A Comparison of MAC Protocols for Wireless Local Networks Based on Battery Power Consumption

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Abstract - *Energy efficiency is an important issue in mobile wireless networks since the battery life of mobile terminals is limited. Conservation of battery power has been addressed using many techniques. This paper addresses energy efficiency in medium access control (MAC) protocols for wireless networks. The paper develops a framework to study the energy consumption of a MAC protocol from the transceiver usage perspective. This framework is then applied to compare the performance of a set of protocols that includes IEEE 802.11, EC-MAC, PRMA, MDR-TDMA, and DQRUMA*[a]*. The performance metrics considered are transmitter and receiver usage times for packet transmission and reception. The analysis here shows that protocols that aim to reduce the number of contentions perform better from a energy consumption perspective. The receiver usage time, however, tends to be higher for protocols that require the mobile to sense the medium before attempting transmission.*

1 Introduction

This paper addresses the issue of energy conservation in medium access control (MAC) protocols for wireless multimedia networks. Third generation wireless networks will be expected to carry diverse multimedia traffic types. A number of access protocols have been proposed to support multimedia traffic [1–8]. These protocols typically address network performance metrics such as throughput, efficiency, and packet delay. We believe that energy consumption at the MAC level should also be an important consideration in the design of the MAC protocol for mobile wireless networks.

The paper considers an infrastructure network where a base station coordinates access to one or more channels for mobiles in its cell. The channels can be individual frequencies in FDMA, time slots in TDMA, or orthogonal codes or hopping patterns in case of spread-spectrum. To provide CBR, VBR and ABR services to end users, a wireless access protocol must be able to provide bandwidth on demand with different levels of service. Typical design goals of access protocols include fairness of access, high channel utilization, and low latency. This paper addresses the additional goal of efficient power usage at the mobiles. The premise is that mobiles will always have limited power, whereas the wired base stations will have virtually unlimited power.

The paper first presents a framework for comparison of energy consumption due to MAC related activities. The activities considered are transmission and reception of a single packet and periodic packets. The average time the transmitter and the receiver are in use for each of the activities is determined through analysis and simulation. This framework is then applied to a set of protocols that includes IEEE 802.11 standard [6], EC-MAC [4], PRMA [7], MDR-TDMA [5], and DQRUMA [8]. The results obtained from mathematical analysis are presented in the paper. These results have been validated through extensive discrete-event simulation, the results of which have not been included in the paper in an effort to conserve space.

2 Energy Conservation Principles

Mobile computers typically have limited energy for computing and communications because of the short battery lifetimes. Conserving battery power in mobiles should be a crucial consideration in designing protocols for mobile computing. This issue should be considered through all layers of the protocol stack, including the application layer. This paper recounts part of the discussion found in [9] pertaining to the MAC layer energy efficiency issues.

The chief sources of energy consumption in the mobile unit considered for MAC related activities are the CPU, the transmitter, and the receiver. Mobile CPU usage may be reduced by relegating most of the high-complexity computation (related to media access) to the stationary network. Therefore, the focus of this work is on transceiver usage. The radio can operate in three modes: standby, receive, and transmit. In general, the radio consumes more power in the transmit mode than in the receive mode, and consumes least power in the standby mode. For example, the GEC Plessey DE6003 2.4 GHz radio requires 1.8W in transmit, 0.6W in receive, and 0.05W in standby mode. In addition turnaround between transmit and receive modes (and vice-versa) typically takes between 6 to 30 microseconds. Also, power consumption for Lucent's 15 dBm 2.4 GHz Wavelan radio is 1.725W in transmit mode, 1.475W in receive mode, and 0.08W in standby mode. The objective of MAC protocol design should be minimize energy consumption while maximizing protocol performance. The protocols should be defined such that energy consumption due to the transceiver and CPU is low. The following are some principles that may be observed to conserve energy at the MAC level:

1. Collision should be eliminated as far as possible since it results in retransmissions that leads to unnecessary energy consumption and also to possibly unbounded delays. Note that retransmissions cannot be completely avoided due to the high link error-rates and due to user mobility. For instance, collision-based random access could be limited to new user registration.

2. In a typical wireless broadcast environment, the receiver has to be powered on at all times resulting in significant energy consumption. The receiver subsystem typically receives all packets and forwards only the packets destined for this mobile. One possible way to reduce receiver power-on time is to broadcast a data transmission schedule for each mobile. This will enable a mobile

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[a] EC-MAC: energy-conserving MAC. PRMA: packet reservation multiple access. MDR-TDMA: multiservices dynamic reservation TDMA. DQRUMA: distributed-queuing request update multiple access.

to be in standby mode except during its alloted slots.

3. Significant time and power is spent by the mobile radio in switching from transmit to receive modes, and vice-versa. This turnaround is a crucial factor in the performance of the protocol. A protocol which allocates permission on a slot-by-slot basis will suffer significant overhead due to turnaround. In order to reduce turnaround, a mobile should be allocated contiguous slots for transmission and reception whenever possible.

4. The IEEE 802.11 standard recommends the following technique for energy conservation. A mobile that wishes to conserve energy may switch to sleep mode. From that point on, the base station buffers packets destined for this mobile. The base station periodically transmits a beacon which contains information about such buffered packets. Upon waking up, the mobile listens for this beacon and informs the base station that it is ready to receive. This approach conserves energy at the mobile but results in additional delays that may affect quality-of-service (QoS).

5. If reservations are used to request bandwidth, it will be more efficient (power-wise and bandwidth-wise) to request multiple cells with a single reservation packet. This suggests that the mobile should request larger chunks of bandwidth to reduce the reservation overhead leading to better bandwidth and energy consumption efficiency.

6. Assume that mobiles transmit requests and that the base station uses a scheduling algorithm to allocate slots as in [4,5,8]. A distributed algorithm where each mobile computes the schedule independently may not be desirable because: (i) it may not receive all the reservation requests due to radio and error constraints, and (ii) schedule computation consumes energy and is thus better relegated to the base station. This suggests that a centralized scheduling mechanism will be more energy efficient.

These principles have been derived from different access protocols and are by no means an exhaustive list of efficient energy utilization techniques at the access protocol level.

3 MAC Protocols

This section briefly describes the wireless access protocols studied in this paper. Fig. 1 shows the channel access methods for these protocols.

The IEEE 802.11 standard [6] for wireless LANs defines multiple access using a technique based on Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). The basic access method is the Distributed Coordination Function (DCF) shown in fig. 1(a). A backlogged mobile may immediately transmit packets when it detects free medium for greater than or equal to a DIFS (DCF Interframe Space) period. If the carrier is busy, the mobile defers transmission and enters the backoff state. The time period following the unsuccessful transmission is called the contention window and consists of a pre-determined number of slots. The mobile, which has entered backoff, randomly selects a slot in the contention window, and continuously senses the medium during the time up to its selected contention slot. If it detects transmission from some other mobiles during this time period, it enters the backoff state again. If no transmission is detected, the mobile transmits the access packet and captures the medium. Extensions to the basic protocol include providing MAC-level acknowledgments and ready-to-send (RTS) and clear-to-send (CTS) mechanisms.

Packet reservation multiple access (PRMA) [7] was proposed for integrating voice and data traffic. The PRMA system is closely related to reservation ALOHA since it merges characteristics of slotted ALOHA and TDMA protocols. Packets in PRMA are grouped into periodic information and random information packets. Once a mobile with periodic information transmits successfully a packet in an available slot, that slot in future frames can b reserved for this mobile. However, mobiles with random information need to contend for an available slot each time. The protoco is depicted in fig. 1(b).

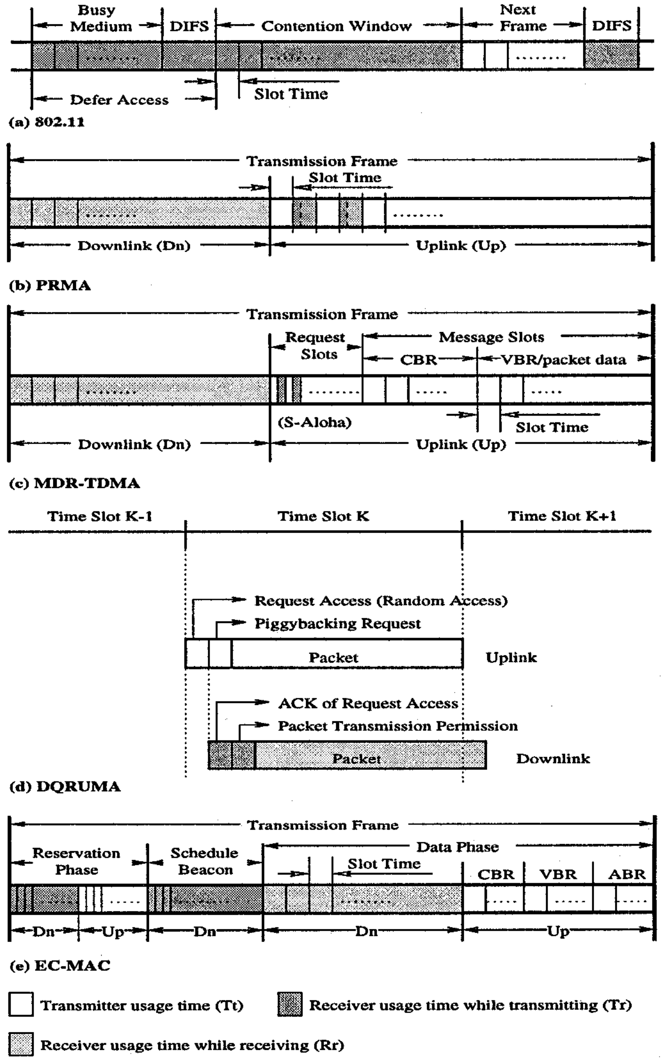

Fig. 1. Channel access methods for different protocols.

The multiservices dynamic reservation TDMA protocol (MDR-TDMA) [5], shown in fig. 1(c) supports CBR, VBR, and ABR traffic by dividing TDMA frames for different types of traffic and allocating them dynamically. The TDMA frame is subdivided int N_r request slots and N_t message slots. Each message slot provides for transmission of a packet or an ATM-like *cell.* Reques slots are comparatively short and are used for initial access in slotted ALOHA contention mode. Of the N_t message slots, a maximum of $N_v < N_t$ slots in each frame can be assigned for CB voice traffic. VBR and packet data messages are dynamically assigned one or more 48-byte slots in the TDMA interval followin the last allocated voice slot in a frame. The basic channel acces scheme follows a combination of circuit mode reservation of slot over multiple TDMA frames for CBR voice calls with dynami assignment of remaining capacity for VBR or packet data traffic In addition to first-come-first-served (FCFS) scheduling, time-of expiry (TOE) approach has been studied to improve delay perfor mance of real-time data traffic. Energy efficiency issues, however, are not specifically addressed in the protocol definition.

The distributed-queuing request update multiple access (DQRUMA) protocol [8] is shown in fig. 1(d). The base station employs a random access protocol and packet scheduling policy based on traffic and service requirements. Mobiles send a transmission request only when packet(s) join an empty queue. All subsequent packets that arrive at the queue can piggyback transmission requests. Two request access protocols have been studied: the ALOHA random access protocol, and a generalization of the Binary Stack Algorithm. The scheduling policy considered is a round-robin packet transmission policy. Since the slots are scheduled on a finer grain in DQRUMA, the requirement that the mobile should listen during every slot places a high burden on the mobile's power resources.

The protocol design of energy-conserving medium access control (EC-MAC) protocol [4] is driven by energy consumption, diverse traffic type support, and QoS support considerations. The protocol is defined using fixed-length frames since each mobile receiver will precisely know the time of the next beacon transmission. This enables the receiver to power off knowing precisely when the next frame will start. The frame is divided into multiple phases: reservation control phase, new-user phase, schedule beacon, and data phase. The reservation phase is made collisionless by letting the base station broadcast a list containing the set of the mobile IDs and the transmission order. During the uplink phase, each registered mobile transmits new connection requests and queue status of established queues according to the transmission order. The base station then broadcasts the transmission schedule for the data phase using a schedule beacon. Mobiles receive the broadcast and power on the transmitters and receivers at the appropriate time. The new-user phase allows new mobiles that have entered the cell coverage area to register with the base station. The comparison analysis in next section assumes that all mobiles in the cell coverage area have already registered with the base station. Fig. 1(e), therefore, does not incorporate the new-user phase.

A number of other access protocols for wireless multimedia networks based on ATM have been proposed in the literature, some of which are summarized in [10]. The protocols described here are chosen to represent the major categories of multiple access protocols for local area wireless networks.

4 Energy Consumption Comparison

This section characterizes the energy consumption during two major protocol activities at the mobile's MAC layer: packet transmission and reception. All the mobile transmissions are directed to, and all mobile receptions are received from the base station. For transmitting either single or periodic packets, T_r and T_t are defined as the average time spent using the receiver and transmitter, respectively. For receiving packet(s), the average receiver usage time is given by R_r.

We assume that time is slotted and the time necessary to receive or transmit a packet is L units of time, where L denotes the length of a data packet. When a reservation or contention packet is used to gain access to the medium, its length is assumed to be l units of time. The parameter a is the time spent decoding a slot while the mobile listens to the downlink for the packet destined to it. The system contains N mobiles. The analysis is based on how much energy a mobile needs for transmitting/receiving a packet or packets while there are other C contending mobile terminals with packet arrival rate λ. Table 1 summarizes the system parameters and definitions used in the analysis.

Name	Description
T_t	Average transmitter usage time while transmitting packet(s)
T_r	Average receiver usage time while transmitting packet(s)
R_r	Average receiver usage time while receiving packet(s)
L	Time to receive/transmit a packet
l	Time to receive/transmit a reservation/contention packet
a	Time spent decoding a slot
X	Number of slots sensed before receiving the packet destined to it
N	Number of mobile stations ($N > 0$)
C	Number of other contention stations ($C = N - 1$)
λ	Packet arrival rate per each mobile
Λ	Total transmission rate per mobile (newly generated + retransmitted)
G	Offered traffic load per mobile ($G = \Lambda L$)
p	Probability of a failure contention

Table 1. System Parameters

4.1 802.11

During packet transmission in 802.11, the mobile needs to listen to the medium until it is free. Fig. 1(a) indicates that the receiver is the most utilized resource. If the medium is active, the average time spent using the receiver is:

$$T_r = E[L] + E[\tau_1] \qquad (1)$$

where $E[L]$ is the *expected value* of time the receiver is turned on when some other mobile is currently transmitting its data packet $E[\tau_1]$ is the expected value of time spent using the receiver when this mobile stays in backoff procedure due to unsuccessful contention before capturing the medium. $E[L]$ can be obtained by:

$$E[L] = \frac{L}{2} + DIFS \qquad (2)$$

To evaluate $E[\tau_1]$, define the probability that some other mobile transmits in the contention window before this mobile does is P_{f1}, and the corresponding average time the receiver is utilized is T_{f1}. The probability that two mobiles sense the medium idle for a sufficient period of time, and attempt transmissions simultaneously is P_{f2}, and the corresponding average time the receiver is utilized is T_{f2}. The probability that it contends successfully is P_s, and the corresponding time receiver is turned on is T_s. Using *regenerative method* [11] to obtain $E[\tau_1]$ as follows:

$$E[\tau_1] = P_{f1}\left(T_{f1} + E[\tau_1]\right) + P_{f2}\left(T_{f2} + E[\tau_1]\right) + P_s T_s \qquad (3)$$

Solving equation (3) for $E[\tau_1]$ gives

$$E[\tau_1] = \frac{P_{f1}T_{f1} + P_{f2}T_{f2} + P_s T_s}{(1 - P_{f1} - P_{f2})} \qquad (4)$$

Let x be the slot that this mobile randomly chooses in the contention window, where $1 \leq x \leq K$ (K is the size of the contention window). If no one transmits in slots before x, this mobile captures the medium and transmits its packet. Therefore, $T_s = x$, for a given x. Assuming uniform probability of selecting a slot in the contention window,

$$T_s = \sum_{x=1}^{K} \left(\frac{1}{K}\right) x = \frac{K+1}{2} \qquad (5$$

If, on the other hand, the mobile detects transmission from other mobiles in time slot d, where $d < x$, it enters the backoff state again. In this case, the receiver is utilized for the duration of

d plus one more packet transmission time. We can estimate d by

$$\sum_{x=1}^{K} \frac{1}{K} \sum_{d=1}^{x-1} \frac{1}{x}\, d = \frac{K-1}{4} \tag{6}$$

Therefore,

$$T_{f1} = \frac{K-1}{4} + L + DIFS \tag{7}$$

When two mobiles attempt transmission simultaneously, d then equals x. Consequently,

$$T_{f2} = \frac{K+1}{2} + L + DIFS \tag{8}$$

To obtain P_{f1}, P_{f2}, and P_s, we calculate the probability (P_f) that $d \leq x$ first.

$$P_f = \sum_{x=1}^{K} \frac{1}{K} \times$$

$$\sum_{m=1}^{C} \left[\binom{C}{m} \left(1 - e^{-G}\right)^m \left(e^{-G}\right)^{C-m}\right] \left[1 - \left(\frac{K-x}{K}\right)^m\right] \tag{9}$$

In equation (9), the first term of the product represents the probability that some other mobile (or mobiles) also generates packet(s) before contention window begins. Some of the packets that arrive in the duration L before the contention window will have to enter the backoff procedure due to unsuccessful contention. As mentioned earlier, there are other C contending mobile stations, with the arrival of packets at each mobile as a Poisson process with rate λ. Let Λ ($\Lambda \geq \lambda$) be the rate of packet attempting transmission over the channel per user. This includes newly generated plus retransmitted packets. Following the analysis in [12], we assume that the composite message generation per user is Poisson distributed. Let G be the average number of total arrivals in the duration of L. Therefore, $G = \Lambda L$. The probability that a mobile is active during time interval L is then $(1 - e^{-G})$. The probability that m over C mobiles are active can be obtained by binomial distribution as above. The second term in equation (9) represents the probability some other mobile (or mobiles) chooses a slot d where $d \leq x$ thereby causing the mobile to enter backoff state again. Please note equation (9) holds for $C > 0$. When $C = 0$, P_f equals 0.

The probability that some other mobile (or mobiles) choose exactly the same time slot as the mobile under consideration does, i.e. $d = x$, is

$$P_{f2} = \sum_{m=1}^{C} \left[\binom{C}{m} \left(1 - e^{-G}\right)^m \left(e^{-G}\right)^{C-m}\right] \left[1 - \left(\frac{K-1}{K}\right)^m\right] \tag{10}$$

From equations (9) and (10), P_{f1} equals $(P_f - P_{f2})$. P_s can be obtained as the probability that there are no other arrivals at the other mobiles plus the probability that every other mobile where packets arrive chooses slot greater than x. P_s can be calculated as $(1 - P_f)$ as well. By replacing T_{f1}, T_{f2}, T_s, P_{f1}, P_{f2}, and P_s in equation (4), we can get $E[\tau_1]$. T_r in equation (1) can then be evaluated by equations (2) and (4).

During the backoff period, the transmitter is not used most of the time. The transmitter is utilized only when the mobile captures the channel or when two mobiles sense the medium idle for a sufficient period of time and attempt transmissions simultaneously, i.e. $d = x$. This will result in collision and will be resolved using backoff techniques. Assume the mobile detects the collision after one slot time. The average transmitter usage time is given by $T_t = E[\tau_2]$:

$$E[\tau_2] = p\,(T_f + E[\tau_2]) + (1-p)\,T_s \tag{11}$$

Solving equation (11) for $E[\tau_2]$ gives

$$E[\tau_2] = \frac{p\,(T_f - T_s) + T_s}{1-p} \tag{12}$$

where $T_f = 1$, $T_s = L$, and $p = P_{f2}$ is obtained from equation (10).

This regenerative method provides accurate performance prediction while also preserving model flexibility. More complicated or accurate arrival processes than Poisson can be obtained by appropriately obtaining P_{f1}, P_{f2}, and P_s values in equation (4), or p in equation (12).

During packet reception, the receiver has to be turned on during the entire downlink transmission. It reads the header of every downlink packet, and moves to standby mode if the packet is not destined for it. If the receiver senses X slots and a is the time spent decoding each slot, the receiver usage time is given by $R_r = aX + L$. Let A be the probability that the receiver senses this slot is destined to it. It is reasonable to assume that destinations of packets sent by the base station are uniformly distributed over all the mobiles in the cell. For N mobiles in the cell, A equals $\frac{1}{N}$. The expected number of slots a mobile has to receive before its intended packet is then obtained by

$$E[X] = N \tag{13}$$

Therefore,

$$R_r = aN + L \tag{14}$$

The analysis above is based on the transmitting and receiving of data packets. Since the 802.11 standard does not describe the handling of voice traffic, we ignore voice packets in our analysis of 802.11.

4.2 PRMA

The PRMA [7] system is closely related to reservation ALOHA. During packet transmission, both the transmitter and receiver are utilized. The mobile transmits its packet in the next slot after the packet is generated. If two or more mobiles transmit simultaneously in the same slot, collision results. It continues to transmit its packet until the base station acknowledges successful reception of the packet. As discussed above, L denotes the length of a data packet. Let L_A be the length of an acknowledgment. By applying the regenerative model, the average time spent using the transmitter can be obtained by replacing $T_f = T_s = L$ in equation (12):

$$T_t = \frac{L}{1-p} \tag{15}$$

In slotted ALOHA, all other packets arriving during previous slot are transmitted together in current slot. Therefore, p is evaluated as follows:

$$p = \sum_{m=1}^{C} \binom{C}{m} \left(1 - e^{-G}\right)^m \left(e^{-G}\right)^{C-m}, \quad C > 0 \tag{16}$$

where G is as defined previously. $p = 0$ if $C = 0$. Similarly, the average time spent using the receiver is:

$$T_r = \frac{L_A}{1-p} \tag{17}$$

During packet reception, the receiver has to be turned on during the entire downlink transmission to decode the intended receiver information. As discussed for 802.11, the receiver usage time is:

$$R_r = aN + L \tag{18}$$

The analysis above is based on the transmitting and receiving of one single packet. Suppose there are two different kinds of packets: data packet and voice packet. If each data packet needs to contend for transmission, T_t, T_r, and R_r for a data packet are same as those in equations (15), (17), and (18), respectively.

Voice packet, however, may reserve the same time slot in future frames until the end of talkspurts. Only the first packet needs to contend by sensing the medium. Voice traffic is modeled as a two-state Markov process representing a source with a *slow speech activity detector* (SAD) [13]. The probability that a principal talkspurt with mean duration t_1 seconds ends in a frame of duration t is

$$\gamma = 1 - e^{-t/t_1} \tag{19}$$

The probability that a silent gap with mean duration t_2 seconds ends in a frame of duration t is

$$\sigma = 1 - e^{-t/t_2} \tag{20}$$

If a voice source generates one voice packet in each frame, a talkspurt of t_1 seconds contains $\frac{t_1}{t}$ packets. Therefore, a talkspurt needs $\frac{t_1 L}{t}$ units of time to be transmitted. At the end of a talkspurt, another talkspurt may follow with probability $1-\gamma$, or the source may go silent with probability γ. Let $E[L_t]$ denote the expected value of time spent using the transmitter until the silent gap begins. $E[L_t]$ can be obtained by equation (12) by applying the regenerative model, where $p = 1-\gamma$, $T_f = \frac{t_1 L}{t}$, and $T_s = 0$. Therefore,

$$E\left[L_t\right] = \frac{p\,T_f}{1-p} = \frac{t_1 L}{t}\left(\frac{e^{-t/t_1}}{1-e^{-t/t_1}}\right) \tag{21}$$

We then get T_t and R_r for *talkspurts* as follows:

$$T_t = \frac{L}{1-p} + E\left[L_t\right] - L \tag{22}$$

$$R_r = aN + E\left[L_t\right] \tag{23}$$

where $E[L_t]$ can be obtained by equation (21). For voice packets, T_t is, in other words, equal to the average time it takes to transmit the first packet using contention $\left(\frac{L}{1-p}\right)$ plus the average time to transmit the rest of the talkspurts ($E[L_t] - L$). Once the first packet has successfully gained access to the medium, the receiver does not need to listen to the channel for the rest of the talkspurt(s). The subsequent packets in the talkspurt(s) will be allocated the same slot in the following frames. Thus, T_r for *talkspurts* is same as that in equations (17).

4.3 MDR-TDMA

The TDMA frame is subdivided into N_r request slots and N_t message slots in MDR-TDMA [5]. The frame structure is defined in fig. 1(c).

Let l denote the length of a contention packet in request slots and the length of an acknowledgment. In slotted ALOHA, all packets arriving in previous slot will be transmitted together in current slot. If packets are generated in the duration N_r and N_t, the probability that the first contention packet in N_r contends unsuccessfully is denoted by p_1. The probability p_1 is computed using equation (16) for $G_1 = \Lambda L N_t$. Other contention packets in N_r have the probability p', for $G = \Lambda l$. If all mobiles generate and retransmit packets only in N_r, $p_1 = p'$. By normalizing the contention period from all slots in the frame to slots in N_r only, we can use the regenerative model. The average time spent using the transmitter can be obtained by equation (12):

$$T_t = \frac{l}{1-p} + L \tag{24}$$

where p can be obtained by equation (16). The average time spent using the receiver is:

$$T_r = \frac{l}{1-p} \tag{25}$$

During packet reception, the receiver has to be turned on during the entire downlink transmission to decode the intended receiver information. As discussed for 802.11, the receiver usage time is

$$R_r = aN + L \tag{26}$$

The analysis above is valid for a single packet and for a data packet if data packets need to contend for an available slot each time. However, once a mobile transmits successfully a voice packe in an available slot, that slot in future frames can be reserved for this mobile until the end of talkspurts. By using the same model in PRMA, we then get T_t and R_r for *talkspurts* as follows:

$$T_t = \frac{l}{1-p} + E\left[L_t\right] \tag{27}$$

$$R_r = aN + E\left[L_t\right] \tag{28}$$

where $E[L_t]$ can be obtained by equation (21). T_r for *talkspurts* is same as that in equation (25).

4.4 DQRUMA

In DQRUMA [8], mobile users send transmission requests during a request-access (RA) subslot of every slot or piggybacked on to current data transmissions. Scheduling is done on a slot-by-slo basis and an explicit announcement at the beginning of each slo identifies the "owner" of next slot.

To transmit a packet, the initial request is sent using slotted ALOHA. The acknowledgment of successful reservation receip may follow in the subsequent slot. The mobile receiver has to be powered on for reception of this acknowledgment. Subsequen reservations may be piggybacked on to outgoing data packets. After the reservation is received, the receiver has to receive the downlink allocation information for every subsequent slot until the mobile is allocated transmission permission.

Let L denote the length of a data packet as before. Let l be the length of packets for RA, piggybacking, and transmission permission. By applying the regenerative model, the average time spen using the transmitter can be obtained by equation (12):

$$T_t = \frac{l}{1-p} + L \tag{29}$$

where p can be obtained by equation (16). Similarly, the average time spent using the receiver is:

$$T_r = \frac{l}{1-p} + \delta l \tag{30}$$

where δl is the average time while the receiver is utilized for transmission permissions. The value of δ depends on the scheduling algorithm executed in the base station.

To achieve downlink packet reception, the receiver has to be turned on during the beginning of each slot to decode the intended receiver information. As the discussion for 802.11, the receiver usage during reception is

$$R_r = aN + L \tag{31}$$

The analysis above is for the initial request packet. Once a mobile transmits the initial packet successfully, subsequent packets are requested by piggybacking until the queue is empty. Both data and voice packets are transmitted by this method in DQRUMA. T_t, T_r, and R_r can be obtained by following equations:

$$T_t = \frac{l}{1-p} + L + (\Delta - 1)\,(l + L) \tag{32}$$

$$T_r = \frac{l}{1-p} + \Delta \delta l \tag{33}$$

$$R_r = \Delta\ (aN + L) \tag{34}$$

where the value of Δ depends on the queue length. For voice talkspurts, Δ equals $E[L_t]$ in equation (21). However, δ depends on the scheduling algorithm executed in the base station.

4.5 EC-MAC

In EC-MAC [4], once a mobile gets admission to this cell coverage area using new-user phase, it listens to the downlink in reservation control phase for the transmission order. The mobile then sends out new connection requests and queue status of established queues by uplink in reservation control phase to the base station. The base station schedules the requests from mobiles, and then broadcasts the schedule that contains the slot allocations for the subsequent data phase. Mobiles, therefore, send out transmission requests and data traffic without collision after they have registered with the base station.

Let l be the length of packets used during reservation control phase and schedule broadcast phase. Mobile first listens to transmission order, and then sends out its request/update. After that, the mobile sends its packet in the data phase during its scheduled time. Therefore,

$$T_t = l + L \tag{35}$$

In the reservation control phase, mobile listens to downlink until it gets transmission order. The maximum time spent using the receiver is $l\ \eta$, where η is the maximum number of downlink transmission. Similarly, the maximum time the receiver is utilized during schedule reception is $l\ \psi$, where ψ is the maximum number of permissions in the schedule. The assumption here is that the downlink in reservation control phase and the schedule beacon are long enough to accommodate all mobiles. Simulation studies in [4] show the assumption is rational. The expected time receiver is turned on for sending a packet is given by:

$$2\,l \le T_r \le l\ (\eta + \psi) \tag{36}$$

To achieve downlink packet reception, the receiver has to be turned on during the schedule beacon. After the mobile gets the schedule, it powers on its receiver at the appropriate time in data phase. Let ψ be the maximum number of schedule beacon as discussed above.

$$l + L \le R_r \le l\,\psi + L \tag{37}$$

Note that the mobile only needs to listen to the schedule beacon once to determine its allocated slots in both uplink and downlink parts of the data phase. Therefore, equations (36) and (37) could be reduced to one of two possibilities: either R_r remains the same and T_r is reduced to

$$l \le T_r \le \eta\, l \tag{38}$$

or else, T_r is the same as (36) but R_r is equal to L.

The analysis above is valid for a single packet and for a data packet if data packets need to contend for an available slot each time. However, once a mobile successfully transmits a voice packet in an available slot, that slot in future frames can be reserved for this mobile until the end of the talkspurts. Using the same voice model as in PRMA, we get T_t and R_r for *talkspurts* as follows:

$$T_t = l + E\,[L_t] \tag{39}$$

$$l + E\,[L_t] \le R_r \le l\,\psi + E\,[L_t] \tag{40}$$

where $E[L_t]$ can be obtained by equation (21). T_r for *talkspurts* is same as that in equation (36).

5 Numerical Results

This section provides the numerical results for the comparison presented in last section. The results are obtained for a channel transmission rate of 2 Mbps. Voice traffic is coded with 32 Kbps. The length of a packet (L) is 64 bytes and the length of a contention packet (l) and acknowledgment (L_A) is 16 bytes. One slot time is 0.256 ms and length of slot is 64 bytes as well. For 802.11, the size of the contention window (K) is 64. The values of DIFS in 802.11 standard are 0.128 ms and 0.052 ms for frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS), respectively. Although figures with DIFS in FHSS are not shown, the results are almost identical to those in DSSS. T_t and T_r are shown for $G = 0.25$. Results were also studied for $G = 0.5$ and showed similar trends. Energy consumption for 2.4 GHz GEC Plessey radio card are also provided as a benchmark. The results indicate more of trends rather than absolute values.

Fig. 2 presents the transmitter and receiver usage times while transmitting a single packet. Please note the y-axis of figures are not in the same range. For 802.11, the mobile senses the medium before attempting to transmit. Collision occurs only when two or more mobiles choose the same slot in the contention window Hence, fig. 2 (a) indicates that the transmitter usage time is almost independent of the number of mobiles. However, the probability that the mobile under consideration contends successfully decreases as the traffic load increases. Fig. 2 (b) indicates that the receiver usage time increases as the number of mobiles increases

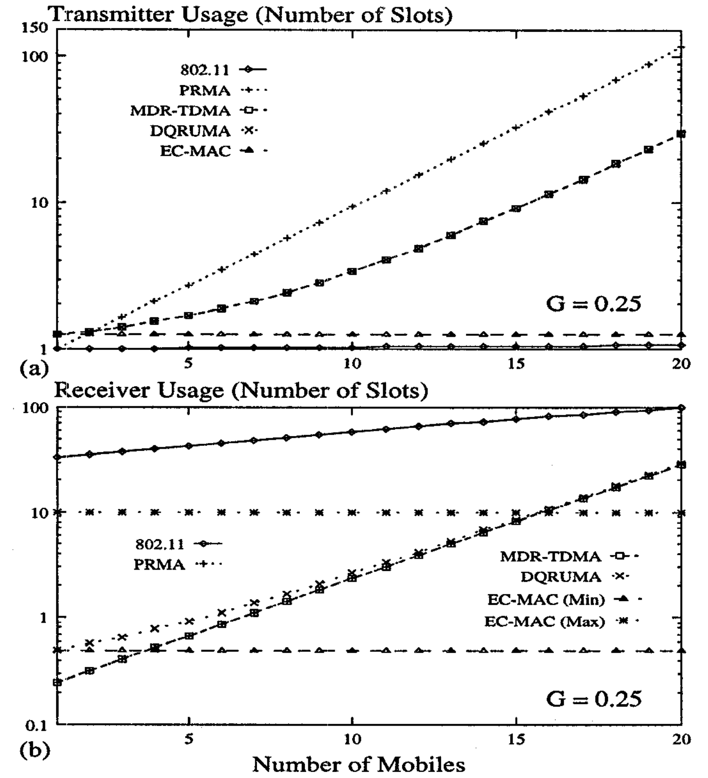

Fig. 2. (a) Transmitter usage time (T_t), and (b) receiver usage time (T_r) versus number of mobiles (N) for transmitting a single packet.

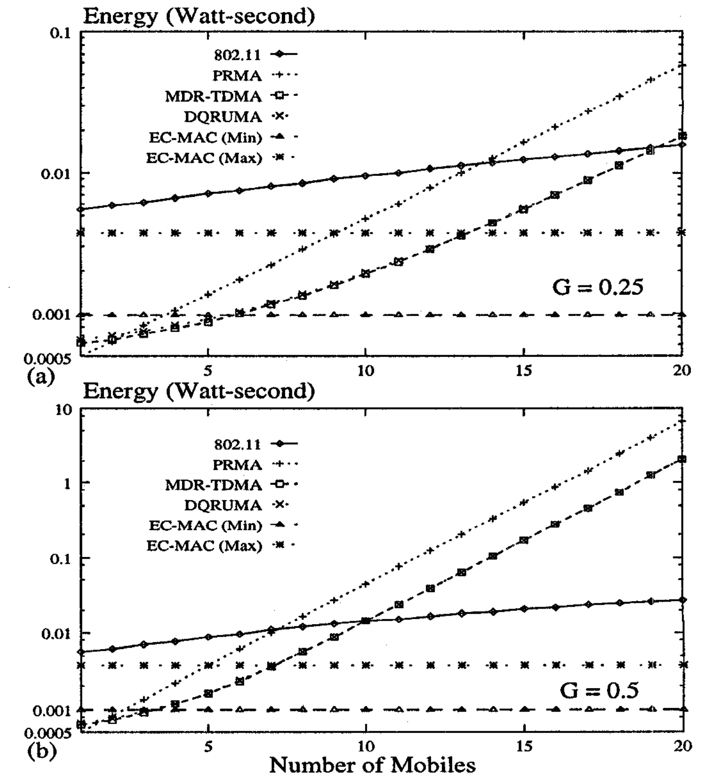

Fig. 3. Energy consumption versus number of mobiles (N) for transmitting a single packet by GEC Plessey 2.4 GHz radio. The figures are plotted for $G \in \{0.25, 0.5\}$.

Since the receiver is the most utilized resource in 802.11, fig. 2 shows the T_r in 802.11 is larger than others. T_t, on the other hand, is much less than other protocols.

For PRMA, both receiver and transmitter need to be powered on in the slotted ALOHA contention mode. The transmitter is utilized for a packet transmission duration and the receiver is turned on to receive the acknowledgment. As the traffic load increases, the packet may suffer more collisions. Therefore, both the receiver and transmitter usage times increase. MDR-TDMA and DQRUMA also use slotted ALOHA to contend for a channel, but they employ a much shorter packet length. Hence, the two protocols have the same characteristics as PRMA does except that the time usage is less. In fig. 2 (a), MDR-TDMA and DQRUMA have the same transmitter usage time. Because reservation ALOHA is used in MDR-TDMA, packets in MDR-TDMA know which slot to transmit after the initial contention. In DQRUMA, however, the mobile needs to listen to transmission permissions explicitly for every slot. Fig. 2 (b) presents the results for DQRUMA when the mobile only listens to one slot for permission. Depending on traffic load and scheduling policy, the mobile may need to listen to more than one slot. Therefore, values plotted for DQRUMA represent its lower bound.

Both the receiver and transmitter usage time remain constant in EC-MAC in fig. 2. Fig. 2 (a) indicates that transmitter usage time is quite small in comparison to other protocols. It is very close to 802.11 when the load is heavy. Fig. 2 (b) shows two lines for EC-MAC which are the minimum and maximum time for the receiver to be utilized while transmitting a packet. Depending on how long the mobile listens to the transmission order and schedule beacon, the receiver usage time may be greater or less than other protocols. The receiver usage time in EC-MAC, however, is independent of the traffic load.

Fig. 3 provides an approximate comparison of energy consumption while transmitting a single packet using GEC Plessey radio card. Adding fig. 2 (a) and fig. 2 (b) together with figures fo GEC Plessey card described above results in fig. 3 (a). Since MDR-TDMA and DQRUMA use the short packet for contention, they consume less energy than PRMA does. IEEE 802.11 senses the channel before transmission, reducing collision. However, it may need to sense several slots before it captures the medium. Therefore, 802.11 consumes more energy than PRMA, MDR-TDMA and DQRUMA do in lightly-loaded systems. On the other hand during heavy system traffic there might be too many contentions for slotted ALOHA. We can see that 802.11 performs better than MDR-TDMA and DQRUMA when there are around 10 mobiles in fig. 3 (b). Fig. 3 also shows that the energy consumption of EC-MAC is independent of the traffic load and number of mobiles. In fact, we see that even the upper bound of energy consumption o the EC-MAC protocol can be significantly less than other protocols for heavily-loaded systems.

Fig. 4 shows the time usage for a voice talkspurt which is around 84 packets. PRMA, MDR-TDMA, and EC-MAC have the slots assigned for voice traffic by reservation. In DQRUMA, subsequent requests for voice packets are piggybacked on to outgoing packets. Since the voice transmission in 802.11 standard is no defined, we do not consider it in this analysis.

Fig. 4 (a) and (b) examine the transmitter and receiver usage time while transmitting a voice talkspurt. The general trends fo PRMA, MDR-TDMA, and EC-MAC are similar to those for a single packet in fig. 2 (a) and (b) except that the transmitter must be powered on for all subsequent packets. In addition to voice packets DQRUMA requires piggyback requests for all subsequent packets

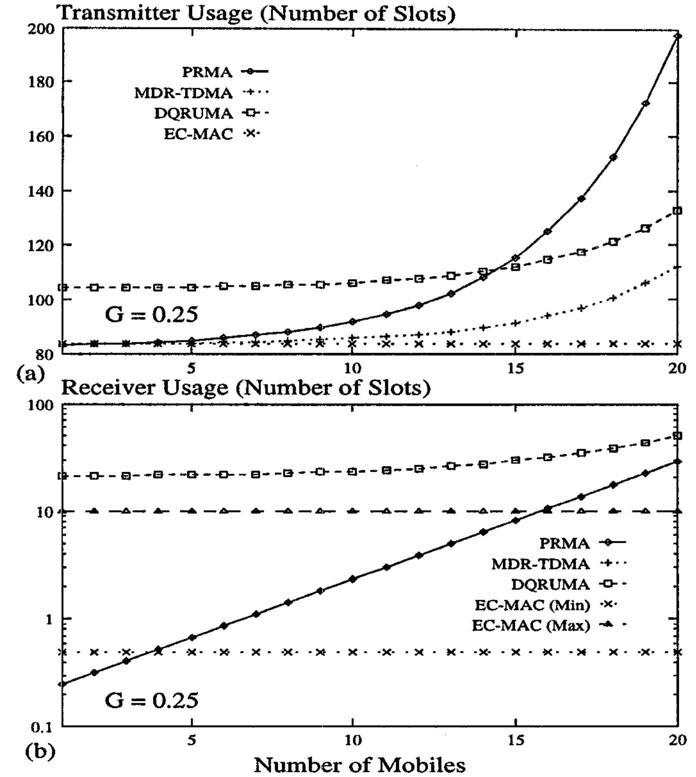

Fig. 4. (a) Transmitter usage time (T_t), and (b) receiver usage time (T_r) versus number of mobiles (N) for transmitting periodic packets.

as well. Hence, in lightly-loaded systems, the transmitter usage time for DQRUMA is higher than that for other protocols. We also note that DQRUMA performs better than PRMA in heavily-loaded systems. This is because PRMA transmits too many full-length packets for contention thus consuming more energy.

Fig. 4 (b) indicates that the receiver in DQRUMA needs to be turned on to receive transmission permissions for all voice packets. On the other hand, in PRMA, MDR-TDMA, and EC-MAC, the mobile has prior knowledge concerning its assigned transmission slot. In other words, it does not need to listen for permissions. The result of this difference between DQRUMA and the other protocols is that the receiver usage time in DQRUMA is higher than the others. We also see that DQRUMA performance is close to PRMA only when the offered traffic load is heavy. In fig. 4 (b), we assume DQRUMA only needs to listen to one slot for transmission permission. Depending on traffic load and scheduling policy, the mobile may need to listen to more than one slot resulting in a larger receiver usage time. Fig. 4 (b) indicates that PRMA and MDR-TDMA have the same receiver usage time. This is because we assume the length of acknowledgment in PRMA is identical to that in MDR-TDMA.

In general, we see that protocols should reduce the number of contentions. 802.11 senses the medium before transmitting. This results in fewer collisions than slotted ALOHA in PRMA. The receiver usage time, however, might be very large due to continuous or frequent medium sensing. Using short packet for contention also reduces the usage time for transmitter and receiver. In terms of energy conservation, reservation ALOHA is better than piggybacking for a message with contiguous packets. In DQRUMA, the explicit slot-by-slot announcement allows the base station to implement “optimal” and “just-in-time” scheduling. Because scheduling is done by a slot-by-slot basis, DQRUMA can potentially reduce packet latency. However, the additional burden placed on the receiver sub-system to receive and decode during every slot weakens this protocol from a practical perspective. EC-MAC, which was specifically designed with low power consumption goals, achieves this by eliminating contention during reservation transmission and by scheduling access.

6 Summary

This paper considers mobile battery power conservation from the medium access protocol perspectives in wireless networks. Energy conservation has typically been considered at physical layer issues, and to a certain extent at the access protocol level. The paper describes various energy conservation techniques proposed in different access protocols including IEEE 802.11, PRMA, MDR-TDMA, EC-MAC, and DQRUMA. The observations from the analysis and a qualitative comparison of the different protocols are presented. The analysis here shows that protocols that aim to reduce the number of contentions perform better from a energy consumption perspective. The receiver usage time, however tends to be higher for protocols that require the mobile to sense the medium before attempting transmission. For messages with contiguous packets, our analysis shows that reservation is more energy conservative than piggybacking.

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