Medium Access Control Protocol for Wireless LANs

(An Update)

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Abstract

This contribution provides an updated and expanded description of a medium access control protocol for wireless LANs that was proposed in [*NAT*91*a*]. The proposal is described with respect to the 21 criteria that have been developed for consideration of MAC proposals.

The medium access control protocol used is a hybrid of reservation and random access based protocols. Channel time is structured as a sequence of frames of equal duration. The protocol divides a frame into three intervals. In the first two intervals, transmission is scheduled by the controller, and a decentralized contention-based medium access control protocol is used in the third interval. An adaptively movable boundary separates the contention-free and contention-based portions in each frame. This provides for flexibility of bandwidth allocation to meet a variety of asynchronous and isochronous services that are anticipated in future wireless applications.

We assume Slow-Frequency-Hopping spread-spectrum radio transmissions for isolating adjacent cells in a multicell network. However, the MAC protocol is applicable to a variety of other PHY layers that require different cell isolation techniques.

The communication architecture is flexible and permits several modes of operation. In particular, wireless communication is supported:

- When an infrastructure backbone network (i.e., a Distribution System) that facilitates extended coverage and mobility is available, and
- When there is no preexisting infrastructure to enable communication between mobile stations.

1.Introduction

The demand for wireless data communications is expected to grow in the coming years as a wide variety of user applications are developed and used in a number of operating environments. The following usage scenarios are expected to become increasingly common in the future.

Infrastructure-based LANs: The network architecture will consist of a finite number of *Access Points* that are attached to a *Distribution System*. The Distribution System, typically an IEEE 802 network, would enable:

- Communication between mobile stations and fixed destinations (ex, servers, applications, data etc) that are attached to the Distribution System. Mobile stations communicate to an Access Point (a fixed station) that acts as a "bridge" between the radio environment and the Distribution System. The Access Point relays messages from/to stations that request its services.
- Communication between mobile stations
  - If communication is between two mobile stations that are not within range of each other, this will occur utilizing the store-and-forward capability of one or more Access Points attached to a Distribution System.
  - If communication is between two mobile stations that are within range of each other, this can occur with direct or indirect support of an Access Point that can serve both of them.

Adhoc LANs: A primary requirement for a segment of user applications would be the capability to accomplish wireless communication without any dependence on a preexisting infrastructure. An adhoc LAN consisting of a set of mobile stations and shared resources like servers may be created, used for wireless communication and "dismantled" when the needs have been satisfied.

In this contribution we propose a communication architecture that is flexible and encompasses the several modes of usage scenarios outlined above. In particular, wireless communication among participating stations is supported:

- When an infrastructure backbone network (i.e., a Distribution System) that facilitates extended coverage and mobility is present and available for the mobile station to use, and
- When there is no preexisting infrastructure available to enable communication between mobile stations that wish to communicate.

2. Proposed Scheme

The proposed MAC scheme is first described in the context of Infrastructure-based LANs. The same scheme is used in Adhoc LANs as described in a later section. A half-duplex wireless link is assumed. The link is shared between inbound (mobile stations to Access Point) and outbound (Access Point to mobile stations) traffic. Channel time is structured as a sequence of frames of equal duration. The duration of a frame is subdivided into three intervals as shown in Fig. 1. Centralized control is used in the first two intervals and decentralized control in the third interval.

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|G|AH|       A   |BH|       B     |CH|       C    |G|

|.|..|||||||||||..||||||||||||||..|||||||||||||.|

| |  |Broadcast|  | Contention |  | Contention| |
| |  |         |  | Free       |  |  based    | |

| |  |AP to    |  | Mobiles to |  | Mobiles   | |
| |  |Mobiles  |  | AP         |  | to AP     | |

| | H|-- TA ---|  |---- TB ----|  |--- TC ----| |

    AH - Header for Period A    AP - Access Point
    BH - Header for Period B
    CH - Header for Period C
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Figure 1. Frame Structure of Medium Access Control Scheme

In the first interval (Period A), the link is used exclusively for outbound data transfer from the Access Point to mobile stations. In the second interval (Period B), bandwidth is allocated for contention-free inbound data transfer from mobile stations to the Access Point. The allocation of bandwidth is performed by a SCHEDULER resident in the Access Point wireless adapter. Bandwidth is allocated in each frame for inbound and outbound transfers. The third interval is used for transmission from mobile stations to Access Point in a random-access mode of operation. Control as well as data packets will use this interval.

The control information for Periods A, B and C are AH, BH and CH respectively. The medium access control protocol is now briefly described with respect to Fig. 1.

2.1 Period A (Outbound Interval)

Header AH (*Broadcast from Access Point to mobile stations*) is the interval during which the Access Point broadcasts a special message to all the mobile stations that identifies the beginning of Period A and contains additional control information shown in Fig. 2.

Period A (*Broadcast from Access Point to mobile stations*) is the interval during which outbound traffic is transmitted. The Access Point broadcasts packets and mobile stations receive packets addressed to them.

Header AH identifies the start of the information frame and contains the Network ID, the Access Point ID, the frequency to be used in the next hop (assuming Slow Frequency Hopping is the underlying PHY), a list of receiving stations and other system control information. The Network ID helps distinguish between several colocated autonomous LANs.

- TA = Length of Period A
- TB = Length of Period B
- TC = Length of Period C
- TAH = Length of Header AH
- TBH = Length of Header BH
- TCH = Length of Header CH
- TREMHOP = Remaining Length of Hop
- BSID = Unique Id of the Access Point
- NET_ID = Network Id
- Next Frequency to be used in the Slow Frequency Hopping pattern
- List of Receiving Stations
- Broadcast Data Indicator Flag

Figure 2. Control Information in Header AH

In Period A the Access Point controls the transmissions outbound to the mobile stations. The corresponding control information, Header AH, for this interval is broadcasted by the Access Point. Each mobile station waits for the header whose contents include those shown in Fig. 2. On correct reception of Header AH, each mobile station sets a timer for TA so that it knows when to receive Header BH and learn about the beginning of Period B. The parameters TA, TB and TC lets the mobile stations know how much time is allocated to the three intervals in the current frame. On correct reception of Header AH, each receiving mobile station can determine whether or not it will receive packets from the Access Point (either broadcast or explicitly directed toward them). If there is no outbound traffic in a frame, then TA will be set to zero in Header AH of the frame.

2. Period B (Inbound Slotted Interval)

Header BH (*Broadcast from Access Point to mobile stations*) is the interval during which the Access Point broadcasts a special message to all the mobile stations signifying the end of the Period A and the beginning of Period B. It also contains additional control information shown in Fig. 3.

Period B (*Contention Free Transfer from Mobile stations to Access Point*) is the interval during which mobile stations take turn to transmit according to the slot allocation specified in BH. At the end of Period A, each mobile station waits for Header BH. When received, each mobile station sets a timer for TB so that it knows when to receive Header CH and learn about the beginning of Period C, the contention interval. A mobile station that requested slot allocation in an earlier frame will check to see if it has been allocated any slots.

- TB = length of Period B
- TC = length of Period C
- NTR = Number of mobile stations that have slots allocated in the current frame
- (I , S(I)) = User I can transmit S(I) packets.
  There will be one such pair for each of the NTR mobile stations that have slots allocated in the current frame.

Figure 3. Control Information in Header BH.

Header BH specifies a list of ordered pairs of the form $< I,\ S(I) >$ that indicates mobile station I is allocated $S(I)$ slots in the current frame. Since the list is ordered, the order in which they are allowed to transmit to the Access Point is known to the mobile stations. Since each mobile station knows the list of stations that precede it and their allocations, it can determine when it should begin its transmission. At its designated time, the mobile station transmits for a fixed period of time whose duration depends on the number of slots allocated to it. Thus, contention-free transfer from mobile stations to Access Point occurs utilizing the slot allocation information specified in BH. If a mobile station fails to receive BH correctly, then it will not make use of any slots that may have been allocated to it in the current frame. At the beginning of a frame, if there is no pending request from any mobile station for inbound data transfer, then TB (the length of Period B) in Header BH of the frame is set to zero.

Adjustment of TA and TB in each frame enables the bandwidth to be allocated on a demand-driven basis. If both TA and TB are set to zero, then the MAC reduces to exclusively random-access mode of operation. For a large class of applications, outbound traffic (from Access Point to mobile stations) tends to be significantly large compared to inbound traffic (mobile stations to Access Point). In such cases, TA is expected to be the dominant component in a frame.

2.3 Period C (Inbound Contention Interval)

Header CH (*Broadcast from Access Point to mobile stations*) is the interval during which the Access Point broadcasts a special message to all the mobile stations, identifying the end of the Period B and the beginning of the Period C. The message also conveys the information in Fig. 4.

- TC = length of Period C
- K = Current estimate of users actively attempting transmission in Random Access Section (expected to be much smaller than the number of users registered with the Access Point).

Figure 4. Control Information in Header CH.

Period C (*Random access from mobile stations to Access Point*) is the interval during which any station may contend for the channel and transmit a message without any explicit allocation from the Access Point. A Slotted-ALOHA protocol with suitable modifications for retransmission scheduling is used in this interval.[1]

[1] The proposed choice of Slotted-ALOHA in Period C allows efficient support for simple and inexpensive radio PHY layers (e.g. radios with long transmit-to-receive turnaround times). However, we note that Period C admits the use of random access protocols that, under a different set of PHY layer assumptions, are theoretically more efficient than Slotted-ALOHA. In particular, a Carrier Sense Multiple Access-based protocol can be used in Period C. Use of such CSMA-based alternative choices, are considered to be within the scope of this MAC proposal.

Period C is used for the following types of information:

- Request messages for registering with an Access Point
- Bandwidth reservation requests
- Data packets

2.3.1 Registration with Access Point

The process by which a mobile station introduces itself and requests the services of an Access Point is called *Registration*. The set of registered users at an Access Point will change dynamically with time. An Access Point does not assume *a priori* knowledge about the number or the identity of mobile stations desiring its services.

After a mobile station has monitored the radio environment and chosen an Access Point to register with, it sends a Request Registration Control Packet. The packet contains the Access Point ID as well as the Network ID of the LAN that the mobile station wishes to join. Other information included are the mobile station MAC address, and other information that may be required for access control purposes.

On receipt of a Request Registration control packet, the designated Access Point processes the request. It responds to the mobile station with a message called Registration Response packet. If the registration request is accepted, then the Access Point becomes the *Owner* of the mobile station. An Access Point provides the MAC functions for all mobile stations for which it is the owner. Ownership of a mobile station can change if it roams within an Extended Service Area and a handoff sequence is initiated.

2.3.2 Reservation Requests for Bandwidth

Mobile stations request bandwidth for transmission in Contention Free mode (Period B). Such requests can be supported by transmitting the appropriate bandwidth reservation request to the Access Point. Both isochronous or non-isochronous services are supported by transmitting the appropriate bandwidth reservation request to the Access Point. Allocations based on reservation requests are specified in the BH header of the subsequent frames.

Bandwidth reservation requests are transmitted by mobile stations to the Access Point using random access Slotted-ALOHA protocol in the third interval (Period C). The Access Point receives reservation requests and processes them according to the SCHEDULER allocation algorithm.

The actual slot allocation information for inbound transmission is conveyed in Header BH of one or more subsequent frames.

Reservation requests have the form shown in Fig. 5. Such a request means mobile station with MAC Address MSID requests Access Point APID to allocate REQ_SIZE slots for inbound transmission (i.e., number of slots needed for transmission in Period B). Successful (i.e. collision-free and error-free) reception of reservation requests are acknowledged by the Access Point as part of the contention protocol in Period C. The field SERVICE_TYPE indicates whether an asynchronous or isochronous service is required. If asynchonous service is required, then no periodicity of request is assumed. If isochronous service is indicated, then REQ_SIZE slots will be allocated in every frame until a cancellation of the request is indicated in a subsequent control packet from the mobile station.

Reservation Request packet	
MAC Address	MSID
Network ID	
Access Point ID	APID
Reservation Request Size	REQ_SIZE
Type of Service (Iso. / Non-Iso)	SERVICE_TYPE

Figure 5. Reservation Request Control Packet

The SCHEDULER maintains a queue of pending requests for inbound data transfer, each request containing information shown in Fig. 6. If there is not sufficient bandwidth to satisfy all reservation requests in a frame, then the unfulfilled requests will be taken up in the following frame. Note that the Access Point processes the reservation requests within Period A of the next frame and communicates it as part of Header BH.

At the end of Period B, each mobile station waits for Header CH corresponding to Period C. The header contains TC, the length of the third interval. When received, each mobile station sets a timer for TC so that it knows when to expect the header for the next frame.

MAC Address	Request Size	Isochronous or Non-Isochronous

Figure 6. An Entry in the Queue of Outstanding Reservation Requests

Phase C is devoted to the transmission of messages using a Slotted-ALOHA protocol. Note that the duration of the Slotted-ALOHA subframe can change from one frame to the next in a manner determined by the Access Point and conveyed in the control headers AH, BH and CH. In the Slotted-ALOHA subframe, each mobile station that has a message to transmit will do so only at the beginning of a time slot. At the end of each transmission, the users must know if their packets were received correctly (i.e., without collisions) or not. If a collision is detected (by lack of a positive ACK), the mobile station schedules a retransmission of the collided packet according to a retransmission scheduling algorithm. Since bursty data, reservation and registration requests must have short response time, parameter *TC*, the length of the random access portion of a frame, is always lower bounded by a value, *TC_MIN*. *TC_MIN* is the minimum number of slots per frame that are always available for use in contention mode (eg, TC_MIN = 20% of the frame length).

At the end of each frame, the Access Point may have outstanding packets to be transmitted to mobile stations registered with it. These are first scheduled for transmission in Period A. Recall that *TB* is the length of Period B. The SCHEDULER allocates bandwidth subject to the constraint ($TA + TB$) is never allowed to exceed 80% of frame length. If there is no outbound traffic and there are no outstanding reservation requests, TC is increased to 100%.

When two stations are within a Basic Service Area and registered with the same Access Point, then there are two choices for communication between them. Fig. 7 shows an Access Point and two mobile stations that are registered with it.

The data transfer can occur in:

- Store-and-Forward (S-F) repeat mode: The Access Point receives from the source station, and retransmits to the destination. This requires two transmissions but has potential to provide coverage over a larger area.
- Direct Data Transfer mode: Stations communicate directly with a single transmission from source to destination station (no active intervention by Access Point during data transfer).

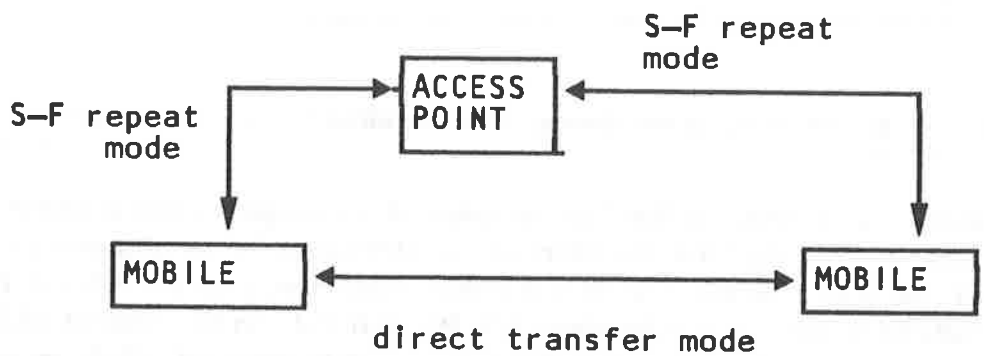

Figure 7.

A mobile station may (or may not) be able to communicate directly to another mobile station registered with the same Access Point. In the Store-and-Forward repeat mode, a mobile station communicates through the Access Point to another mobile station in the network.

The following are two modes of system operation for direct data transfer between mobile stations.

- Mode 1: The first mode of operation is *Random Access Direct Data Transfer*. In this mode, a mobile station communicates directly to another mobile station in Period C. The Access Point will not receive the packet for store-and-forward transmission.

mode 1	source address	destination address	Data

Mode 2: The second mode of operation is *Reserved Access Direct Data Transfer*. In this mode, a mobile station communicates directly to another mobile station in Period B of the frame. Bandwidth allocation is requested from the Access Point in Period C. The Access Point then includes the following in Header BH of Period B in a subsequent frame. The message has the following form:

mode 2	source address	destination address	allocated time slots

The message allows both the sender and the receiver know when data transmission will happen, and that the second mode operation is active in the assignment slots.

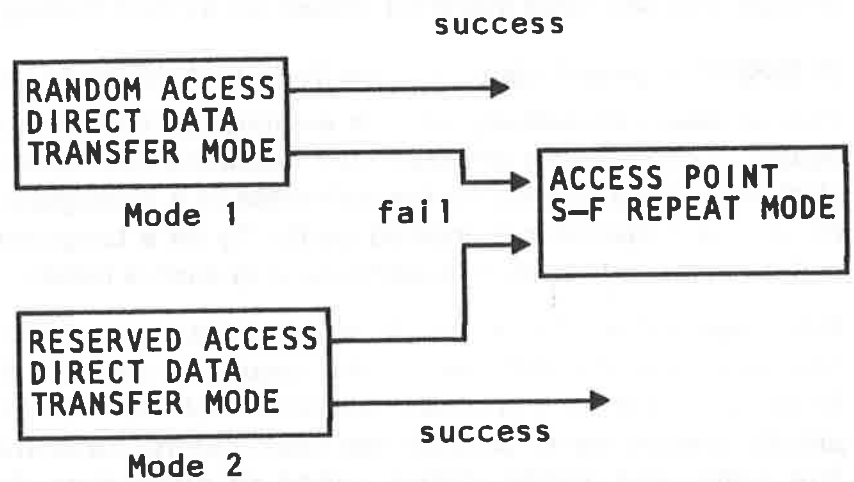

Figure 8. Different Modes of Data Transfer in a Basic Service Area

The above two modes of operation permit a mobile station to use Direct Data Transfer mode whenever it is in range of the destination station. The source station first tries the Direct Data Transfer mode. If not successful (lack of success in a number of retries), it enters the S-F repeat mode. Using the Access Point, the packets are delivered to the destination. Fig. 8 summarizes the different modes of operation.

Response to 21 Criteria

1) Unauthorized network access impact on throughput

The proposed MAC protocol is a hybrid of Reservation TDMA and random access schemes. Slow Frequency Hopping Spread Spectrum communication is used for intercell isolation in a multicell radio network. Users in a BSA can utilize the channel only after successfully registering with an Access Point. The registration procedure will exclude an unauthorized user from accessing a network. Users in adjacent cells of the same network as well as cells of colocated networks will typically be hopping in non-interfering channels (please see response to Item 8). Their access of their networks should have marginal impact of system throughput.

In an Adhoc-LAN, only the users that belong to the network will impact each other. Users belonging to other networks will again be isolated in frequency domain and will have marginal impact on system throughput.

2) Establish peer-to-peer connectivity without prior knowledge

Peer-to-peer connectivity can be established by creation of Adhoc LAN networks. Such networks are created to facilitate communication between mobile stations *without* relying on the existence of a distinguished entity *a la* Access Point. The networks are created on-the-fly on a temporary basis consisting of mobile stations that wish to participate in such a network.

This section describes a simple approach to create Adhoc networks. With this approach, mobile stations would require implementation of Access Point functions in software in mobile station adapter cards. A mobile station is *explicitly* designated to provide the basic control functions of an Access Point. The designated mobile station, called an *Adhoc-type Access Point*, performs only the *core functions* of an Infrastructure-type Access Point. These include the following:

1. Bandwidth allocation based on reservation requests
2. Registration of stations that wish to join the Adhoc network
3. Timing and framing information for coordinating the stations in the Adhoc network. With a Frequency Hopping PHY layer, the control functions includes specifying the frequency hopping pattern to use, time instants when the stations should hop and how long they should stay in a hop. The above

control information facilitates synchronized frequency-hopping by all mobile stations that belong to the Adhoc LAN. Data transfer will occur using the same MAC protocol as in Infrastructure-based LAN. The primary mode of operation is Direct Data Transfer between stations that belong to the Adhoc LAN. The Adhoc Access Point need not function as a Store-and-Forward repeater for data communication between peer stations that are in direct range of each other. However, Store-and-Forward repeat is a backup option available at the Adhoc Access Point and can be used for extending the coverage range of the Adhoc LAN.

A promising direction for *automatic* creation of Adhoc LANs is to create systems in which a station is elected as an Adhoc-type Access Point, performs the core functions of an Access Point for some duration and the responsibility for performing Adhoc-type Access Point functions is rotated among the participating stations in an equitable manner.

3) Throughput

The MAC protocol is a hybrid of contention-free (Periods A and B) and random-access protocols (Period C). Suppose the fraction of bandwidth used in Periods A and B is f. The fraction used in Period C is $(1 - f)$. The maximum throughput achievable is $[100(f + A_{SALOHA}(1 - f))]\%$, where $A_{SALOHA} = 0.36$. If we set $f = 0.8$, the maximum throughput is about 87.2%.[2] The average throughput is a function that depends very much on the traffic model assumptions.

The following simulations show that high link utilization in an environment of heavy traffic is achievable and the system is stable even under high load conditions. Periods A and B are based on reservation and are unconditionally stable. Stability in Period C is achieved using adaptive retransmission strategies.

The system modeled consists of a Server attached to the wired network and a set of mobile stations executing a Hypothetical File Transfer protocol. Each mobile station generates a Request to the File Server (500 bits long packet) and transmits it in the contention interval (Period C). The server replies with a Response message (5000 bits long, occupying 10 slots in the outbound direction). The Response is broadcast by the Access Point in contention-free mode (Period A). As soon as the mobile station successfully transmits a Request to the Access Point, it becomes eligible to generate another Request

[2] If a theoretically more efficient random access protocol, say a Nonpersistent-CSMA protocol is used in Period C, the maximum throughput achievable is $[100(f + A_{NPCSMA}(1 - f))]\%$, where $A_{NPCSMA} = 0.83$. If we set $f = 0.8$, the maximum throughput achievable is over 96%.

according to a specified distribution. The mobile station may generate a request before a response from the File Server is received to a prior request. All the mobile stations in the system execute the same protocol simultaneously. The average throughput shown in the following graphs depict the following scenarios.

In Fig. 9, a frame length of 100 slots (each 500 bits long) is assumed. The simulation assumed that the bandwidth allocation for Period C is fixed (20 % of frame length) over the entire simulation run. The throughput increases to a maximum of about 85% with 6 users. The decrease in throughput as the number of users is increased beyond 6 is because fewer of the Request messages are getting through due to increased contention in Period C. Thus the contention-free intervals are underutilized.

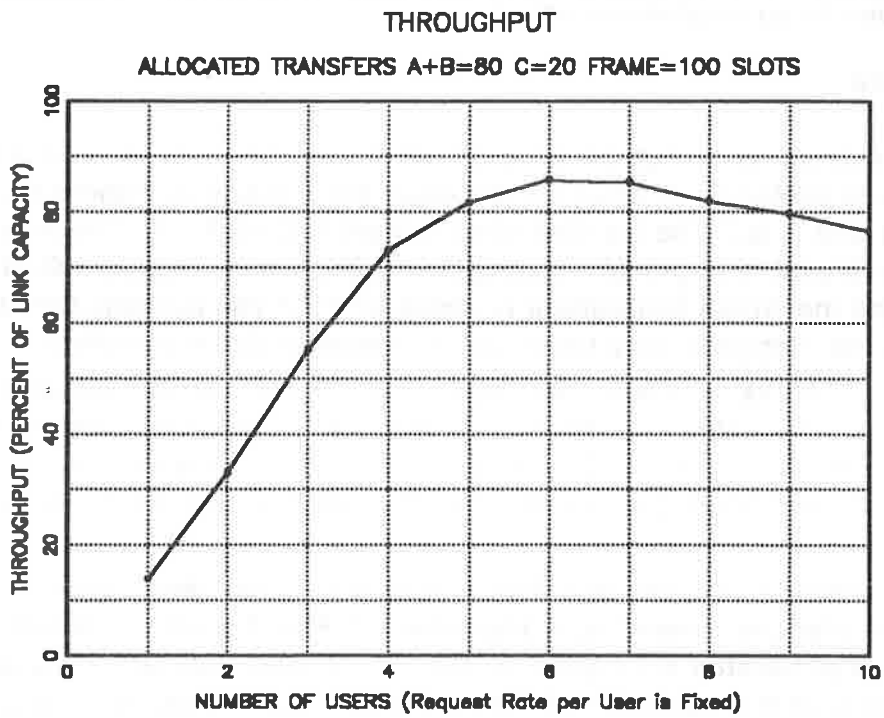

Figure 9.

In Fig. 10, Period C has 40% of bandwidth per frame. Throughput saturation occurs at 75% with 10 users. With increasing number of users the throughput does not decrease rapidly. There is sufficient bandwidth available in Period C that the contention for Request messages is low even with 15 users.

It should be noted that with fixed allocation, the utilization in contention-free mode cannot exceed 60%. Additional users beyond 10 can not result in higher utilization.

In Fig. 11, a frame length of 25 slots (20% bandwidth for Period C) is assumed. Requests from users are made (each request = 10 slots) in Period C. Link utilization is plotted as a function of arrival rate for the contention-free and the random access intervals.

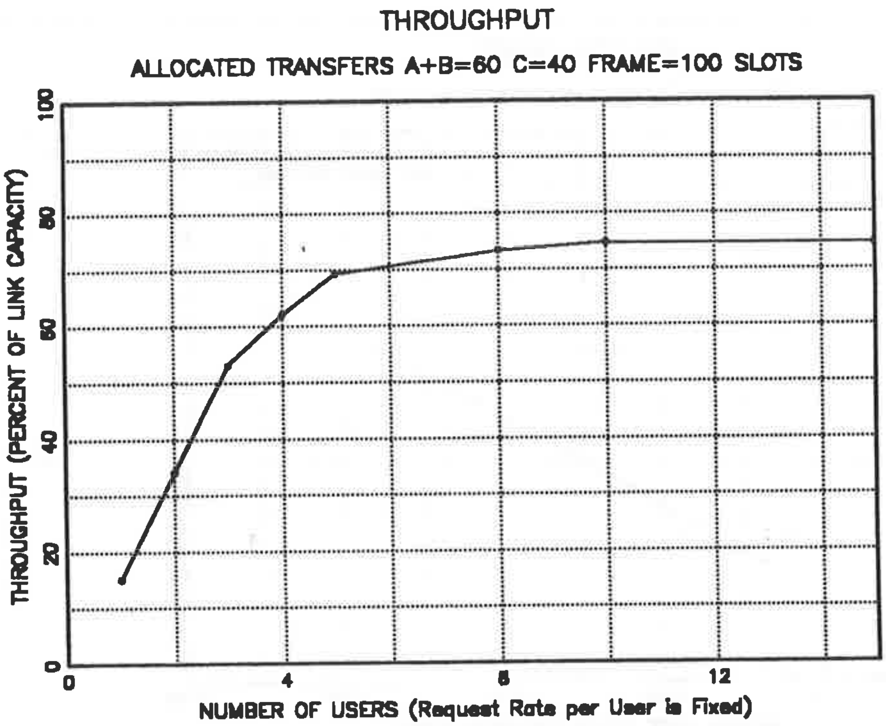

Figure 10.

4) Delays

The following general observations are made with respect to the delay characteristics. Under light load conditions (< 20% utilization), the limiting behavior approaches that of the random access protocol used in the contention interval (i.e., delay performance of Slotted-ALOHA). If a CSMA-based protocol were used in Period C, the delay characteristic of that protocol would likely be the limiting behavior under light to moderate load conditions. Under heavy load conditions (high utilization in Periods A and/or B), the delay characteristic of the MAC would be primarily influenced by the delay performance of a reservation-based scheme.

A comprehensive characterization of the delay performance of the hybrid MAC that includes an adaptive boundary adjustment policy is underway. We expect to drive the performance models, under different PHY layer assumptions, with realistic traffic models that may be developed (or agreed upon) in the 802.11 committee. We hope to present the results of such a characterization in a future contribution.

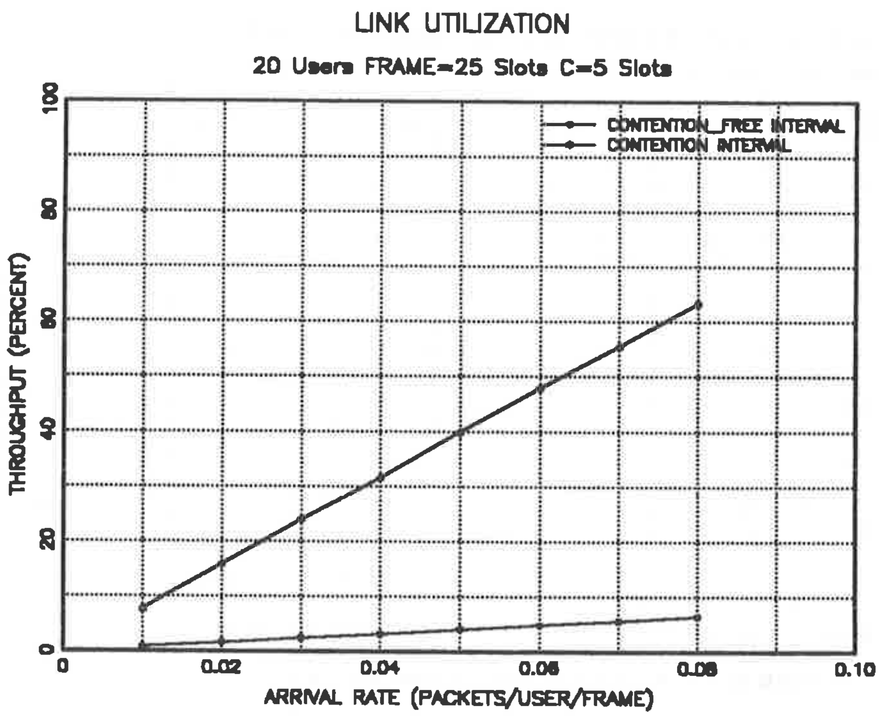

Figure 11.

5) *Maximum number of stations*

The maximum number of stations that can be supported depends on a number of factors. Important factors that impact the maximum number of stations include the following.

1. Peak data rate of the channel
2. Traffic model
   a. Client-server model - A request from a client is followed by a response from the server followed by another request from the client. The model has been described in [*KAM*91].
   b. Peer-to-Peer model - Are traffic flows uniformly distributed among pairs of users ?

The MAC protocol does not impose any intrinsic limitations on the maximum number of stations.

6) Ability to serve data, voice and video (isochronous service)

The proposed MAC protocol is a hybrid combination of reservation and contention protocols. Handling isochronous service requirements is an integral part of the MAC protocol.

7) Transparent to PHY layer

In designing a multicell Wireless LAN, interference between users belonging to the network must be minimized within a cell and between cells. The proposed frame-structured MAC protocol addresses the problem of sharing bandwidth within a cell. We have described in some detail how the MAC protocol works assuming Slow-Frequency-Hopping Spread Spectrum PHY layer.

Other PHY layers can be supported by the proposed MAC protocol. Here we describe how other PHY layers that may require different cell isolation techniques can be handled.

If the PHY layer is based on *Direct Sequence Spread Spectrum* radio (as proposed in [*CHE*91]) we can suppress cell to cell interference using the code division capability provided by DSSS transmission.

If the PHY layer is based on diffuse *Infrared* with a single channel PHY, the following is a possible method for providing intercell isolation within an autonomous network. One may position the Access Points and their coverage area in such a way that neighboring cells do not overlap. Each BSA will be optically isolated from others in space domain. The frame-based MAC protocol works with the Access Point providing timing and control information at the beginning of each frame. A similar spatial isolation approach may be used for interference rejection in colocated autonomous infrared networks.

If the PHY layer is based on allocated RF spectrum, a number of *possibilities* exist.

1. Divide the available spectrum into an appropriate number of subchannels and use a form of spread spectrum radio transmission (Frequency-Hopping or Direct-Sequence SS).
2. Use only the contention interval in each frame.

8) Robustness with respect to Colocated Networks

An autonomous WLAN installation will consist of a set of Access Points with overlapping coverage areas. Each autonomous network has an associated network administrator. Two autonomous networks are distinct and independent entities that do not *explicitly* coordinate with each other. Multiple autonomous LANs that are physically within radio range of each other are called *Colocated Networks*. A key function in successful operation of autonomous WLANs is the control of interference by suitable management of frequency hopping patterns followed by the different Access Points. The network administrator will perform FH pattern management and control functions within his autonomous WLAN installation. Interference between adjacent cells is minimized by proper assignment of FH patterns to the Access Points.

In a physical site, there may be several FH-based LAN installations that can potentially interfere with each other. Interference can be classified as follows.

- Interference that occurs between multiple BSAs of a single autonomous network. In Fig. 12, LAN1 is an autonomous WLAN with three Access Points (A, B and C) that overlap with each other. LAN2 is another autonomous WLAN with two Access Points (D and E) that overlap with each other.
- Interference that occurs between multiple BSAs across different autonomous WLAN installations. In Fig. 12, Cell E of LAN2 interferes with all three cells of LAN1 while Cell D of LAN2 interferes with Cells B and C of LAN1.

Each network administrator will assign distinct FH patterns to Access Points that are under his jurisdiction. We evaluated the extent of interference in a colocated network environment using simulation. Using random FH patterns consisting of 79 frequencies per pattern, we have observed in our simulations that the expected number of hops interfering with a given cell is approximately (K-1) in a network with K overlapping cells. Furthermore, the observed variance in the expected interference is small.

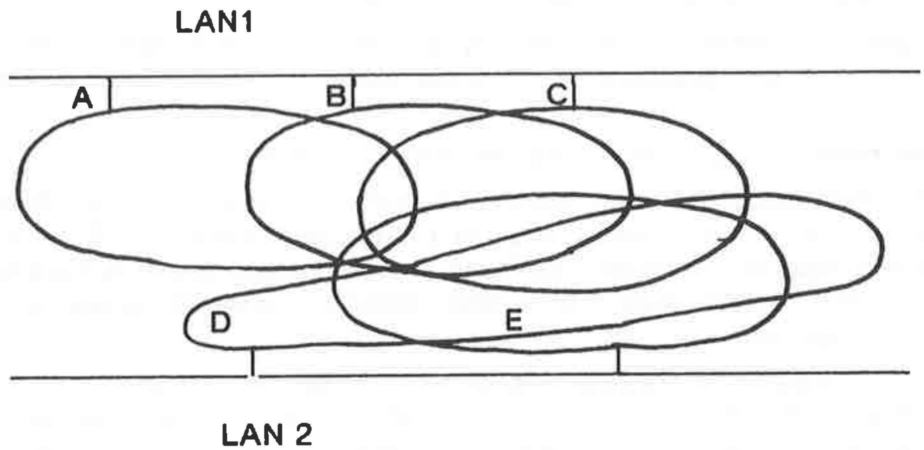

Figure 12. Frequency hopping: overlapping cells example

The table in Fig. 13 shows interference levels with use of random FH patterns. If a cell has 2 adjacent overlapping cells, then the expected hop interference is about 2.5%. With a more careful choice of FH patterns, we believe that the expected hop interference levels can be considerably reduced.

K	Mean	Stand. Devn.
2	0.99	0.97
3	1.97	1.35
4	3.00	1.72
5	3.97	1.94
8	6.81	2.44

K = Number of overlapping cells

Figure 13. Number of Hops interfered per cell

9) Battery power consumption

There are a number of power conservation strategies. These include the following:

- Access Point scheduling of mobile stations.
- Fine-grained power control techniques for selective control of the state of receivers at the granularity of slots within a frame was described in [*NAT*91*b*].)
- Power switching to adapter (as proposed in [*BIB*91*b*]).

The MAC protocol minimizes battery power consumption in mobile station adapters as follows. The basic idea is to utilize knowledge of receiver and transmitter schedules of mobile stations. Power consumption is kept to a minimum when the mobile station is neither actively transmitting nor actively receiving information.

On correct reception of Header AH, a mobile station can power down its receiver for time duration TA (total length of Period A). The receiver is put to *sleep* after scheduling to *wake* itself up at the end of Period A. Before going to sleep a timer is set with duration equal to TA, the length of the sleep period. Mobile station with data to receive will keep its receiver ON for the entire duration of Period A. All mobile stations that went to *sleep* at the beginning of Period A will wake up just in time to receive Header BH corresponding to Period B.

At the end of Period A, on correct reception of Header BH, each mobile station that previously made an allocation request will scan Header BH to check if it has any slots allocated to it. The mobile stations with no allocated slots will put their receiver to sleep by setting the timer for duration *TB*, the length of Period B. The mobile stations which did not make any allocation requests will not scan Header BH but immediately put their receiver to sleep in Period B. The timer will wake up the receiver at the end of Period B just in time to receive Header CH. Mobile stations that have slots allocated will turn their transmitter ON and transmit packets to the Access Point according to the allocation information received in Header BH. In Period C, mobile stations that do not wish to transmit go to sleep till the end of the current frame.

A mobile station's adapter is most likely to be in a state in which it is neither receiving nor transmitting packets most of the time. The actual times will depend on transmitter and receiver duty cycles averaged over the duration the mobile station is powered up. If a mobile station is in such a state, it must still receive Headers AH, BH and CH in every frame. Estimating the overhead due to headers per frame is 2%, the effective power consumption is significantly reduced. For representative figures and an example, please see [*NAT*91*b*].

10) Any critical delays which limit large area coverage

There are no critical delays in providing large area coverage. Specifically, propagation delay (which tends to limit performance of Carrier Sense based protocols in high capacity broadcast channels) is not a critical factor with our proposed MAC protocol.

11) Fairness of access

The MAC protocol relies on the Access Point scheduler to make bandwidth allocation to requesting stations. Priority scheduling policies can be incorporated in the scheduler to meet desired fairness criteria. As a default strategy, a First-In-First-Out scheduling scheme will provide a measure of fairness to competing station requests.

12) MAC needs to enforce insensitivity to capture effects

The MAC protocol has contention-free and contention-based intervals. There are no capture phenomena in the contention-free intervals because exactly one transmission will occur at any time instant. Reservation-based access to the channel ensures that even a mobile mobile station that is located in a disadvantageous location (from a radio propagation point-of-view) will get exclusive access to the channel. Such users are prevented from being captured by other stations that may be more advantageously located in the network.

In the contention-based interval, an Access Point may receive a packet correctly even in the presence of simultaneous transmissions from other stations. Power capture effect occurs when the strongest of several transmitted packets is received correctly regardless of other simultaneous packet transmissions. Power capture, if present, will help improve the throughput in the contention-based interval.

Thus, capture effects, if present, are likely to increase throughput.

13) Support for priority traffic

The MAC protocol relies on the Access Point scheduler to process bandwidth reservation requests. Priority scheduling policy can be designed to meet the requirements of priority traffic.

14) Ability to support non-reciprocal traffic - one way terminals

The lack of ACKs from a missing peer is detected and recovery occurs via the Access Point.

15) Time to market and complexity

The MAC protocol is amenable to low cost / low complexity implementation.

16) Ability to work in simple, small and large systems.

The proposed MAC is identical for operation in small Adhoc LANs as well as in a large Infrastructure-based LAN (with multiple Access Points interconnected by a Distribution System) that provide service over an extended coverage area.

17) (Unused)

18) Ability to support handoff/roaming between service areas

A key problem in providing transparent communication service for freely roaming mobile stations in an Extended Service Area is *handoff* . Our proposed MAC can be used in conjunction with any of the following three methods by which handoff can be initiated.

- Access Point Initiated handoff
- Mobile Station Initiated handoff
- Mobile Assisted Access Point Initiated

Whatever the technique is used to initiate a handoff, a handshake procedure is proposed to accomplish handoff.

Each mobile station, say MS, is registered with exactly one Access Point at any time. If a decision to handoff MS occurs, then Access Point AP_NEW communicates with Access Point AP_OLD via the Distribution System with a message that requests AP_OLD to *Unregister* (i.e., relinquish ownership) the mobile station. In response to this message, AP_OLD communicates any status information that may be associated with Mobile Station MS to AP_NEW. Thereafter, wireless communication needs of MS are served by the new owner AP_NEW until another handoff sequence is initiated.

19) Implication on complexity of PHY

The MAC protocol does not require a complex PHY layer but can benefit from it. The MAC protocol can support simple and inexpensive PHYs.

20) Ability to support broadcast

Broadcast transmission is supported by the MAC. Within each BSA, a special address is set aside to distinguish broadcast transmissions. Such transmissions are not individually acknowledged by receiving stations.

21) Preservation of time order of MSDU's to end systems

The time ordering of MSDUs is preserved.

References

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