel bandwidth and battery energy. In this chapter, we illustrated the motivations leading to a new design and tuning of existing and new MAC protocols, based on the new wireless systems' assumptions. Some assumptions, problems and limiting constraints of the wireless communication channels have been sketched as a background information. The evolutionary perspective of distributed random-access MAC protocols has been presented, to illustrate in incremental way the problems considered and solutions proposed, leading to current IEEE 802.11 definition. The illustration of contention control in IEEE 802.11 DCF, with a discussion of related problems and solutions has been shown. Specifically, single-hop WLANs, and multi-hop MANETs contention problems have been illustrated. Finally a perspective of power saving solutions to be considered at the MAC layer has been presented. Many prototype solutions have been described. Anyway, the research in this field can be considered still in preliminary phase. One of the most challenging problems for the future will be the design and tuning of stable, fair, low-overhead and adaptive distributed MAC protocols supporting multi-hop communication, contention control and power saving for WLANs and MANETs.

References

[1] N. Abramson, “The ALOHA system - another alternative for computer communications”, Proc. Fall Joint Comput. Conf. AFIPS, 1970

[2] G. Anastasi, M. Conti, E. Gregori, A. Passarella, “Power Saving in Wi-Fi Hotspots: an Analytical Study”, in proc. of PWC 2003, Venice, September 2003

[3] N. Bambos, “Toward Power-Sensitive Network Architectures in Wireless Communications: Concepts, Issues and Design Aspects”, IEEE Personal Communications, June 1998, pp. 50-59

[4] L. Bao, J.J. Garcia-Luna Aceves, “A New Approach to Channel Access Scheduling for Ad Hoc Networks”, Sigmobile: ACM SIG on Mobility of Systems, Users, Data and Computing, pp. 210-221, 2001

[5] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, “MACAW: A Media Access Protocol for Wireless LAN’s” in proc. ACM SIGCOMM’94, pp.212-225, London, 1994

[6] V. Bharghavan, “Performance Evaluation of Algorithms for Wireless Medium Access” IEEE Performance and Dependability Symposium ’98, Raleigh, NC. August 1998.

[7] Bianchi G., Fratta L. and Olivieri M. (1996). “Performance Evaluation and Enhancement of the CSMA/CA MAC protocol for 802.11 Wireless LANs”, Proc. of PIMRC 1996, Oct. 1996, Taipei, Taiwan, pp. 392-396.

[8] K. Bieseker, “The Promise of Broadband Wireless”, IT Pro November/December 2000, pp. 31-39.

[9] L.Bononi, M.Conti, L.Donatiello, “Design and Performance Evaluation of a Distributed Contention Control (DCC) Mechanism for IEEE 802.11 Wireless Local Area Networks”, Journal of Parallel and Distributed Computing (JPDC), Vol. 60, N.4, April 2000, pp. 407-430.

[10] L.Bononi, M.Conti, L.Donatiello, “A Distributed Mechanism for Power Saving in IEEE 802.11 Wireless LANs”, ACM Mobile Networks and Applications (ACM MONET) Journal, Volume 6 (2001), N.3, pp. 211-222

[11] L.Bononi, M.Conti, E.Gregori, “Run-Time Optimization of IEEE 802.11 Wireless LANs performance”, to appear on IEEE Transactions on Parallel and Distributed Systems (IEEE TPDS), Vol.14, No.12, December 2003

[12] R. Bruno, M. Conti, E. Gregori, “WLAN technologies for mobile ad-hoc networks”, Proc. HICSS-34, Maui, Hawaii, January 3-6, 2001.

[13] F. Cali’ , Conti M., E. Gregori, “Dynamic IEEE 802.11: design, modeling and performance evaluation”, IEEE Journal on Selected Areas in Communications, 18(9), September 2000. pp. 1774-1786.

[14] Cali' F., Conti M., Gregori E., "Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit", IEEE/ACM Transactions on Networking, Volume 8 , No. 6 (Dec. 2000), pp. 785 - 799.

[15] J.I. Capetanakis, "Tree Algorithms for Packet Broadcast Channels", IEEE Trans. Inform. Theory, vol.25, pp. 505-515, 1979

[16] A. Chandra V. Gumalla, J.O. Limb, "Wireless Medium Access Control Protocols", IEEE Communications Surveys, Second Quarter 2000.

[17] J.-C. Chen, K.M. Sivalingam, P. Agrawal, S. Kishore, "A Comparison of MAC Protocols for Wireless LANs Nased on Battery Power Consumption", proc. INFOCOM'98, (San Francisco, CA), pp. 150 - 157, Mar. 1998

[18] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks", ACM Wireless Networks Journal, 8(5), September 2002

[19] Chen K.C. (1994). "Medium Access Control of Wireless LANs for Mobile Computing", IEEE Networks, 9-10/1994.

[20] Chhaya H.S. (1996). "Performance Evaluation of the IEEE 802.11 MAC Protocol for Wireless LANs", Master Thesis, Graduate School of Illinois Institute of Technology, May 1996.

[21] H.S. Chhaya, S. Gupta, "Performance Modeling of asynchronous data transfer methods in the IEEE 802.11 MAC protocol", ACM/Balzer Wireless Networks, Vol. 3, 1997, pp. 217-234.

[22] C. F. Chiasserini and R. R. Rao, "A Distributed Power Management Policy for Wireless Ad Hoc Networks,", IEEE Wireless Communication and Networking Conference, pp. 1209–1213, 2000

[23] A. Colvin, "CSMA with Collision Avoidance", Computer Communications, 6(5):227-235, 1983

[24] C.Cordeiro, S.R.Das, D.P.Agrawal, "COPAS: Dynamic Contention Balancing to Enhance the Performance of TCP over Multi-hop Wireless Networks", proc. 10-th ICCCN 2003, pp.382-387, Oct. 2002

[25] M. S. Corson, J.P. Maker, J.H. Cerincione, "Internet-based Mobile Ad Hoc Networking", Internet Computing, July-August 1999, pp. 63-70.

[26] Crow B.P. (1996). "Performance Evaluation of the IEEE 802.11 Wireless Local Area Network Protocol", Master thesis. University of Arizona, 1996.

[27] G.H. Forman, J. Zahorjan, "The challenges of mobile computing", IEEE Computer, April 94, pp.38-47.

[28] Z.Fu, P.Zerfos, H.Luo, S.Lu, L.Zhang, M.Gerla "The Impact of Multihop Wireless Channel on TCP Throughput and Loss", proc. Infocom 2003

[29] C.L. Fullmer, J.J. Garcia-Luna-Aceves, "Floor Acquisition Multiple Access (FAMA) for Packet Radio Networks", Proc. ACM Sigcomm'95 Cambridge, MA, 1995

[30] . C. L. Fullmer. Collision Avoidance Techniques for Packet radio Networks. Ph.D. Thesis, UC Santa Cruz, 1998.

[31] IEEE 802.11 Std. (1999). IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Jun. 1999

[32] http://grouper.ieee.org/groups/802/11/main.html

[33] Gallagher R.G. (1986). "A perspective on multiaccess channels", IEEE Trans. Information Theory, vol. IT-31, No.2, 3/1985, pp. 124-142.

[34] R. Garces, "Collision Avoidance and Resolution Multiple Access", PhD thesis, University of California at Santa Cruz, 1999

[35] L. Georgiadis, P. Papantoni-Kazakos (1985). "Limited Feedback Sensing Algorithms for the Packet Broadcast channel", IEEE Trans. on Info. Theory, Vol IT-31, No.2, 3/1985, pp. 280-294.

[36] L.Georgiadis, P. Papantoni-Kazakos, "A Collision Resolution Protocol for Random Access Channels with Energy Detection", IEEE Trans. on Communications, vol. 30, no. 11, 1982

[37] M. Gerla, L. Kleinrock, "Closed loop stability control for S-Aloha satellite communications", Proc. Fifth Data Communications Symp., Sept. 1977, pp. 2.10-2.19.

[38] Javier Gomez, and Andrew T. Campbell, Mahmoud Naghshineh, C. Bisdikian, "Power-aware Routing in Wireless Networks", in Proc. MoMuC 1999, San Diego, 114-123

[39] Goodman J., Greenberg A.G., Madras N. and March P. (1988). "Stability of Binary Exponential Backoff", Journal of the ACM, Volume 35, Issue 3, pp. 579 - 602, 1988

[40] B. Hajek, T. Van Loon, "Decentralized dynamic control of a multiaccess broadcast channel", IEEE Trans Automat. Control, Vol.27, 1982, pp. 559-569.

[41] Hastad J., Leighton T. and Rogoff B. (1996). "Analysis of Backoff Protocols for Multiple Access Channels", Siam J. Computing vol. 25, No. 4, 8/1996, pp. 740-774.

[42] L. Hu, "Topology Control for Multihop Packet Radio Networks", IEEE Transactions on Communications, vol. 41, pp. 1474-1481, Oct. 1993

[43] C.F. Huang, Y.C. Tseng, S.L. Wu, J.P. Sheu, "Increasing the Throughput of Multihop Packet Radio Networks with Power Adjustment", proc. ICCCN 2001

[44] T. Imielinsky, B.R. Badrinath, "Mobile Wireless Computing: Solutions and Challenges in Data Management", Communications of ACM , Vol. 37, No. 10, Oct. 1994.

[45] A.J.E.M. Janssen, M.J.M. de Jong, “Analysis of Contention-Tree Algorithms”, proc. IEEE Inform. Theory Workshop, Killarney, Ireland, 1998

[46] E.-S. Jung, N.H. Vaydia, “A Power Control MAC Protocol for Ad Hoc Networks”, proc. MOBICOM 2002, Sept. 2002, Atlanta, GA.

[47] P. Karn, “MACA - A new Channel Access Method for Packet Radio”, proc. 9-th Computer Networking Conference, September 1990

[48] V. Kawadia, P.R. Kumar, “A Cautionary Perspective on Cross Layer Design”, Submitted for publication, 2003 (*http : //black1.csl.uiuc.edu/ prkumar/*)

[49] S. Khanna, S. Sarkar, I. Shin, “An Energy Measurement based Collision Resolution Protocol”, proc. ITC 18, Berlin, Germany, Sep. 2003

[50] L. Kleinrock, F.A. Tobagi “Packet Switching in Radio Channels: Part I - Carrier Sense Multiple-Access modes and their throughput-delay characteristics”, IEEE Transactions on Communications, Vol Com-23, No. 12, pp.1400-1416, 1975

[51] R. Kravets, P. Krishnan, “Power Management Techniques for Mobile Communication”, Proceedings of The Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM’98).

[52] J.P. Monks, J.-P. Ebert, A. Wolisz, W.-M.W. Hwu, “A Study of the Energy Saving and Capacity Improvment Potential of Power Control in Multi-Hop Wireless Networks”, proc. 26-th LCN and WLN, Tampa, FL, Nov. 2001

[53] S. Narayanaswamy, V. Kawadia, R.S. Sreenivas, P.R. Kumar, “Power Control in Ad Hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW Protocol”, proc. European Wireless Conference, Feb. 2002

[54] W.F. Lo, H.T. Mouftah, “Carrier Sense Multiple Access with Collision Detection for Radio Channels”, IEEE 13th Intern’l Communication and Energy Conference, pp.244-247, 1984

[55] J.R. Lorch, A.J. Smith, “Software Strategies for Portable Computer Energy Management”, IEEE Personal Communications, June 1998, pp. 60-73

[56] R.M. Metcalfe, D.R. Boggs, “Ethernet: Distributed Packet Switching for Local Computer Networks”, Comm. ACM, Vol. 19, 1976

[57] C.Parsa, J.J. Garcia-Luna Aceves, “Improving TCP Performance over Wireless Networks at the Link Layer”, ACM Mobile Networks and Applications, 5(1):57-71, 2000

[58] E. Poon, B. Li, “SmartNode: Achieving 802.11 MAC Interoperability in Power-efficient Ad Hoc Networks with Dynamic Range Adjustments” in the Proceedings of IEEE International Conference on Distributed Computing Systems (ICDCS 2003), pp. 650-657, May 2003.

[59] B. Ramamurthi, D.J. Goodman, A. Saleh, “Perfect capture for local radio communications”, IEEE JSAC, vol. SAC-5, no.5, June 1987

[60] R. Ramanathan, R. Rosales-Hain, “Topology Control of Multihop Wireless Networks using Transmit power adjustment”, proc. IEEE INFOCOM 2000, pp. 404-413

[61] T.S. Rappaport, Wireless Communications: Principles and Practice, Second Edition, Prentice Hall, Upper Sadle River, NJ, 2002

[62] Rivest R.L. (1987). “Network Control by Bayesian Broadcast”, IEEE Trans. on Info. Theory, Vol IT-33, No.3, 5/1987, pp. 323-328.

[63] R. Rom, “Collision Detection in Radio Channels”, Local Area and Mutiple Access Networks, pp.235-249, CS Press, 1986

[64] M. Rulnick, N. Bambos “Mobile Power Management for Wireless Communication Networks”, Wireless Networks, Vol. 3, No. 1, Mar. 1996

[65] A.K. Salkintzis, C. Chamzas, “Performance Analysis of a downlink MAC protocol with Power-Saving Support”, IEEE Transactions on Vehicular Technology, vol 49, May 2000

[66] S. Sheng, A. Chandrakasan, R.W. Brodersen, “A Portable Multimedia Terminal”, IEEE Communications Magazine, December 1992

[67] G. Sidhu, R. Andrews, A. Oppenheimer, Inside Appletalk, Addison-Wesley, 1989

[68] S.Singh and C.S. Raghavendra, “PAMAS - Power Aware Multi-Access protocol with Signalling for Ad Hoc Networks” in ACM Communications Review, July 1998.

[69] Stallings W. (1996). *Local & Metropolitan Area Networks*, Fifth Edition, Prentice Hall 1996, pp. 356-383.

[70] M. Stemm , R.H. Katz, “Measuring and Reducing Energy Consumption of Network Interfaces in Hand-Held Devices”, Proc. 3rd International workshop on Mobile Multimedia Communications (MoMuC-3), Princeton, NJ, September 1996

[71] K. Sunderasan, V. Anantharaman, H.-Y. Hsieh, R. Sivakumar, “ATP: A reliable transport protocol for ad hoc networks”, Proc. ACM MOBIHOC 2003, June 2003

[72] F. Talucci and M. Gerla. “MACA-BI (MACA by Invitation): A Wireless MAC Protocol for High Speed Ad Hoc Networking,” Proc. IEEE ICUPC’97, vol. 2, pp. 913-17, San Diego, CA, Oct. 1997.

[73] F.A. Tobagi, L. Kleinrock, “Packet Switching in Radio Channels: Part II - the Hidden Terminal Problem in Carrier Sensing Multiple Access and Busy Tone Solution”, IEEE Transactions on Communications, Vol Com-23, No. 12, pp.1417-1433, 1975

[74] F.A. Tobagi, L. Kleinrock, “Packet Switching in Radio Channels: Part III - Polling and (Dynamic) Split Channel Reservation Multiple Access”, IEEE Transactions on Comput., Vol 24, pp. 832-845, 1976

[75] F.A. Tobagi, L. Kleinrock, “The Effect of Acknowledgment Traffic on the Capacity of Packet Switched Radio Channels”, IEEE Transactions on Communications, Vol Com-26, No. 6, pp.815-826, 1978

[76] B.S. Tsybakov, V.A. Mikhailov, “Random Multiple Access of Packets: Part and Try Algorithm”, Probl. Inform. Trans. Vol 16, pp. 305-317, 1980

[77] A. Tzamaloukas, “Sender- and Receiver-Initiated Multiple Access Protocols for Ad Hoc Networks”, PhD Thesis, University of California at Santa Cruz, 2000

[78] Yu-Chee Tseng, Chin-Shun Hsu, Ten-Yueng Hsieh, “Power-Saving Protocols for IEEE 802.11-Based Multi-hop Ad Hoc Networks”, in Proceedings of INFOCOM’02, New York, June 2002, pp. 200-209

[79] Tsitsiklis J.N. (1987). “Analysis on a multiaccess Control Scheme”, IEEE Trans. on Auto. Contr., Vol AC-32, No. 11, 11/1987, pp. 1017-1020.

[80] R. Wattenhofer, L. Li, P. Bahl, Y.M. Wang, “Distributed Topology Control for Power Efficient Operation in Multihop Wireless Ad Hoc Networks”, proc. IEEE INFOCOM 2001, pp. 1388-1397

[81] Weinmiller J., Woesner H., Ebert J.P. and Wolisz A. (1996). “Analyzing and tuning the Distributed Coordination Function in the IEEE 802.11 DFWMAC Draft Standard”, Proc. Int. Workshop on Modeling, MASCOT 96, San Jose, CA.

[82] H. Woesner, J.P. Ebert, M. Schlager, A. Wolisz, “Power-Saving Mechanisms in Emerging Standards for Wireless LANs: The MAC Level Perspective”, IEEE Personal Communications, June 1998, pp. 40-48

[83] . Kaixin Xu, Gerla, M., Sang Bae, “How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks?” GLOBECOM 2002, Vol 1, Nov 2002, Page(s): 72 -76

[84] Ya Xu, John Heidemann, and Deborah Estrin. Geography-informed energy conservation for ad hoc routing. In Proceedings of the Seventh Annual ACM/IEEE International Conference on Mobile Computing and Networking, Rome, Italy, July 2001

[85] Ya Xu, John Heidemann, and Deborah Estrin “Adaptive energy-conserving routing for multihop ad hoc networks” Submitted for publication, May 2000

[86] S. Xu, T. Saadawi, “Revealing the problems with 802.11 medium access control protocol in multi-hop wireless ad hoc networks”, Computer Networks, Vol. 38, pp. 531-548, 2002

[87] Z. Ye, D. Berger, P. Sinha, S. Krishnamurthy, M. Faloutsos, S.K. Tripathi, “Alleviating MAC layer Self-Contention in Ad hoc Networks”, ACM Mobicom 2003 Poster session

[88] M. Zorzi, R. R. Rao “Energy Management in Wireless Communication”, 6th WINLAB Workshop on Third Generation Wireless Information Networks, Mar. 1997