

Wireless LAN MAC protocols

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1 Introduction

The MAC (Medium Access Control) protocols can be roughly categorized into three broad classes [16]. The *fixed assignment* set will have schemes like TDMA, CDMA and FDMA. These protocols lack the flexibility in allocating resources and thus have problems with configuration changes. This makes them unsuitable for dynamic and bursty wireless packet data networks. The *random assignment* class consisting of ALOHA[1] and CSMA is very flexible instead and is what is predominantly used in wireless LAN protocols. The *demand assignment* with schemes like Token Ring, GAMA[20] and PRMA[7] attempt to combine the nice features of both the above but special effort is needed to implement them in the wireless case (Eg. Token Ring needs to know its neighbors). There are systems designed using one or more of these classes. For instance cellular networks use ALOHA to get the code when entering a cell and CDMA for subsequent communication. For the purposes of this paper we restrict ourselves to second (more interesting) class of random assignment. To have a reasonable working set at hand, we do not consider protocols proposed in the context of wireless ATM; these deal with ATM specific issues like different traffic types.

The multiple access problem arises for broadcast media, when multiple users share a common channel to communicate (as against point-to-point connection)[19]. The two major objectives of any such protocol are maximization of the channel capacity utilization and minimization of latency between a station deciding to transmit and able to transmit. There is an inherent tension in these two desirable goals. Other goals which might be equally important in some cases could be fairness and stability.

We briefly mention some of fundamental techniques used in the wireless LAN communication. In *Carrier Sense Multiple Access* (CSMA) a station senses the medium before transmitting and defers to any ongoing transmission. This requires a special carrier sensing circuit. Two extensions to CSMA are collision detection (CSMA/CD) and collision avoidance (CSMA/CA). In the former the senders detect collision (and thus immediately learns of transmission failure) and stops transmitting to reduce the overhead of a collision. In collision avoidance, the sender waits for an Inter Frame Spacing (IFS) before contending for the channel after the channel becomes idle. Collision avoidance can also be achieved by the second basic primitive RTS/CTS exchange. In RTS/CTS exchange a sender transmits an RTS (ready to send) packet to the receiver before the data transmission. The data is transmitted only after reception of a CTS (clear to send) from the receiver, which the receiver sends on reception of a successful RTS. This technique is referred to

as packet sensing (PSMA), (a station takes decision based on semantics of the packet received in full and not carrier sense).

2 Issues in Wireless Communication

While some concepts and design experience gained in the wired world can be brought into the wireless domain, there are some problems which are unique to this medium. In this section we brief a give description of these new faced by the protocol designers.

Usually a wireless node has one antenna, for both sending and receiving. This makes collision detection difficult if not impossible. The problem does not go away even if the node has two antennas. The reason being that the sending signal has much higher power and thus swamps any signal that might be coming in. There have been methods proposed in the literature [5, 6] to get over this problem by pausing while transmitting. Unfortunately even this approach does not enable a node to detect all kinds of collisions (even if we don't consider the overheads of this scheme in the low load case). The trouble is that collisions happen at the receiver and not the sender. Thus all the protocols we talk about in this paper don't even attempt collision detection.

A common problem which has long been recognized in the wireless world is that of *hidden terminal* [2]. This problem occurs when two senders are not in the vicinity of each other (so cannot carrier sense each other's signals) but both of them are in the range of the common receiver. So carrier sensing fails in this case. The RTS/CTS exchange helps alleviate this problem to a certain extent (see below) but does not make it go away completely. A related issue is the *exposed terminal* problem, where a station can sense the medium busy because of a nearby sender and thus refrains from sending even when its transmission would not have collided at its destined receiver. This problem is not considered as serious as the hidden terminal problem and becomes irrelevant in case of protocols which ack at link layer (eg. MACAW, DFWMAC) as in this case we cannot afford a collision even at the sender because of the incoming acks.

Another problem in similar vein as those above is that of *capture*. This occurs when the received power at the receiver from two senders is significantly different. The sender with higher power "captures" the receiver, which will never be able to sense the second signal. This leads to significant fairness problems.

The wireless medium inherently has higher error rates because of interference between co-located LAN's, self-interference, fading, interference caused by other electronic devices and collisions. This needs to be taken into account in the protocol design phase. For instance, DFWMAC has link level acknowledgements to provide a better end-to-end service.

A transceiver circuit has a turn around time, known as Rx/Tx-turnaround, to switch between receiving and transmitting. This imposes a restriction on how fast one can receive and respond back. Wireless protocols have to deal with this and it becomes a more serious issue when different transceivers are being used in the same LAN. For this reason there have been protocols proposed [17] that try to reduce the number of turnarounds.

Power has always been a scarce resource in wireless devices. MAC protocols are expected to contribute towards efficient power utilizations. There have been very few solutions to this problem. The standards [14, 13] have not been able to deal with this effectively..

The ability to support QoS is a difficult undertaking. This is not because of processing limitations like in the wired world, but because most of the protocols are contention based with no limits on how long the contention will last. Making these protocols contention free might sound like a solution but is not, because of low resource utilization achieved by these protocols. Also dealing with multiple hops in a potentially dynamic network is a hard problem.

In spite of the fact the medium here inherently broadcast, the issues of multicast and broadcast has not been addressed by any MAC protocol [10]. Multicast functionality has eluded the wireless LAN at the MAC layer. The problem comes because of high error rates. In a large receiver set there are chances that one of the receivers will receive the packet in error. Also for obvious reasons acks cannot be used here for reliability (implosion effect). Because of this and other difficulties no MAC protocol has come forward to supporting multicasting in wireless LAN's (multiple unicast based solutions are employed).

Security becomes a bigger issue in wireless domain because of ease of snooping. Another problem area for wireless MAC protocols is dealing with high speed mobility.

3 Wireless LAN MAC Protocols

This section presents an overview of the existing body of research in the area of wireless LAN MAC protocols.

3.1 ALOHA

The history of wireless communication can be traced back to **ALOHA** [1]. Aloha was designed by Abramson in 1970 [1] for linking the various Hawaiian islands. It is a very simple protocol in which a station sends data whenever it has data to send. The receipt of an acknowledgement (which might be implicit) assures the sender that data has been delivered successfully, else it is sent again after a random time gap. Aloha is useful in cases in which carrier sensing is not possible or impractical (like in satellite communications). It can be easily shown using simple traffic load assumptions that peak Aloha performance is only 18 %. While this channel utilization might seem bad, Aloha's biggest strength is its simplicity which can justify its usage in cases where high utilizations is not the primary concern. Subsequent variations like slotted ALOHA and reservation ALOHA significantly improve the performance.

3.2 CSMA

The fundamental reason for low channel utilization of Aloha protocol is that senders don't defer to each other even when another transmission is in progress. **CSMA** rectifies this problem by carrier sensing (explained above). In *p-persistent* CSMA, the station sends a packet with probability p as soon as the carrier becomes idle. In *nonpersistent* CSMA a station will set a random time interval when it senses that the channel is busy and tries to transmit again after that instead of continuously monitoring the channel. Without a scheme like exponential backoff *p-persistent* CSMA can be unstable when offered loads are high, as many stations begin transmission simultaneously when the current transmission ends.

3.3 BTMA

It was recognized by Kleinrock and Tobagi [2] that wireless systems suffer from, the now well known, *hidden terminal* problems. In the same document the authors presented **BTMA**, a solution to deal with the hidden terminal problem. BTMA is an acronym for busy tone multiple access. The available frequency is divided into data channel and a control channel. While a station is receiving data on the former channel, it places a *busy-tone* on the control channel. This signals to other potential senders that the receiver is busy and they should defer their transmissions. This protects the system from hidden terminal problems. BTMA can also be used to get rid of the exposed terminal problems if the sender ignores the carrier sense signal when there is no busy-tone on the control channel. The problem with BTMA is that it requires to split the channel into two making receivers more complex. The two bands also need to be separated by a guard band, which wastes channel frequency. Also since the propagation characteristics of the radio link are dependent on frequency, a station might hear just one of the two signals (busy-tone or data)[8].

3.4 SRMA

The first protocol to propose handshake between the sender and receiver was **SRMA** or split-channel reservation multiple access[3]. SRMA proposes use of a separate channel for RTS/CTS exchange (explained above). SRMA gets rid of the need for transmitting a continuous busy-tone signal and thus might end up saving some power. While the original proposal required two separate channels and the associated hardware complexity, there is nothing in the scheme that prevents it from being used only in a single channel.

3.5 MACA

MACA (multiple access collision avoidance) was the first modern protocol which used RTS/CTS exchange and underscored the benefit of it over the then existing protocols (which were largely CSMA/CA based). The motivation was again the hidden terminal problem and the inspiration *AppleTalk*[4]. In MACA before a station sends the data it sends an RTS message to the receiver. On success the receiver responds with a CTS. The nearby stations are also listening to this exchange. If a station hears RTS it waits for the corresponding CTS. If it does not hear CTS, it means any transmission it has will not interfere with the receiver. The assumption here is if you cannot hear the receiver, the receiver cannot hear you too. This helps alleviate the exposed terminal problem. Any station, other than the original RTS sender, on hearing CTS will defer its transmission. The time for which to defer transmission depends on the packet length to be transmitted which is contained in the CTS packet. This takes care of the hidden terminal problem. Binary exponential backoff was used in case of collisions of RTS packets. MACA requires much simpler hardware because of absence of carrier sense.

3.6 MACAW

Various practical problems with MACA were identified by **MACAW** (MACA for Wireless)[10] and proposed changes that solves some of them. This was one of the first wireless MAC protocol that was designed with fairness in mind. MACAW gets rid of Ethernet like unfairness associated

with binary exponential backoff algorithms by proposing a copying form of backoff counter in which nodes use the backoff counter of a successful transmission to contend fairly in the next cycle. Also separate backoff parameters were introduced (corresponding to different streams) to avoid this copied parameter to spread widely even to areas with no congestion. It also proposed a multiple stream model for fairness among streams emerging from the same station. MACAW acknowledged the importance of link layer acknowledgements and made the protocol from RTS-CTS-Data to RTS-CTS-Data-ACK. With the introduction of this ACK packet means that exposed terminals should not transmit now, or else they will trash the incoming ack. There are two ways of dealing with this, carrier sense or an explicit packet specifying the length of the transmission at the start of it. MACAW takes the latter approach to keep the hardware simple and calls this packet DS (data sending). Another control packet RRTS (Request for RTS) was added to let the receiver contend for the sender to improve fairness in cases when there are two receivers in the vicinity of each other (thus only one can receive). By making the protocol significantly more complex MACAW lost performance when the channel was lightly loaded but led to much better throughput and fairer allocation in presence of high loads.

3.7 FAMA

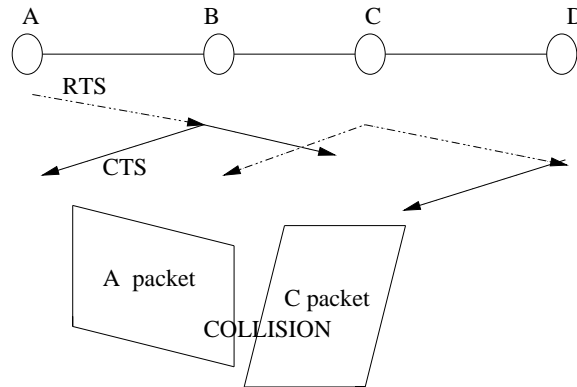


Figure 1: Complex hidden terminal problem

On first thought MACA seems to solve the hidden terminal problem, but that's not quite true. This happens primarily because the neighbors may not be able to hear CTS/RTS messages correctly. For example consider the topology in figure 1 in which only adjacent nodes can hear each other. A completes a successful RTS-CTS exchange with B and starts transmitting data. C which is a neighbor of B also started a RTS sequence just at the time B replied CTS to A, and hence is not able to realize that B is going to be in conservation. (B's CTS, C's RTS collide at C). D sends a CTS signal to C and C now thinks he has acquired the channel and starts transmitting the data which collides at B. One solution to this problem would be to make the length of CTS packet longer then the RTS packet, which would make sure that C hears the B's CTS message. This is only one instance in which the protocol fails and one can easily come up with other scenarios where it fails.

Floor acquisition multiple access, **FAMA**, [11] represents a family of MAC protocols which operate in two phases, acquire the channel(floor acquisition) followed by the actual transmission of data.

These protocols ensures that data packets will be collision free and multiple packets can be sent by the sender. A key distinguishing observation is that this guarantees once channel is successfully acquired transmission of data packets is collision free unlike in MACA (or MACAW), where even after a successful RTS-CTS exchange, data packets can collide with other nearby transmissions (like above). FAMA has various variants each having different timing requirements for floor acquisition and performance characteristics. The variants are based on techniques used to acquire the floor and scope of the problem addressed (like single hop vs ad hoc networks). For example [15] author's prove that sending RTS packets without sensing the medium is inherently inefficient than using non persistent CSMA based techniques. An important and novel contribution of the work is derivation of sufficient timing requirements that must be met for correctness based on propagation delay, packet sizes, RTS/CTS sending timings, and Rx/Tx-turnarounds.

3.8 GAMA

GAMA-PS (Group Allocation Multiple Access with Packet Sensing) [20] is a channel access protocol for asynchronous, packet-sensing wireless networks. The idea is to organize the channel into cycles dynamically. Each cycle is composed of a contention period and a group-transmission period. Every member interested in transmission contends for membership in the *transmission group*. Once a station is in the group, it is able to transmit a data packet during each cycle without collision. The membership persists as long as it has some data to send. The group is maintained in a distributed manner. All members of the group hear to the channel to learn about other members in the group, its own position in the group etc. Joining a group is based on RTS/CTS mechanism. In some sense this is a mixture of TDMA and CSMA. When the network is lightly loaded it's behavior is much like CSMA. As the number of senders increases the cycle size increases up to a maximum and it behaves pretty much like TDMA.

3.9 DFWMAC

Apart from all the pure “researchy” protocol design described above, there have been many important standardization efforts. For space and time constraints we mention only two of them here (the important ones missed out are **Bluetooth** and **HomeRF**). The **IEEE 802.11** standard can be used in either an ad hoc infrastructure less setup or with a supportive base station based environment. The sharing is achieved using either a distributed coordination function (DCF) or a point coordination function (PCF). The DCF protocol **DFWMAC**[14] (Distributed Foundation Wireless MAC), which uses IFS (Inter Frame Spacing) for collision avoidance. The 802.11 standard defines three types of IFS's for three different access priorities. After SIFS (Short IFS), only acks, CTS and data frames in response to a poll by base station may be sent. After PIFS (PCF-IFS), any frames from the contention free period maybe sent and all other packets may be sent after DIFS (DCF-IFS). A SIFS is the shortest while DIFS is the longest duration. A station that intends to transmit and senses channel busy will wait for the end of transmission followed by a time period of DIFS length. After this it randomly selects a time slot within the backoff window. If no other station has started transmitting before the end of this slot is reached, it starts its own transmission. If another station has seized the channel, the station freezes its backoff counter, waits for the end of transmission and now only waits for the slots remaining from the previous competition. This provides better delay bounds in presence of high loads and avoids starvation. This basic access scheme can optionally be extended by use of a RTS/CTS message exchange.

The stations in this case compete for sending the RTS messages. The DCF service above does not provide any sort of guarantees. In order to provide time bounded traffic the PCF mode maybe used for contention free asynchronous transfers. In this the base station polls the stations that are on its polling list and allows them undisturbed access. To get on the polling list (either once or periodically), the stations contend through the DCF mode.

3.10 EY-NPMA

The **ETSI Hiperlan** is a standard for wireless communication in Europe. It uses **EY-NPMA**[13] (elimination yield - non-preemptive multiple access) protocol. EY-NPMA supports time bounded delivery of packets. This is achieved by dynamic assignment of access priorities which depend on the remaining lifetime of the packet (the exact priority is a function of the user assigned priority and lifetime of the packet). The MAC protocol for Hiperlan is a unique one, which does not resemble anything we have talked about till now. The multiple access problem in EY-NPMA is broken down into three phases. In the *priority resolution* phase the station listens to the medium till the priority slots for the higher priorities have gone idle. If the channel was idle for some number priority slots only the stations with the same highest priority survive. The *elimination* phase every station transmits a burst with a random length, bounded and defined by a certain discrete probability distribution. In this phase the station transmitting the longest burst wins, which the winning station finds out because the channel will be idle when it stops transmitting. This station will then wait for a random period in the *yield* phase. If it does not sense anything on the channel at the end of this phase, it transmits its data.

Comparison between the two standards was carried out in [16]. Both protocols were found to be stable even at offered loads of 400%. DFWMAC gives better throughput percentage (of total achievable) than EY-NPMA. The mean access delay seen in DFWMAC is generally lower than that in EY-NPMA. But since the EY-NPMA protocol requires a minimal number of Rx/Tx-turnarounds it might provide better throughput in low load conditions. For a given packet size, throughput and delay are inverse of each other in both protocols which is expected in such contention based protocols. Detailed simulations were carried out in [14] to analyze the performance of DFWMAC for fairness and throughput.

4 Future Research

In this section we discuss interesting research issues which are still open in this area. This might not be an exhaustive list but just a brief description of what we feel the ongoing research should address.

Increasingly it is being observed that multi-hop ad hoc networks are not easy to deal with. The recurrence of hidden terminals was the first sign of this[15]. The simple protocols which were designed with a base station or single-hop network in mind are lacking in many desirable features. It is difficult to provide any sophisticated services or guarantees or fairness across multiple hops. Specifically we need MAC protocols that preserve delivery guarantees across the network even if loosely. Since there are contentions at every hop this becomes non-trivial job. The newer protocols being proposed [18, 24, 7] bring back the reservation based schemes in some form or the other to achieve this. However, because of space and time limitations an analysis of these protocols

has been left out. Ozugur et. al. [21] proposes a p-persistent CSMA based protocol in which fair access is provided using link access probabilities. However this scheme like other reservation based scheme is sensitive to network topology. How does it effect the protocol when a new station without reservations steps in the radio range or how to use the channel efficiently when a station with reservations departs quietly?

Detailed theoretical analyses of various protocols across various aspects like correctness, performance, security, fairness and complexity remains open. The work done by Fuller [11, 15] scratch the surface of these issues and provides insight into the constraints on various parameters for correctness. Performance analysis is done based on Poisson based models for network traffic which may not be realistic. A thorough analyses could provide how the protocols can be optimized for power awareness, QoS and security. Real world testing would require a real world implementation which most of the current studies lack.

MAC protocols with decent power adaptation are yet to make an impact. The power saving effort can be traced back to MACA, which proposed calibrating the transmitted power according to the distance from the receiver. Power savings proposal in DFWMAC use the base station support and in EY-NPMA waking up at pre-arranged intervals. PAMAS [22] advocates going into the sleep mode when you know that you won't be transceiving for a given time, like when a transmission is going on in the vicinity (a node can learn this by listening to RTS/CTS exchanges). Feasibility of the protocol is yet to be ascertained and the original proposal needs a separate control channel. This is certainly not the last word on the subject given the importance of it in wireless devices and thus we should see some more sophisticated technologies in this domain soon.

Connecting these wireless LAN's to other networks out there is a problem which should be addressed at the MAC layer. Most current research is on doing this at higher layers. But some integration problems like fragmentation should be handled at the MAC layer because of high error rates in the media. DFWMAC has some support for this using PIFS which, we felt, is not entirely satisfactory solution given the dynamism of the network.

Link layer Multicast remains an open issue because of problems stated in section 2. Another issue not addressed by the current body of work is security. With the ease of snooping in wireless media it becomes more relevant. However we are not sure at what layer this should be addressed at.

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Appendix A: Comparing MAC Protocols

We provide a limited feature comparison of the protocols we have talked about in this paper. The legend is:

CS/PS Carrier Sense or Packet Sense

Msg The messages exchanged as part of the protocol.

Ch No of channels used

C/D whether centralized or distributed scheme

QoS whether the protocol address any QoS related issue at all like time bound service or priorities

PA whether the protocol has any sort of power adaptive feature built into it (effectiveness notwithstanding)

Protocols	Year	CS/PS	Msg	Ch	C/D	QoS	PA
Aloha	1975	none	Data-Ack	1	D	No	No
CSMA/CA	-	CS	Data	1	D	No	No
BTMA	1975	CS	Data	2	D	No	No
SRMA	1976	PS	RTS-CTS-Data	2	D	No	No
MACA	1990	PS	RTS-CTS-Data	1	D	No	No
DFWMAC-DCF	1994	CS(PS)	(RTS-CTS)-Data-Ack	1	D	No	Yes
DFWMAC-PCF	1994	PS	RTR-Data-Ack	1	C	Yes	Yes
EY-NPMA	1994	CS	Data	1	D	Yes	Yes
MACAW	1994	PS	(RRTS)-RTS-CTS-DS-Data-Ack	1	D	No	No
FAMA	1995	both	RTS-CTS-Data	1	D	No	No
GAMA	1998	both	RTS-CTS-Data	1	D	Yes	No
PAMAS	1998	-	RTS-CTS-Data	2	D	-	Yes

Table 1: Comparison of various MAC protocols