Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks

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Abstract— **A family of medium access control protocols for single-channel packet radio networks is specified and analyzed. These protocols are based on a new channel access discipline called floor acquisition multiple access (FAMA), which consists of both carrier sensing and a collision-avoidance dialogue between a source and the intended receiver of a packet. Control of the channel (the floor) is assigned to at most one station in the network at any given time, and this station is guaranteed to be able to transmit one or more data packets to different destinations with no collision with transmissions from other stations. The minimum length needed in control packets to acquire the floor is specified as a function of the channel propagation time. The medium access collision avoidance (MACA) protocol proposed by Karn and variants of CSMA based on collision avoidance are shown to be variants of FAMA protocols when control packets last long enough compared to the channel propagation delay. The throughput of FAMA protocols is analyzed and compared with the throughput of non-persistent CSMA. This analysis shows that using carrier sensing as an integral part of the floor acquisition strategy provides the benefits of MACA in the presence of hidden terminals, and can provide a throughput comparable to, or better than, that of non-persistent CSMA when no hidden terminals exist.**

I. Introduction

Packet-radio networks based on a single common channel extend packet switching technology into environments with mobile users, can be installed quickly in emergency situations, and are self configurable [12]. As such, they are likely to play an important role in the future of computer communication. The medium access control (MAC) protocol with which packet-radios (or stations) can share a common broadcast channel is essential in a packet-radio network. The CSMA (carrier sense multiple access) protocols [11] have been used in a number of packet-radio networks in the past [12]; these protocols attempt to prevent a station from transmitting simultaneously with other stations within its transmitting range by requiring each station to listen to the channel before transmitting.

The hardware characteristics of single-channel packet-radios are such that a packet-radio cannot transmit and listen to the channel simultaneously. Because of this, such improved protocols as CSMA/CD (collision detection) [15] cannot be used in a single-channel packet-radio network. However, the throughput of CSMA protocols is quite acceptable, except in the case in which multiple transmitters within range of the same receivers cannot sense one another's transmissions [20]. Such "hidden terminal" problems degrade the performance of CSMA substantially, because carrier sensing cannot prevent collisions in that case, making the protocol behave essentially as the pure ALOHA protocol [1].

To address the problems of hidden terminals in single-channel networks, Karn [9] proposed a protocol called MACA (multiple access collision avoidance) which attempts to detect collision at the receiver by establishing a request-response dialogue between senders and intended receivers. When a sending station wants to transmit, it sends a request-to-send (RTS) to the receiver, who responds with a clear-to-send (CTS) if it receives the RTS correctly. Several other MAC protocols based on similar RTS-CTS exchanges, or RTSs followed by pauses, have been proposed [2], [7], [18] for single-channel wireless and wireline networks. Interestingly, none of these protocols specify any provision to prevent data packets from colliding with control packets (RTS and CTS packets).

In theory, the throughput of a MAC protocol based on an RTS-CTS dialogue can be improved by increasing the length of the data packet that follows each successful RTS-CTS exchange. However, in practice, different applications may utilize the same channel; therefore, while some applications can benefit from very large data packet sizes (e.g., transfers of video files), others do not (e.g., a telnet session). Furthermore, if the time it takes for a radio to transition from transmit to listen mode can take a few milliseconds, the effective duration of an RTS becomes comparable to the duration of a data packet in a high-speed terrestrial radio channel (e.g., 1Mbps), because the sender of an RTS takes on the order of an average data packet length to be able to receive the CTS it needs, regardless of how long an RTS and CTS lasts. Accordingly, enabling a transmitter to send multiple packets in the clear for each successful RTS-CTS exchange can be used to eliminate the hidden-terminal problems in CSMA while providing better throughput in low-speed or high-speed packet-radio networks than can be achieved by sending a single data packet per successful RTS-CTS exchange.

In this paper, we unify the basic schemes used in many MAC protocols for carrier sensing and collision avoidance into a new channel access discipline that we call FAMA (floor acquisition multiple access). The objective of a FAMA protocol is for a station that has data to send to acquire control of the channel (which we call the floor) before sending any data packet, and to ensure that no data packet collides

Supported in part by the Office of Naval Research under Grants N00014–92–J–1807 and N00014–94–1–0688

with any other packet. We show that the MACA protocol and its derivatives (e.g., MACAW [2]) become a variant of FAMA protocols when RTS and CTS transmissions last long enough. We also show that, contrary to what some previous approaches have suggested [2], [9], contention avoidance should be done at both sender and receiver, and that combining carrier sensing and the RTS-CTS exchange provides a very efficient MAC protocol that performs as well as MACA under the hidden-terminal situation, and as well as CSMA otherwise.

Section II introduces a couple of variants of FAMA protocols (MACA and FAMA-NTR). Section III demonstrates that both variants correctly enforce floor acquisition provided that RTSs and CTSs are of at least a certain minimum length. Section IV analyzes the throughput of such FAMA protocols and compares them against the throughput of non-persistent CSMA. Section V discusses other related work, and Section VI provides our conclusions.

II. FAMA Protocols

The objective of a FAMA protocol is to allow a station to acquire control of the channel (the floor) dynamically, and in such a way that no data packets ever collide with any other packet. This can be viewed as a form of dynamic reservations; however, in contrast to prior approaches to dynamic reservations, which are also called collision avoidance schemes (e.g., SRAM [21], MSAP [10] and BRAM [6]), the FAMA protocols presented in this paper do not require separate control sub-channels or preambles to reserve the channel. Instead, a FAMA protocol requires a station who wishes to send one or more packets to acquire the floor before transmitting the packet train. The floor is acquired using control packets that are multiplexed together with the data packets in the same channel in such a way that, although control packets may collide with others, data packets are always sent free of collisions.

There are many different schemes with which stations can acquire the floor, and any single-channel MAC protocol that does not require a station to sense the channel while it is transmitting can be adapted to support floor acquisition for our purposes.

A floor acquisition strategy based on an RTS-CTS exchange is particularly attractive in the control of packet-radio networks because it provides a building block to solve the hidden-terminal problem that arises in CSMA [20]. Within the context of using an RTS-CTS exchange for floor acquisition, there are many ways in which such control packets can be transmitted. We address only two variants in this paper.

- RTS-CTS exchange with no carrier sensing.
- RTS-CTS exchange with non-persistent carrier sensing.

The first variant corresponds to using the ALOHA protocol for the transmission of RTS packets; the second consists of using the non-persistent CSMA protocol to transmit RTS packets. We choose to consider non-persistent carrier sensing over persistent carrier sensing, because the throughput of non-persistent CSMA is much higher under high load and only slightly lower under low load than the throughput of p-persistent CSMA [11].

Although the original motivation for MACA was to solve the hidden-terminal problem of CSMA, the basic RTS-CTS dialogue of MACA, and even a four way handshake (RTS, CTS, data, acknowledgment) does not solve all hidden-terminal problems. For example, as Figure 1 shows, given three stations S,R and H, if H is "hidden" from S (i.e., S and H cannot hear each others transmissions) it could happen that S sends an RTS to R in the clear and R sends a CTS to S; the problem occurs when H transmits an RTS to R, or another station that can hear R and H, at the same time that R transmits its CTS to S. If that is the case, S will send data packets to R, and H may transmit an RTS that R can hear and that collides with S's data packets. Clearly, an ad-hoc solution would be to make H wait a very long time before attempting to retransmit, but that would degrade the network throughput. The four-way handshake advocated in the IEEE 802.11 [8] only helps to detect hidden-terminal interference *after* it occurs, it does not prevent it.

The RTS-CTS dialogue can be used as the building block to eliminate the hidden-terminal problem; however, this paper focuses only on using such a dialogue to establish a floor acquisition discipline, and focuses on single-hop networks in which no hidden terminals exist. The design of FAMA protocols for multihop packet-radio networks is addressed elsewhere; the basis for such protocols is the use of additional feedback from the receiver, in the form of CTSs and partial acknowledgments to packet trains.

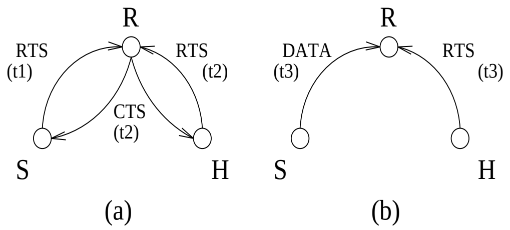

Fig. 1. Hidden-Terminal Example:
The transmissions from R and H collide at t_2, leading to a collision of S's data with H's RTS.

A. MACA

The first variant of FAMA that we address has been recently proposed by Karn [9] and has been called MACA (Multiple Access Collision Avoidance). According to MACA, a station that has a data packet to send first transmits a request-to-send packet (RTS) to the receiver. A station that receives a complete RTS that it can understand defers transmission for an amount of time specified in the RTS; upon reception of a correct RTS that is understood by the intended receiver, the receiver sends a clear-to-send packet (CTS) and waits long enough for the data packet to arrive from the sender. Figure 2 specifies MACA in detail, following from Karn's original description [9]. MACA and improvements over it are also discussed in detail in [2]. The key aspect of this variant of FAMA protocols that is important to highlight is that, as specified in [2] and [9], stations do not sense the channel before transmissions. A station defers its transmission only *after* it has received and understood a *complete* RTS or CTS (just as the ALOHA protocol permits a station to send a data packet whenever it is ready). As Figure 3 illustrates, without proper precautions, data packets can collide with RTSs. Section III demonstrates that the duration of an RTS must be at least twice the maximum channel propagation delay in order for MACA to ensure that data packets do not collide with RTS or CTS transmissions. MACA can also be modified to permit the transmission of packet bursts by enforcing waiting periods on stations proportional to the channel propagation time; these changes are straightforward and can be derived from the specification of

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Variable Definitions
        T_PROP = Propagation Delay across the channel
        T_RTS = Time to transmit an RTS packet
        T_CTS = Time to transmit a CTS packet
        T_DATA = Time to transmit a DATA packet

Procedure START()
Begin
        call PASSIVE()
End

Procedure PASSIVE()
Begin
        While(No Packet Received ∧ No Local Packet) wait;
        If(Packet Received) Then call REMOTE(received packet)
        Else call RTS();
End

Procedure RTS()
Begin
        Transmit RTS;
        Timer ← T_CTS + 2T_PROP;
        While(Timer not expired ∧ No Packet Received) wait;
        If(Timer expired) Then call BACKOFF();
        Else DO CASE of (received packet type)
        Begin
                Local CTS: call XMIT();
                Default: call REMOTE(received packet);
        End;
End

Procedure BACKOFF()
Begin
        Retransmit Timer ← 2 × Retransmit Timer;
        Timer ← RANDOM(0,Retransmit Timer);
        While(Timer not expired ∧ No Packet Received) wait;
        If(Timer expired) Then call PASSIVE();
        Else call REMOTE(received packet);
End

Procedure XMIT()
Begin
        Transmit Data Packet;
        Retransmit Timer ← 1;
        call PASSIVE();
End

Procedure REMOTE(packet)
Begin
        DO CASE of (packet type)
        Begin
                Local RTS:
                        Transmit CTS;
                        timer ← T_DATA;
                Other RTS:timer ← T_CTS;
                CTS:      timer ← T_DATA;
                DATA:
                        If(Local DATA) Then pass packet to upper layer;
                        call PASSIVE();
        End;
        While(Timer not expired ∧ No Packet Received) wait;
        If(Timer expired) Then call PASSIVE();
        Else call REMOTE(received packet);
End
```

Fig. 2. MACA Specification

FAMA-NTR, described next.

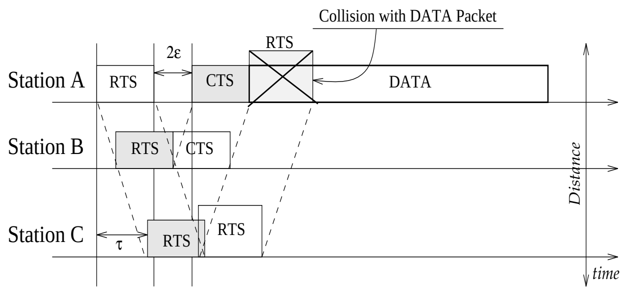

Fig. 3. MACA unsafe transmission:
An RTS from C collides with A's data packet due to differences in propagation time from A to B and from A to C and the length of RTS and CTS packets.

B. FAMA-NTR (Non-persistent Transmit Request)

The second variant of FAMA, which we call FAMA-NTR (Non-persistent Transmit Request) combines non-persistent carrier sensing with the RTS-CTS exchange of MACA. Figure 4 specifies FAMA-NTR in detail. When a station has one or multiple packets to deliver, it first listens to the channel. If the channel is busy, the station backs off and tries to retransmit at a later time using a random value for the backoff time; if the channel is clear (i.e., no carrier is detected), the station transmits an RTS. The sender listens to the channel for one round-trip time plus the time needed for the destination to send a CTS. If the CTS packet is corrupted or is not received within the time limit, the sender goes into the backoff state and tries to retransmit at a later time. When the originator receives the CTS from the destination, it begins its transmission of the data packet burst. The burst is limited to a maximum number of data packets, after which the station must release the channel and contend to re-acquire the floor. This variant of FAMA is similar to the protocol proposed for IEEE 802.11 [3], and Apple's Local Talk Link Access protocol [18].

FAMA-NTR enforces a waiting period on stations at strategic points in the operation of the protocol. Receiving stations (those stations in the REMOTE state) have a required waiting period of τ seconds after processing a data packet, to allow the current transmitting station the capability to send a burst of packets once it acquires the floor. A receiving stations' waiting period for any control packet is 2τ seconds; this is done to allow the RTS-CTS exchange to take place (see the timing for Station A during the successful transmission period in Figure 6).

Transmitting stations in the RTS state require a waiting period of 2τ seconds after transmitting their RTS to allow the destination to receive the RTS and transmit the corresponding CTS. A sending station must also use a waiting period of τ seconds after a final data packet to allow the destination to receive the complete packet and to account for the enforced waiting time at the destination. After the waiting period expires (assuming no further transmission on the channel, specifically, after a transmission period) all stations transition either to the PASSIVE state (if they have no packets pending) or the BACKOFF state (if a local packet is pending delivery). The channel becomes idle when all stations are in either the PASSIVE or BACKOFF state. The next access to the channel is driven by the arrival of new packets to the network and retransmission of packets that have been backed off.

Different backoff strategies can be adopted in the versions of FAMA addressed in this paper (e.g., see the one proposed for MACAW [2]). Exact distributions of the retransmission times are not necessary in our throughput analysis, which simply assumes that retransmissions are, on the average, long enough to make them independent of the original arrival of packets for transmission. Furthermore, stability and optimization of the channel (e.g, [14]) are not addressed in this paper.

The three-way handshake (i.e., RTS-CTS exchange followed by data packets) assumed in FAMA-NTR can also be extended to include an acknowledgment by the receiver after processing the last packet in the packet train. This four-way handshake is part of IEEE 802.11 and has also been proposed in MACAW.

III. Floor Assignment in FAMA along a Single Hop

For FAMA protocols to work correctly, they must ensure that all data packets delivered to the channel reach their proper destination without collisions. Theorems 1 and 2 below show this under the following assumptions:

- *A0)* The maximum end-to-end propagation time in the channel is $\tau < \infty$.
- *A1)* A packet sent over the channel that does not collide with other transmissions gets delivered free of errors to a station with probability $p > 0$.
- *A2)* A station transmits an RTS that does not collide with other transmission with probability $q > 0$.

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Variable Definitions
      CD = Carrier Detected
      T_PROP = Propagation Delay across the channel
      T_PROC = Processing time for carrier detection
      Burst = Number of packets to send in a burst

Procedure START()
Begin
      Timer ← to 2 × T_PROP;
      While(C̅D̅ ∧ Timer not expired) wait;
      If (CD) Then call REMOTE(2 × T_PROP + T_PROC);
      Else call PASSIVE()
End

Procedure PASSIVE()
Begin
      While(C̅D̅ ∧ No Local Packet) wait;
      If (CD) Then call REMOTE(2 × T_PROP + T_PROC);
      Else call RTS(2 × T_PROP)
End

Procedure RTS(T_σ)
Begin
      Transmit RTS Packet;
      Timer ← T_σ;
      While(C̅D̅ ∧ Timer not expired) wait;
      If (Timer Expired) Then call BACKOFF();
      Else Begin
            Receive Packet;
            DO CASE of (received packet type)
            Begin
                  CTS:        call XMIT();
                  Default:    call BACKOFF()
            End;
      End;
End

Procedure BACKOFF()
Begin
      Timer ← RANDOM(0,10 × T_RTS);
      While(C̅D̅ ∧ Timer not expired) wait;
      If (CD) Then call REMOTE(2 × T_PROP + T_PROC);
      Else call RTS(2 × T_PROP)
End
```

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Procedure XMIT()
Begin
      Burst ← maximum burst;
      While ((Burst > 0) ∧ Local Packet)
      Do Begin
            Transmit Data Packet;
            Burst ← Burst - 1;
      End;
      Timer ← T_PROP;
      While(Timer not expired) wait;
      If (Local Packet) Then call BACKOFF();
      Else call PASSIVE();
End

Procedure REMOTE(T_σ)
Begin
      Timer ← T_σ;
      While(C̅D̅ ∧ Timer not expired) wait;
      If (Timer Expired)
      Then Begin
            If (Local Packet) Then call BACKOFF();
            Else call PASSIVE();
      End
      Else Begin
            Receive Packet;
            DO CASE of (received packet type)
            Begin
                  RTS: call REMOTE(2 × T_PROP + T_PROC);
                  CTS:
                        If(Destination ID = Local ID)
                              Then Transmit CTS Packet;
                        call REMOTE(2 × T_PROP + T_PROC);
                  DATA:
                        If(Destination ID = Local ID)
                              Then pass packet to upper layer;
                        call REMOTE(T_PROP + T_PROC);
                  ERROR:   call REMOTE(2 × T_PROP + T_PROC)
            End
      End
End
```

Fig. 4. FAMA-NTR Specification

A3) All stations are within one maximum propagation delay (τ) of all other stations, i.e., there are no hidden terminals.

A4) All stations execute a FAMA protocol correctly.

A5) The transmission time of an RTS or CTS packet is γ, the transmission time of a data packet is δ, and the processing time is t_p, where $\gamma \leq \delta < \infty$, and $t_p < \infty$.

Theorem 1: FAMA-NTR ensures that each new data packet, or any of its retransmissions, is sent to the channel within a finite time after it becomes ready for transmission, and that a data packet does not collide with any other transmission, provided that $\tau < \gamma < \infty$.

Proof: By this theorem's assumption, an RTS lasts longer than the channel propagation time. Therefore, if an arbitrary station A is able to send its RTS to station B without colliding with other transmissions, all other stations must detect carrier before A ends transmitting its RTS and must enter the remote state, which forces them to enter a waiting period of longer than 2τ seconds (2 times the propagation time plus a maximum processing time) after detecting the end of station A's RTS transmission. Because the maximum channel propagation time is τ, a station other than B can receive A's RTS at most τ seconds before B does.

Therefore, given that station B's CTS can take at most τ seconds to reach all stations, the backoff time used in the remote state is long enough to make every station backoff again for station B's CTS, allowing only station A to use the channel if it receives station B's CTS with no errors. Accordingly, it follows that if an arbitrary station A sends a packet i to the channel, such a packet can collide with no other packet.

Let t_0 be the time when, in order to transmit packet i (which can be a new data packet or a retransmission), an arbitrary station A sends an RTS to station B. From assumptions A0 through A5, there must be a time t_1 such that $t_0 \leq t_1 < \infty$ when A sends an RTS that

(a) Forces all stations other than A to enter the remote state by time $t_2 = t_1 + \tau < \infty$ after detecting a carrier in the channel.

(b) Causes station B to send a CTS to station A by time $t_3 = t_2 + \gamma < \infty$.

(c) Makes station A start processing a CTS from B by time $t_4 = t_3 + \tau < \infty$ and send packet i by time $t_5 = t_4 + \gamma + t_p < \infty$.

It follows that, for any given packet, any station takes a finite time to send the packet in the channel, and that such packet does not collide with any other packets. □

Because in MACA a station must understand a packet before deferring transmissions and it takes up to τ seconds for a transmission to reach all stations, a station (call it C) may begin an RTS up to τ seconds after another station (call it A) has finished sending its RTS request intended for another station (call it B). In addition, the beginning of the RTS transmission from station C can take up to τ seconds to reach station A. Therefore, there is a maximum period of 2τ seconds between the end of stations A's RTS and the beginning of an RTS from C that can collide with A's RTS. If station B is very close to station A, it will respond with its corresponding CTS in a very short time ($\epsilon \ll \tau$) after the complete reception and processing of the RTS from A; in turn, this CTS will arrive at station A in ϵ seconds and the data packet from A will begin immediately after the processing of the CTS from B. As $\epsilon \to 0$, if $\gamma \leq 2\tau$, it is possible for station A to receive a correct CTS from B and send a data packet within 2τ seconds after the end of its RTS. This data packet collides with the RTS from C, which does not arrive at A until 2τ seconds after the end of A's RTS. Figure 3 illustrates this situation.

Theorem 2: MACA ensures that data packets do not collide with any other transmissions, provided that $2\tau < \gamma < \infty$.

Proof: If $\gamma > 2\tau$ (as shown in Figure 5), it is guaranteed that, at station A, the CTS sent by B to A will collide with station C's RTS. Here, stations A and B are close neighbors (B receives A's complete RTS in ϵ seconds, with $\epsilon \to 0$), and station C receives A's RTS in exactly τ seconds and B's transmission in at most τ seconds. After station A completes its clear transmission of an RTS to station B, B receives the entire RTS in ϵ more seconds, when it sends its CTS. The end of the CTS from B reaches A ϵ seconds after B stops its transmission. For station C to be able to begin transmitting its own RTS after A has started its RTS, station C must transmit in at most τ seconds after the completion of A's RTS, just before understanding A's RTS. The RTS from C reaches A in at most τ seconds (2τ seconds after the completion of A's RTS) and must collide with the CTS from B – even if $\epsilon = 0$ – because $\gamma > 2\tau$, causing the RTS-CTS exchange between A and B to fail and A to backoff and retry later. It follows that, if $\gamma > 2\tau$, station A cannot send a data packet if any other station starts an RTS within τ seconds of the end of A's RTS. Furthermore, every station must understand A's RTS in at most τ seconds if no other station sends an RTS before that time. Therefore, the theorem is true. □

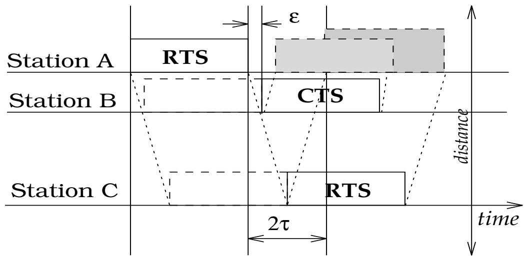

Fig. 5. MACA RTS/CTS collision

Under the conditions demonstrated in Theorems 1 and 2, both MACA and FAMA-NTR assign the channel dynamically to different stations in such a way that data packets are always sent in the clear. However, as the next section shows, using carrier sensing together with the RTS-CTS exchange provides substantial performance improvements over the basic MACA scheme.

Theorems 1 and 2 apply to the case in which stations transmit asynchronously. Alternatively, a global clock can be used to force all stations to start packet transmissions at the beginning of time slots.

In slotted MACA, the duration of a time slot should equal one RTS duration plus one maximum propagation delay, with all transmissions being of lengths that are multiples of such a slot time. With such slotting, any control packet transmitted at the beginning of a given slot is received in its entirety before another station is allowed to start transmitting any packet it has scheduled for transmission during the same slot. Therefore, if a station A sends an RTS during slot i, any other station scheduling an RTS transmission for slot $i+1$ must defer its transmission after receiving the intended RTS from A by the end of slot i. Accordingly, collisions of data packets and RTSs cannot occur in slotted MACA, and slotted MACA constitutes a variant of FAMA.

Slotting can also be applied in FAMA-NTR; i.e., in this case, the duration of a slot equals the maximum propagation delay and all packets have a duration that is a multiple of a slot duration. Therefore, if a station sends an RTS at the beginning of slot i, any station scheduling an RTS transmission for slot $i+1$ must detect carrier by the beginning of that slot and defer transmission. Accordingly, even if an RTS lasts τ seconds, data packets cannot collide with RTSs.

The above shows that the size of the RTS and CTS packets in relation to the data packets is critical to the efficient operation of a FAMA protocol. If the size of RTS and CTS packets approaches the size of the data packets, the overhead of the contention period will degrade the performance considerably. Therefore, RTS and CTS packets must be kept as small as possible compared to the size of data packets, while ensuring that RTS and CTS packets last longer than the maximum propagation time across the network when no slotting is used.

IV. Approximate Throughput Analysis

We present an approximate throughput analysis that assumes the same traffic model first introduced in [11] to analyze the throughput of CSMA protocols, and the conditions for floor acquisition derived in Section III. The protocols we analyze are non-persistent CSMA, MACA, FAMA-NTR, and the slotted versions of these FAMA protocols. The throughput of non-persistent CSMA used in this analysis was reported in [11].

A. Assumptions and Notations

There is an infinite number of stations who constitute a Poisson source sending RTS packets (for the case of FAMA), or new or retransmitted data packets (for the case of CSMA) to the the channel with an aggregate mean generation rate of λ packets.

Each station is assumed to have at most one data block to be sent at any time. In all protocols, a station transmits the entire data block as a single packet (which is the case of CSMA and MACA as it is described in [9]) or as multiple packets (which is the case of FAMA-NTR). The average size of a data block is δ seconds. RTS and CTS packets are of size γ seconds, and the maximum end-to-end propagation delay of the channel is τ seconds. Collisions (e.g., RTS packets in FAMA-NTR, data packets in CSMA) can occur in the channel, and we assume that, when a station has to retransmit a packet, it does so after a random retransmission delay that is much larger than δ on the average. The average channel utilization is given by [11]

$$S = \frac{\overline{U}}{\overline{B} + \overline{I}} \qquad (1)$$

where $\overline{B}$ is the expected duration of a busy period, defined to be a period of time during which the channel is being utilized; $\overline{I}$ is the expected duration of an idle period, defined as the time interval between two consecutive busy periods; and $\overline{U}$ is the time during a busy period that the channel is used for transmitting user data successfully.

The channel is assumed to introduce no errors, so packet collisions are the only source of errors, and stations detect such collisions perfectly. To further simplify the problem, we assume that any station can listen to the transmissions of any other station, that two or more transmissions that overlap in time in the channel must all be retransmitted, and that a packet propagates to all stations in exactly τ seconds [11]. The later assumption provides a lower bound on the performance of the protocols we analyze.

The time stations take to transition from transmit to listening mode and from listening to transmit mode is assumed to be negligible. This assumption is in agreement with implementation parameters in IEEE 802.11 [8]. When such turn-around times are not negligible, it is easy to show that the only impact on our approximated model is an increase in the effective duration of transmissions in the channel.

Of course, this model is only a rough approximation of the real case, in which a finite number of stations access the same channel, some stations may not be able to hear some other stations' transmissions, stations can queue multiple packets for transmission, and the stations' transmissions and retransmissions (of RTS or data packets) are highly correlated (e.g., a failed RTS is followed by another RTS within a bounded time, and a data packet is always preceded by a successful RTS). However, our analysis helps to understand why it is beneficial to listen for any type of channel activity, rather than for specific packet types, and provides additional insight on the performance of the FAMA protocols and the impact of channel speed, propagation delay, and hidden terminals on the floor acquisition technique. Our analysis favors CSMA and MACA, in that we assume that the applications accessing the channel can efficiently use data packets that are much longer than an RTS.

Insofar as the hidden-terminal problem is concerned, our analysis provides only an approximation of the performance that a modified FAMA-NTR would have in the two extreme cases in which either all or none of the sender-receiver interactions are affected by it. More specifically, we assume that every station can listen to the transmissions of any other station and our analysis of FAMA-NTR corresponds to the case in which no hidden terminals exist. However, when the sender of an RTS is unable to sense another station's RTS, a modified FAMA-NTR that can provide floor acquisition over multiple hops should behave much like MACA with no hidden terminals; therefore, MACA's throughput represents the worst case of a modified FAMA-NTR when all senders experience hidden-terminal problems.

B. FAMA-NTR

Figure 6 shows the transmission periods of FAMA-NTR. A transmission period begins with a source station transmitting an RTS at some time t_0. The transmission is vulnerable for a period of τ seconds, during which another RTS from some other station may collide with it, causing the transmissions to fail. After the vulnerability period, if no other station has transmitted, all other stations will sense the channel busy, defer their transmissions, and the RTS transmission will be successful. According to FAMA-NTR, the RTS is followed by the CTS response from the destination and the data packet(s) from the source. As Figure 6 illustrates, because of the enforced waiting times and idle periods discussed in Section II-B, a FAMA-NTR busy period is exactly one transmission period in length, either a successful or failed transmission, followed by an idle period.

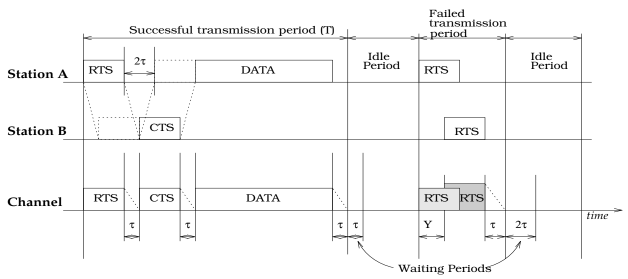

Fig. 6. FAMA-NTR transmission periods

Theorem 3: The throughput of FAMA-NTR is given by

$$S = \frac{\delta}{\gamma + \delta + \frac{(2-e^{-\tau\lambda})}{\lambda} + e^{\tau\lambda}(\gamma + 4\tau)} \tag{2}$$

Proof: A successful transmission consists of an RTS with one propagation delay to the intended recipient, a CTS and propagation delay back to the sender, and the data packet followed by a propagation delay. The time for a successful transmission, T, is then

$$T = 2\gamma + 3\tau + \delta \tag{3}$$

Because FAMA-NTR guarantees that data packets sent after a successful RTS will not collide with any other packet (Theorem 1), an unsuccessful transmission will consist of one RTS being sent to the channel at time t_0 followed by one or more RTSs transmitted by other stations within time Y (see Figure 6), where $0 \le Y \le \tau$, plus one final propagation delay. Therefore, as in non-persistent CSMA, the duration of the average failed transmission period is given by [11]

$$T_{FAIL} = \gamma + \tau + \overline{Y} \tag{4}$$

The cumulative distribution function for Y is the probability that no arrivals occur in the interval of length $\tau - y$ and equals $F_Y(y) = e^{-\lambda(\tau-y)}$[11] (where $y \le \tau$); therefore, the expected value of Y is [11]

$$\overline{Y} = \tau - \frac{(1-e^{-\tau\lambda})}{\lambda} \tag{5}$$

Substituting $\overline{Y}$ in (4), we obtain [11]

$$T_{FAIL} = \gamma + 2\tau - \frac{(1-e^{-\tau\lambda})}{\lambda} \tag{6}$$

The probability of success for an RTS equals the probability that no arrivals occur in τ seconds, because there is a delay across the channel of τ seconds before all the other stations in the network detect the carrier signal. After this vulnerability period of τ seconds, all stations detect the carrier signal in the channel and defer their own transmissions. Therefore, given that arrival of RTSs to the channel are Poisson with parameter λ,

$$P_S = \mathrm{P}\{\text{No arrivals in } \tau \text{ seconds}\} = e^{-\tau\lambda} \tag{7}$$

Because each FAMA-NTR busy period is always either a single successful or failed transmission period, the average busy period can be expressed as the percentage of successful transmission periods times the duration of T, plus the percentage of unsuccessful transmission periods times their average duration T_{FAIL}. Therefore,

$$\begin{aligned}\overline{B} &= T \cdot P_S + T_{FAIL} \cdot (1 - P_S) \\ &= e^{-\tau\lambda}(\gamma + \delta + \tau + \frac{(1-e^{-\tau\lambda})}{\lambda}) \\ &\quad + \gamma + 2\tau - \frac{(1-e^{-\tau\lambda})}{\lambda}\end{aligned} \tag{8}$$

The average utilization is the average amount of time during which useful data are sent during a successful busy period; therefore,

$$\overline{U} = \delta \cdot P_S = \delta e^{-\tau\lambda} \tag{9}$$

According to FAMA-NTR's definition, stations must incur a fixed time waiting period after each transmission period on the channel before making the transition to the PASSIVE or BACKOFF state (Figure 4). If the transmission period is a successful data packet, then the waiting period is τ; otherwise the waiting period is 2τ. Because the waiting period is directly related to the transmission period preceding it, the average waiting period can be expressed as the percentage of successful transmissions with a waiting period of length τ, plus the percentage of failed transmissions with waiting periods of length 2τ. Therefore, the average idle time $\overline{I}$ can be expressed by

$$\overline{I} = \frac{1}{\lambda} + \tau \cdot P_S + 2\tau \cdot (1 - P_S)$$
$$= \frac{1}{\lambda} + \tau e^{-\tau\lambda} + 2\tau(1 - e^{-\tau\lambda}) \tag{10}$$

Substituting Eqs. (8), (9) and (10) in (1), we obtain Eq. (2). □

C. Slotted FAMA-NTR

We consider slotted FAMA-NTR with the assumptions that the slot size equals the propagation delay τ, and that the duration of RTS, CTS and data packets are all exact multiples of τ. With slotting, stations are restricted to start transmissions only at slot boundaries. Figure 7 shows the transmission periods for slotted FAMA-NTR; arrivals of RTSs scheduled for transmission in the channel at the beginning of the next slot are indicated by vertical arrowheads. As in FAMA-NTR, slotted FAMA-NTR enforces a waiting period after each transmission period. A waiting period of τ seconds is required after a data packet is received, and a 2τ waiting period is required after any other transmission is heard on the channel. Again, as in FAMA-NTR, this limits the busy period to exactly one successful or failed transmission period.

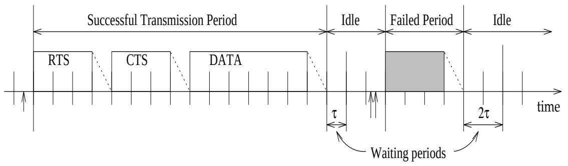

Fig. 7. Slotted FAMA-NTR transmission periods

Theorem 4: The throughput of slotted FAMA-NTR is given by

$$S = \frac{\delta\lambda\tau e^{-\lambda\tau}}{\lambda\tau e^{-\lambda\tau}(\gamma + \delta + \tau) + (1 - e^{-\lambda\tau})(\gamma + 3\tau) + \tau} \tag{11}$$

Proof: A successful transmission period (T) is made up of a clear RTS followed by a CTS and data packet. Therefore, T is given by Eq. (3).

A failed transmission period consists of one or more stations detecting no carrier and sending an RTS during a given slot. The failed period is the length of one RTS, and a slot used at the end for propagation delay. The total time of a failed transmission period is

$$T_{FAIL} = \gamma + \tau \tag{12}$$

For an RTS to be successful, it must be the only packet in the channel during its transmission. The probability of an RTS being sent in the clear is

$$P_S = \mathrm{P}\{\text{One arrival in a slot} \mid \text{Some arrivals in the slot}\}$$
$$= \frac{\lambda\tau e^{-\lambda\tau}}{1 - e^{-\lambda\tau}} \tag{13}$$

A busy period is made up of both successful and failed transmission periods. Because FAMA-NTR forces an idle period between each transmission (successful or failed) period, the duration of an average busy period equals the sum of the average transmission period size (which equals the percentage of successful transmission periods times their duration T), plus the percentage of unsuccessful transmission periods times their duration, T_{FAIL}. Accordingly,

$$\overline{B} = T \cdot P_S + T_{FAIL} \cdot (1 - P_S) \tag{14}$$

Substituting Eqs. (3), (12) and (13) into Eq. (14) gives

$$\overline{B} = (\gamma + \delta + 2\tau)\left[\frac{\lambda\tau e^{-\lambda\tau}}{(1 - e^{-\lambda\tau})}\right] + \gamma + \tau \tag{15}$$

The utilization of the channel is the data portion of the successful transmission period. Therefore, because a transmission period is successful with probability P_S and the data portion of such period is δ, we obtain

$$\overline{U} = \delta \cdot P_S = \delta\frac{\lambda\tau e^{-\lambda\tau}}{(1 - e^{-\lambda\tau})} \tag{16}$$

The idle period consists of consecutive idle slots preceded by the enforced waiting period after each transmission period, as defined in the FAMA-NTR specification. The number of consecutive idle slots has a geometric distribution whose mean is the same as that derived for non-persistent CSMA [11], [17] and is equal to $1/(1 - e^{-\lambda\tau})$. The average idle period is equal to the average number of consecutive idle slots plus the average enforced waiting period. Therefore,

$$\overline{I} = \tau \cdot \left(\frac{1}{1 - e^{-\lambda\tau}}\right) + (\tau \cdot P_S + 2\tau \cdot (1 - P_S))$$
$$= \frac{\tau - \lambda\tau^2 e^{-\lambda\tau}}{(1 - e^{-\lambda\tau})} + 2\tau \tag{17}$$

Substituting Eqs. (15), (16) and (17) into Eq. (1) we obtain Eq. (11). □

D. MACA

Figure 8 shows the transmission periods in MACA under the assumption that $\gamma > 2\tau$. Note that, because a station using MACA does not enforce any waiting times after transmission periods (see [2] and Figures 3, 5 and 8), the RTS and CTS specify how long stations should defer [9]. MACA does not use carrier sensing before transmitting an RTS, and a station can start transmitting an RTS (or CTS) even while another RTS has reached the station but has not been received in its entirety (this is similar to the operation of ALOHA [1]). However, a station that understands a clear RTS from another station defers its own transmission for the duration of the balance of a successful transmission period. Following this deferment, there is a random waiting period before transmission begins again. The random waiting time enforces an idle period after a successful transmission, the same as in FAMA-NTR. An unsuccessful period is also followed by an idle period, because any transmission attempt during (or adjacent to) the failed period would be included as part of the unsuccessful period. Therefore, it follows that a MACA busy period is limited to either a single successful transmission period, or a failed transmission period.

Theorem 5: The throughput of MACA is given by

$$S = \frac{\delta}{e^{\lambda(2\gamma+\tau)}\left[\gamma + \tau + \frac{1}{\lambda} + F\right] + e^{\lambda\tau}\left[\gamma + \frac{\tau}{2} + P(\tau - F)\right]}$$
$$\cdots \overline{+\delta + \frac{3\tau}{2} + F + P(\tau - F)} \tag{18}$$

$$\text{where } F = \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right]; P = \left[\frac{e^{-\lambda\gamma} - e^{-\lambda(\gamma+\tau)}}{(1 - e^{-\lambda(\gamma+\tau)})}\right] \tag{19}$$

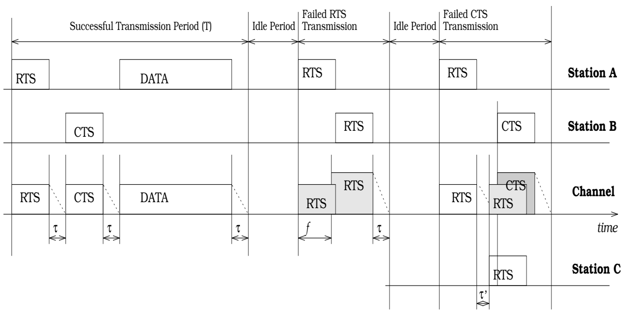

Fig. 8. MACA transmission periods

Proof: A successful transmission includes the RTS, CTS and data packet with a delay of τ seconds across the channel. Therefore, the size of a successful transmission is given by Eq. (3).

As stated above, a busy period is formed by a single transmission period. Under the assumptions that every packet takes τ seconds to reach all stations and that $\gamma > 2\tau$, RTSs and CTSs do not collide with data packets (Theorem 2), and an unsuccessful transmission period is made up of colliding RTSs and CTSs only. A failed period can take one of two possible scenarios in MACA. In the first case, the RTS that starts the busy period collides with one or more RTSs from other stations; in the second case, an RTS is received in the clear by the intended destination, but during the τ seconds of propagation delay incurred by the RTS, and prior to understanding the RTS, at least one other station has an arrival and transmits an RTS of its own that collides with the CTS sent in response to the first RTS of the busy period. In both cases, the length of the average failed transmission period is unbounded. In the first case, the length of a failed transmission period T_{FRTS} consists of only RTSs. In the second case, the average length of the failed period (T_{FCTS}) consists of an RTS; the average time of an RTS arrival within an interval of τ seconds after the end of the first RTS (τ'); a period of either failed RTSs (in which case its average is identical to T_{FRTS}), or if no RTS arrives once the CTS of the period begins, the time needed for a CTS to clear the channel.

Figure 9 illustrates in more detail the MACA failed RTS transmission period. The transmission period shown consists of four failed RTS packets; the time periods $f1$, $f2$, $f3$ are the interarrival times of the failed RTS packets. An average failed transmission period consists of a geometrically-distributed indefinite number (L) of interarrival times whose average duration is $\overline{f}$ seconds (the average time between failed arrivals), plus the duration of an RTS (γ) and τ seconds of propagation time. This is exactly the same as in pure ALOHA! The values for $\overline{L}$ and $\overline{f}$ are derived in [19] for pure ALOHA as functions of λ and, according to our notation, δ. Substituting γ for δ in such results we obtain $e^{\lambda\gamma}$ and $(\lambda\gamma)^{-1} - e^{-\lambda\gamma}/(1-e^{-\lambda\gamma})$, respectively. Therefore, when the first RTS of the period collides with other RTSs, the average time of a failed transmission period, T_{FRTS}, equals

$$T_{FRTS} = \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right] + \gamma + \tau \qquad (20)$$

The probability that a failed CTS transmission period ends when the failed CTS has cleared the channel is the probability that no other RTSs arrive to the channel once the CTS begins. This is the probability that there are no

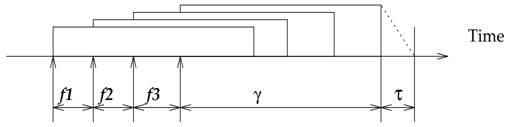

Fig. 9. A failed RTS transmission period in MACA

arrivals in γ seconds (the CTS duration) given that there has been at least one RTS arrival in $\gamma + \tau$ seconds (the time between the end of the RTS that started the period and the end of the corresponding CTS). Therefore,

$$\begin{aligned} P_{FCR} &= \frac{P\{\text{No arrivals in } \gamma\} \cdot P\{\text{at least one arrival in } \tau\}}{P\{\text{at least one arrival in } (\gamma + \tau)\}} \\ &= \frac{e^{-\lambda\gamma} \cdot (1 - e^{-\lambda\tau})}{(1 - e^{-\lambda(\gamma+\tau)})} \end{aligned} \qquad (21)$$

Because the arrival process is Poisson, arrival times during any given time interval are independent and uniformly distributed [22], which implies that, on the average, τ' equals $\tau/2$. Therefore the average length of a failed CTS transmission period is,

$$T_{FCTS} = \gamma + P_{FCR}(\gamma + 2\tau) + (1 - P_{FCR}) \cdot (T_{FRTS} + \tau/2) \qquad (22)$$

The probability of a successful transmission period (P_S) is the probability that a data packet is sent over the channel. This can happen only if an RTS and its corresponding CTS are transmitted without collisions. An RTS is sent in the clear if no other RTS is sent within γ seconds before or after it starts. Because that RTS takes τ seconds to reach all stations, its corresponding CTS is sent in the clear if no RTS is sent within τ seconds after the RTS. Therefore,

$$P_S = \mathrm{P}\{\text{No RTS arrivals in } 2\gamma + \tau\} = e^{-\lambda(2\gamma+\tau)} \qquad (23)$$

The probability that an RTS fails is simply the probability that RTS arrivals occur within the transmission time of another RTS, i.e., $P_{FRTS} = 1 - e^{-2\lambda\gamma}$.

The probability that a CTS fails is the probability that an RTS succeeds and at least one RTS is sent within τ seconds after the end of that RTS; therefore, colliding with the corresponding CTS, i.e., $P_{FCTS} = e^{-2\gamma\lambda}(1 - e^{-\lambda\tau})$.

Because a MACA busy period can be only a single successful transmission, or any of two types of unsuccessful transmission periods. Accordingly,

$$\overline{B} = T \cdot P_S + T_{FRTS} \cdot P_{FRTS} + T_{FCTS} \cdot P_{FCTS} \qquad (24)$$

Substituting P_S, P_{FRTS}, P_{FCTS}, T, T_{FRTS} and T_{FCTS} into Eq. (24) we obtain

$$\begin{aligned} \overline{B} = e^{-\lambda(2\gamma+\tau)} & \left[\delta + \frac{3\tau}{2} - \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right]\right. \\ & \left. - \frac{e^{-\lambda\gamma} \cdot (1 - e^{-\lambda\tau})}{(1 - e^{-\lambda(\gamma+\tau)})}\left(\tau - \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right]\right)\right] \\ & + e^{-2\gamma\lambda}\left[\gamma + \frac{\tau}{2} + \frac{e^{-\lambda\gamma} \cdot (1 - e^{-\lambda\tau})}{(1 - e^{-\lambda(\gamma+\tau)})}\left(\tau - \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right]\right)\right] \\ & + \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right] + \gamma + \tau \end{aligned} \qquad (25)$$

Because all arrivals to the channel, either new or retransmitted, are preceded by an RTS, the average idle period ($\overline{I}$) for MACA is equal to the average interarrival time of RTSs,

Protocol	*Unslotted version*	*Slotted Version*
CSMA [11]	$\frac{Ge^{-aG}}{G(1+2a)+e^{-aG}}$	$\frac{aGe^{-aG}}{1+a-e^{-aG}}$
MACA	$\frac{1}{e^{G(2b+a)}\left(b+a+\frac{1}{G}+F'\right)+e^{Gb}\left(b+\frac{a}{2}+P'\cdot(a-F')\right)+1+\frac{3a}{2}+F'+P'\cdot(a-F')}$ where $F'=\left[\frac{e^{Gb}-1-Gb}{Gb(1-e^{-Gb})}\right];P'=\left[\frac{e^{-Gb}-e^{-G(b+a)}}{(1-e^{-G(b+a)}}\right]$	$\frac{1}{1+4(b+a)+\frac{e^{G(b+a)}}{G}}$
FAMA-NTR	$\frac{1}{b+1+\frac{(2-e^{-aG})}{G}+e^{aG}(b+4a)}$	$\frac{Gae^{-Ga}}{Gae^{-Ga}(b+1+a)+(1-e^{-Ga})(b+3a)+a}$

TABLE I
Throughput Equations for CSMA and FAMA protocols

i.e., $\frac{1}{\lambda}$. As in the case of FAMA-NTR, $\overline{U} = \delta \cdot P_S$. Substituting Eq. (23) in $\overline{U}$ we obtain

$$\overline{U} = \delta e^{-\lambda(2\gamma+\tau)} \tag{26}$$

Substituting $\overline{U}$, $\overline{I}$, and $\overline{B}$ into Eq. (1) we obtain Eq. (19). □

E. Slotted MACA

The operation of slotted MACA is similar to MACA, except that a station that receives a packet to be sent cannot start its transmission until the next time slot. We assume that the duration of a slot in slotted MACA equals the size of an RTS or CTS packet (γ) plus a propagation delay τ. Figure 10 shows the transmission periods in slotted MACA versus time.

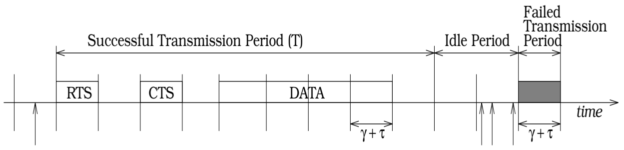

Fig. 10. Slotted MACA transmission periods

Theorem 6: The throughput of slotted MACA is given by

$$S = \frac{\delta}{\delta + 4(\gamma+\tau) + \frac{e^{\lambda(\gamma+\tau)}}{\lambda}} \tag{27}$$

Proof: The probability of success (P_S) equals the probability of having only one RTS in a given slot, given that there is a busy period, i.e.,

$$P_S = P\{1 \text{ arrival in a slot} \mid \text{at least one arrival in a slot}\}$$
$$= \frac{(\gamma+\tau)\lambda e^{-(\gamma+\tau)\lambda}}{(1-e^{-\lambda(\gamma+\tau)})}$$

The duration of an average successful transmission period (T) equals the number of slots used to resolve contention successfully, plus the slots containing the data packet (see Figure 10), i.e.,

$$T = \delta + 5(\gamma+\tau) \tag{28}$$

where $5(\gamma+\tau)$ accounts for: an RTS slot followed by the empty slot needed for the destination to schedule the CTS; the CTS slot, also followed by a slot for the originator to schedule the data packet; and an empty slot after the data packet where requests for the next period may occur. A successful transmission period can only begin if the RTS packet is sent collision free (i.e., the RTS is the only packet transmitted during a given slot).

Because we assume a slot size to be $\gamma+\tau$, all stations will hear a clear RTS before the next slot begins, and defer. In addition, RTS packets will only collide with other RTS packets in the same slot, and not CTS packets, or data packets. Therefore, a failed transmission period (T_{FAIL}) lasts $(\gamma+\tau)$ seconds (i.e., one RTS packet time plus the propagation delay, or one slot).

The probability that a busy period consists of l slots equals the probability that at least one arrival must be scheduled for transmission in the first $l-1$ slots and no arrivals can be scheduled for transmission in the last slot. This is geometrically distributed and equals

$$\text{P}\{\text{busy period has } l \text{ slots}\} = (1-e^{-\lambda(\gamma+\tau)})^{(l-1)} e^{-\lambda(\gamma+\tau)}$$

Therefore, the average number of slots a busy period contains is $\overline{l} = e^{\lambda(\gamma+\tau)}$. The average busy period is made up of both successful and unsuccessful transmission periods, and can be expressed in terms of the percentage of successful and unsuccessful slots from a set of $\overline{l}$ slots (see Figure 11). Therefore, the average busy period is

$$\begin{aligned}\overline{B} &= \overline{l}\,[T \cdot P_S + T_{FAIL} \cdot (1-P_S)] \\ &= e^{\lambda(\gamma+\tau)} \left[\left(\frac{(\gamma+\tau)\lambda e^{-(\gamma+\tau)\lambda}}{(1-e^{-\lambda(\gamma+\tau)})} \right) (\delta + 5(\gamma+\tau)) \right. \\ &\quad \left. + \left(1 - \frac{(\gamma+\tau)\lambda e^{-(\gamma+\tau)\lambda}}{(1-e^{-\lambda(\gamma+\tau)})} \right) (\gamma+\tau) \right]\end{aligned} \tag{29}$$

Because $\overline{l}$ is the average number of slots in a busy period, the average number of successful slots in a busy period is $\overline{l} \cdot P_S$. Therefore, given that each successful slot corresponds to the use of the channel for data traffic for δ seconds,

$$\begin{aligned}\overline{U} &= \overline{l} \cdot \delta \cdot P_S \\ &= \frac{\delta(\gamma+\tau)\lambda}{(1-e^{-\lambda(\gamma+\tau)})}\end{aligned} \tag{30}$$

The idle period is determined similarly to the case of slotted ALOHA [17], and is based on the RTS instead of the

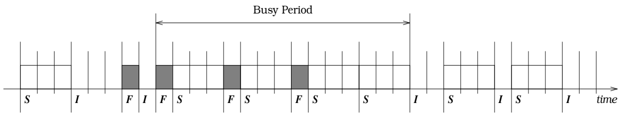

Fig. 11. Slotted MACA transmission periods.
S = The Beginning of a successful transmission.
F = The beginning of a failed transmission period.
I = The beginning of an idle period.

data packet

$$\overline{I} = \frac{(\gamma + \tau)}{1 - e^{-(\gamma+\tau)\lambda}} \tag{31}$$

Substituting Eqs. (29), (30) and (31) into Eq. (1) we obtain Eq. (27). □

F. Performance Comparison

To facilitate the comparison of the various protocols, we normalize the results obtained for S by making $\delta = 1$ and introducing the following variables

$a = \frac{\tau}{\delta}$ (normalized propagation delay)

$b = \frac{\gamma}{\delta}$ (normalized control packets)

$G = \lambda \times \delta$ (Offered Load, normalized to data packets)

Table I lists the normalized throughput equations for non-persistent CSMA and the two FAMA variants addressed in this paper.

We first compare the throughput of FAMA protocols with that of non-persistent CSMA, in both a low speed network (9600 b/s) and a high speed network (1 Mb/s), using both small data packets of 53 bytes (as in ATM cells) and longer packets of 296 bytes (as in a SLIP link). We assume a network with a maximum diameter of 10 miles, which gives us a propagation delay of approximately 54μs. The minimum size of RTSs and CTSs is 20 bytes to accommodate the use of IP addresses for destination and source, a CRC, and framing bytes. Table II shows the values of a and b used to approximate the results for the comparison. Figures 12 and 13 show the throughput (S) versus the offered load (G) for non-persistent CSMA and the FAMA protocols under these conditions. Figure 14 assumes a high-speed network of 1 Mb/s and packet trains of 10 SLIP packets for different propagation delays. Figure 15 shows the impact of b on the throughput of FAMA-NTR compared to non-persistent CSMA. The exact values assumed in the network parameters are not as important as the relative differences in throughput among the various protocols.

Network	a	b
Low Speed, small packets	0.0012	0.375
Low Speed, SLIP packets	0.0002	0.067
High Speed, small packets	0.127	0.375
High Speed, SLIP packets	0.022	0.067

TABLE II
FAMA PROTOCOL VARIABLES

Our results indicate the importance of using carrier sensing as an integral part of the floor acquisition strategy (see Figures 12 and 13). In the absence of hidden terminals FAMA-NTR provides a much higher throughput than MACA or slotted MACA, and its performance under high offered load in high-speed networks is even better than non-persistent CSMA. Of course, FAMA-NTR is more attractive for small values of $b = \gamma/\delta$, as shown in Figure 15. In practice, the effect of a small b can be obtained by allowing a station to transmit multiple packets per floor acquisition. Our results on MACA throughput are in agreement with the empirical simulation results presented in [2] for single-hop networks. In FAMA-NTR, slotting adds little performance improvement over the basic protocol. This should be expected, as slotting adds little benefit in non-persistent CSMA [11]. An interesting result, however, is that even with slotting, MACA does not match FAMA-NTR's performance.

The effect of the hidden-terminal problem can be appreciated indirectly in our analysis for the two extreme cases in which either all or none of the senders and receivers are affected by it, which provides a lower and upper bound on the network's throughput, respectively. Figures 12 and 13 show two curves for non-persistent CSMA for each throughput comparison. One corresponds to the values of a listed in Table II, and the other corresponds to $a = 1$. This throughput of non-persistent CSMA for $a = 1$ marked as CSMA (h.t.) is plotted to show the impact of hidden terminals. With hidden-terminals, the throughput of non-persistent CSMA becomes as low as the throughput of the ALOHA protocol (which has a maximum throughput of $\frac{1}{2}e \approx 0.18$), because stations are unable to sense the channel reliably and the vulnerability period of each packet is the whole packet. Under the same conditions, the throughput of a protocol similar to FAMA-NTR that can successfully prevent collisions of data packets with other packets can become no lower than the throughput of the MACA protocol, because even if the carrier sensing part of the floor acquisition strategy is unable to detect collisions due to the fact that stations cannot hear one another, the modified RTS-CTS exchange prevents data packets from colliding with any other packets. Hence, without hidden terminals FAMA-NTR achieves a throughput comparable to CSMA's; with hidden terminals, a modified RTS-CTS exchange in FAMA-NTR can achieve throughputs comparable to MACA under no hidden terminals. Of course, without some modifications, the throughput of both MACA and FAMA-NTR degrades with hidden terminals, because data packets can collide with RTSs from hidden terminals.

The importance of acquiring the floor (i.e., ensuring that data packets are sent without collisions) is also made clear by our results. In both low-speed and high-speed channels, it is clear that a larger throughput can be obtained with a larger ratio of δ/γ. Because transmitting very long data packets may not be appropriate in some applications using the network, allowing a station to send packet bursts in the clear after a successful RTS-CTS exchange becomes very attractive. Furthermore, once a station acquires the floor, it can send different packets to different receivers in support of multiple applications. Figure 14 further illustrates the importance of floor acquisition in the performance of the network for applications requiring either the transfer of large amounts of data (e.g., video transmissions) or the distribution of different information to different destinations. Again, a large ratio of δ to γ gives a high throughput in FAMA-NTR. For applications able to use larger packet trains, FAMA-NTR in a high-speed channel is even more effective than non-persistent CSMA.

It is also apparent that using MACA (or its derivatives) in low or high-speed channels to transfer single small packet (i.e., comparable to the size of an RTS) is not attractive at

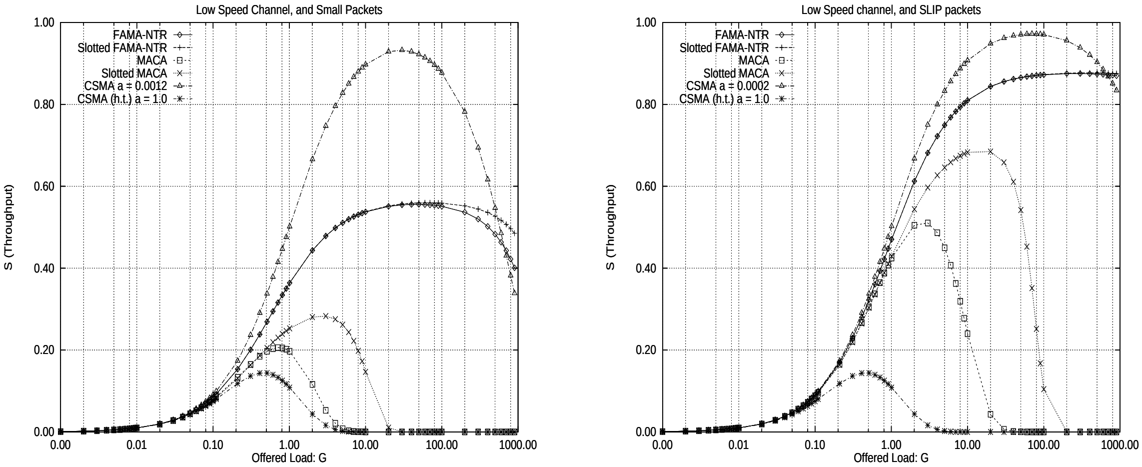

Fig. 12. Throughput of FAMA protocols in a low-speed network.

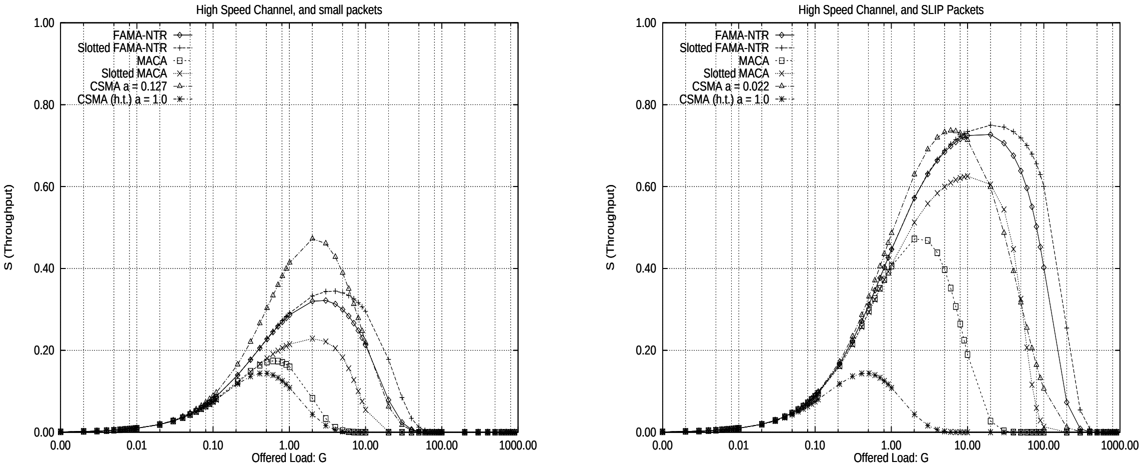

Fig. 13. Throughput of FAMA protocols in a high-speed network.

all. In such a case, the throughput of MACA is almost as low as what is expected in the ALOHA channel. That is, even though collisions are being detected at the receivers, the overhead incurred to do so is so large that the performance of the network is not much better than allowing a station to transmit its (small) packets whenever it is ready.

In conclusion, combining carrier sensing with RTS-CTS exchanges to assign a random access channel dynamically, and allowing stations to transmit finite packet bursts once they acquire the floor, is the best approach.

V. Related Work

There are several prior proposals for single-channel MAC protocols similar to the FAMA protocols we have discussed. As we have stated, the protocol used in Apple's local talk link access protocol [18] and the protocol proposed for IEEE 802.11 [8] use an RTS-CTS exchange with non-persistent carrier sensing. These protocols become FAMA-NTR when the duration of RTS packets is longer than the longest propagation time and a single data packet is sent after each successful RTS-CTS exchange.

Lo [13] and Rom [16] have proposed protocols similar to non-persistent CSMA that detect collisions by means of pauses. A station that senses the channel busy defers transmission, a transmitter that senses the channel idle starts transmitting but pauses during transmission and senses the channel. If the channel is sensed idle, the sender completes

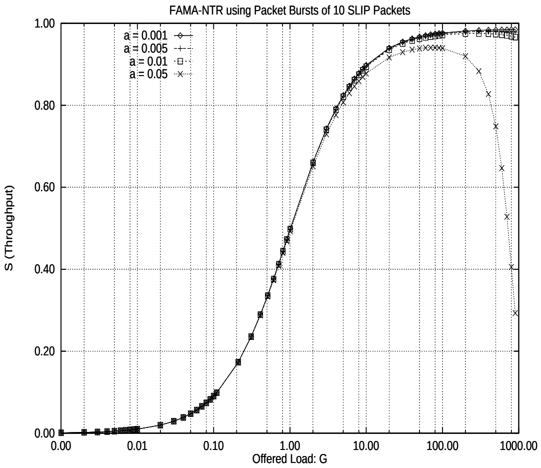

Fig. 14. Throughput of FAMA-NTR protocols for different values of a using a 10 packet train in a high-speed network.

its transmission; otherwise, the sender continues to transmit for a minimum transmission duration (called the collision detection interval or CDI). Unfortunately, this protocol does not guarantee that a station can sense all collisions [16]. Furthermore, these protocols cannot tolerate hidden terminals.

Another CSMA-like protocol based on the idea of sending a request signal and pausing to sense collisions was proposed by Colvin [7] and analyzed in [4]. This protocol, however,

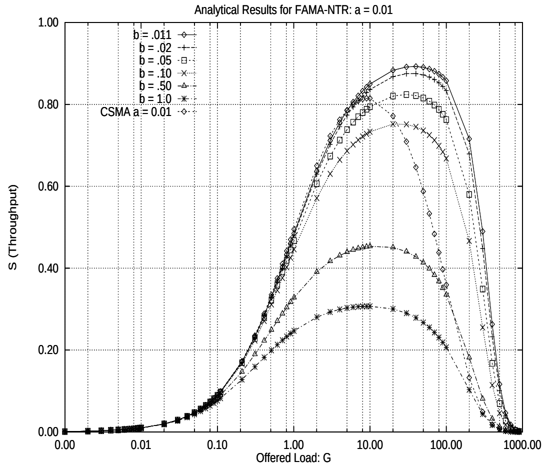

Fig. 15. Throughput of FAMA-NTR versus traffic for different values of b in a high speed network.

was designed for LANs in which stations can sense the channel while transmitting.

A number of techniques have been proposed in [2] to improve the performance of MACA [9], which constitutes a variant of FAMA using RTS-CTS exchange and no carrier sensing. These techniques consist of different retransmission strategies and additional handshaking between sender and receiver. The resulting protocol is called MACAW. Like MACA, MACAW is based on the basic premise that collisions are detected not by sensing the channel, but by the receivers being able to understand the transmissions they receive. Given that we have assumed the minimum RTS-CTS handshake of MACA and full connectivity in our analysis, our results on MACA provide an upper bound on MACAW's throughput. Chen [5] presents an approximate analysis of the modification of non-persistent CSMA that is part of IEEE 802.11 and based on a four-way RTS-CTS handshake. This analysis assumes that the RTS-CTS transmission cycle occupies a normalized time with respect to the duration of a data packet, and that CTSs are perfectly reliable and consume no overhead. This implies that the only source of losses for the protocol is the collision of RTSs. However, as our throughput analysis shows, collisions of CTSs with RTSs play an important role in the calculation of throughput.

VI. Conclusions

We have introduced and analyzed a new type of channel access discipline for single-channel packet-radio networks, which we call floor acquisition multiple access (FAMA). FAMA protocols permit a station to acquire control of the channel dynamically before transmitting data packets. The floor acquisition strategy is based primarily on a request-response (RTS-CTS) control dialogue between a sender and an intended proxy receiver. In addition, carrier sensing is used to increase substantially channel throughput.

Although many MAC protocols have been introduced in the past based on RTS-CTS exchanges, our analysis shows, for the first time, sufficient conditions under which an RTS-CTS dialogue becomes a floor acquisition strategy (i.e., one with which data packets are sent without ever colliding with other transmissions) with and without carrier sensing.

FAMA-NTR's throughput is that of non-persistent CSMA when all the senders wanting to transmit to a receiver can hear one another, and a modified version of FAMA-NTR that eliminates hidden terminals can have a throughput no lower than MACA's throughput with no hidden terminals. Slotting in the FAMA protocols analyzed provided substantial performance improvements only for the case of MACA (i.e., FAMA-NTR with hidden terminals). Our results clearly show that carrier sensing should be used together with the RTS-CTS handshake in MAC protocols for packet-radio networks.

Our work continues to analyze the behavior of FAMA protocols in multi-hop networks and to develop and analyze additional variants of floor acquisition strategies.

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