Floor Acquisition Multiple Access (FAMA) in Single-Channel Wireless Networks *

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The FAMA-NCS protocol is introduced for wireless LANs and ad-hoc networks that are based on a single channel and asynchronous transmissions (i.e., no time slotting). FAMA-NCS (for floor acquisition multiple access with non-persistent carrier sensing) guarantees that a single sender is able to send data packets free of collisions to a given receiver at any given time. FAMA-NCS is based on a three-way handshake between sender and receiver in which the sender uses non-persistent carrier sensing to transmit a request-to-send (RTS) and the receiver sends a clear-to-send (CTS) that lasts much longer than the RTS to serve as a "busy tone" that forces all hidden nodes to back off long enough to allow a collision-free data packet to arrive at the receiver. It is shown that carrier sensing is needed to support collision-free transmissions in the presence of hidden terminals when nodes transmit RTSs asynchronously. The throughput of FAMA-NCS is analyzed for single-channel networks with and without hidden terminals; the analysis shows that FAMA-NCS performs better than ALOHA, CSMA, and all prior proposals based on collision avoidance dialogues (e.g., MACA, MACAW, and IEEE 802.11 DFWMAC) in the presence of hidden terminals. Simulation experiments are used to confirm the analytical results.

1. Introduction

Multihop packet-radio networks (i.e., ad-hoc networks) extend packet switching technology into environments with mobile users, can be installed quickly in emergency situations, and are self configurable [16]. As such, they are

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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. CSMA (carrier sense multiple access) protocols [15] have been used in a number of packet-radio networks in the past [16]; 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 packet-radios are such that a packet-radio cannot transmit and listen to the same channel simultaneously; therefore, collision detection (CSMA/CD [18]) cannot be used in a single-channel packet-radio network. The throughput of CSMA protocols is very good, as long as the multiple transmitters within range of the same receivers can sense one another's transmissions. Unfortunately, "hidden terminal" problems [23] degrade the performance of CSMA substantially, because carrier sensing cannot prevent collisions in that case.

The busy tone multiple access (BTMA) protocol [23] was the first proposal to combat the hidden-terminal problems of CSMA. BTMA is designed for station-based networks and divides the channel into a message channel and the busy-tone channel. The base station transmits a busy-tone signal on the busy-tone channel as long as it senses carrier on the data channel. Because the base station is in line of sight of all terminals, each terminal can sense the busy-tone channel to determine the state of the data channel. The limitations of BTMA are the use of a separate channel to convey the state of the data channel, the need for the receiver to transmit the busy tone while detecting carrier in the data channel, and the difficulty of detecting the busy-tone signal in a narrow-band channel.

A receiver initiated busy-tone multiple access protocol for packet-radio networks has also been proposed [30]. In this scheme, the sender transmits a request-to-send (RTS) to the receiver, before sending a data packet. When the receiver obtains a correct RTS, it transmits a busy tone in a separate channel to alert other sources nearby that they should backoff. The correct source is always notified that it can proceed with transmission of the data packet. The limitations of this scheme is that it still requires a separate busy-tone channel and full-duplex operation at the receiver.

One of the first protocols for wireless networks based on a handshake between sender and receiver was SRMA (split-channel reservation multiple access) [24]. According to SRMA, the sender of a packet uses ALOHA or CSMA to decide when to send a request-to-send (RTS) to the receiver. In turn, the receiver responds with a clear-to-send (CTS) if it receives the RTS correctly; the CTS tells the sender when to transmit its data packet. Although SRMA was proposed with one or two control channels for the RTS/CTS exchange, the same scheme applies for a single channel.

Since the time SRMA was first proposed, several other medium access control (MAC) protocols have been proposed for either single-channel wireless networks or wireline local area networks that are based on similar RTS-CTS exchanges, or based on RTSs followed by pauses [2,27,8,17,19,21]. Karn [13] proposed a protocol called MACA (multiple access collision avoidance) to address the problems of hidden terminals in single-channel networks. MACA amounts to a single-channel SRMA using ALOHA for the transmission of RTSs; it attempts to detect collisions at the receiver by mans of the RTS-CTS exchange without carrier sensing. The IEEE 802.11 committee proposed a MAC protocol for wireless LANs that includes a transmission mode based on an RTS-CTS handshake (DFWMAC [6,12]).

Lo [17] and Rom [19] 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 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 [19].

Another CSMA-like protocol based on the idea of sending a request signal and pausing to sense collisions was proposed by Colvin [8] and analyzed in [4]. This protocol, however, was designed for LANs in which stations can sense the channel while transmitting.

In this paper, we introduce a new variation on MAC protocols based on RTS-CTS exchanges that is particularly attractive for ad-hoc networks. We call the new protocol FAMA-NCS (floor acquisition multiple access with non-persistent carrier sensing). The objective of FAMA-NCS is for a station that has data to send to acquire control of the channel in the vicinity of the receiver (which we call "the floor") before sending any data packet, and to ensure that no data packet collides with any other packet at the receiver.

Ensuring that floor acquisition is enforced among competing senders hidden from one another and who have requested the floor (i.e., sent an RTS) can only be achieved by the receivers. Accordingly, in FAMA-NCS, the length of a CTS is longer than the duration of an RTS and ensures that the CTS from a receiver lasts long enough for any hidden sender that did not hear the RTS being acknowledged to hear what amounts to a jamming signal from the receiver. Section 2 describes FAMA-NCS and a variant of FAMA based on packet sensing (i.e., the transmission of RTSs without carrier sensing), which amounts to MACA or SRMA using ALOHA.

Although the original motivation for such protocols as MACA, IEEE 802.11 DFWMAC, MACAW [2], and BAPU [27] was to solve the hidden-terminal problems of CSMA by using RTS-CTS handshakes, it is easy to show by example that simply introducing three-way handshakes (RTS-CTS-data) or even more complex handshakes (RTS-CTS-data-ACK or others) does not suffice to eliminate all instances in which two or more senders are led to believe that they can transmit data packets to their intended receivers, only to create collisions. This is the case even if carrier sensing and RTS-CTS based handshakes are used in combination. Section 3 verifies a sufficient condition for correct floor acquisition in single-channel networks with hidden terminals. We show that carrier sensing is necessary in protocols based on RTS-CTS handshakes to eliminate hidden-terminal problems efficiently in single-channel networks in which nodes can transmit control packets without using time synchronization.

Section 4 analyzes the throughput of FAMA-NCS in fully-connected networks and wireless LANs with hidden terminals. The objective of our analysis is to address several important questions: How useful is carrier sensing when RTS-CTS handshakes are used? What is the impact of the RTS-CTS overhead on the performance of the network? How important is the role of the CTS as a busy-tone signal? Our analysis shows that, with or without hidden terminals, protocols that use carrier sensing in combination with RTS-CTS handshakes attain higher throughput than protocols that do not use carrier sensing. In wireless LANs with hidden terminals, FAMA-NCS achieves higher throughput than ALOHA, CSMA, MACA, and DFWMAC, which is due to the CTSs acting as same-channel busy tones. Due to space considerations, we do not address the average delay of FAMA protocols; however, it is easy to show that FAMA protocols provide smaller average delays than CSMA [10].

Section 5 compares by simulation the performance of FAMA-NCS with MACAW and DFWMAC. Our results show very clearly that carrier sensing at the sender and the longer duration of CTSs compared to RTSs are critical to the performance and simplicity of MAC protocols based on RTS-CTS handshakes for networks with hidden-terminals in which nodes can transmit packets asynchronously. The simulations also help to validate our analytical results.

2. FAMA Protocols

2.1. Overview

FAMA-NCS 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 an an RTS-CTS exchange multiplexed together with the data packets in such a way that, although multiple RTSs and CTSs may collide, data packets are always sent free of collisions. The basic principles of floor acquisition are inspired on earlier work by Kleinrock and Tobagi on BTMA [23], the use of RTS-CTS exchanges first described for SRMA [24], and the provision of priorities among packets introduced for the transmission of priority acknowledgments in ALOHA and CSMA [25].

To acquire the floor, a station sends an RTS using either packet sensing or carrier sensing. The first variant corresponds to using the ALOHA protocol for the transmission of RTSs; the second consists of using a CSMA protocol to transmit RTSs. A station sends a CTS after receiving an error-free RTS addressed to it. When a station receives an error-free CTS, it knows that the floor has been acquired by the station to whom the CTS is addressed. After floor acquisition the floor holder is able to send data packets free of collisions over the channel. Any reliable link control scheme can be implemented on top of FAMA-NCS between the floor holder and the stations with whom it wishes to communicate. This is accomplished by forcing stations that do not have the floor to wait a predefined minimum amount of time (at least twice the maximum propagation delay) before being able to bid for the floor. This is similar to the schemes for the provision of priority acknowledgments proposed for CSMA and ALOHA by Kleinrock and Tobagi [25].

To ensure that floor acquisition is enforced among competing senders hidden from one another and who have requested the floor (i.e., sent an RTS), the CTS sent by a receiver is guaranteed to last long enough (or to be repeated enough times) to jam any hidden sender that did not hear the RTS being acknowledged.

This corresponds to a single-channel BTMA scheme in which sensing of error-free CTSs (for packet sensing) or the carrier of a CTS (for carrier sensing) over the data channel is used instead of the busy-tone signal.

When a station with data to send fails to acquire the floor or detects the floor being held by another station, it must reschedule its bid for the floor. This can be done using different persistence and backoff strategies. In this paper, we choose to consider non-persistent protocols over persistent protocols, 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 [15]. We also specify FAMA-NCS as using a uniform distribution when choosing backoff times; however, other backoff strategies can be adopted (e.g., see those proposed for MACAW [2]).

To simplify our analysis and description of FAMA-NCS, we do not address the effect of acknowledgments in the rest of this paper, and assume the simplest three-way handshake (RTS-CTS-data) with no acknowledgments.

2.2. FAMA-NCS

FAMA-NCS combines non-persistent carrier sensing with the RTS-CTS exchange. This is similar to SRMA with CSMA, IEEE 802.11 DFWMAC [3], and Apple's Local Talk Link Access protocol [21]. However, none of these and other protocols based on carrier sensing and RTS-CTS handshakes provide floor acquisition in networks with hidden terminals.

The length of a CTS in FAMA-NCS is larger than the aggregate of the length of an RTS plus one maximum round trip time across the channel, the transmit to receive turn around time, and any processing time. The length of an RTS is larger than the maximum channel propagation delay plus the transmit-to-receive turn around time and any processing time. This is required to avoid one station hearing a complete RTS before another has started to receive it. The relationship of the size of the CTS to the RTS gives the CTS *dominance* over the RTS in the channel. Once a station has begun transmission of a CTS, any other station within range of it that transmits an RTS simultaneously (i.e., within one propagation delay of the beginning of the CTS) will hear at least a portion of the dominating CTS (which acts as a jamming signal) and backoff, thereby letting the data packet that will follow to arrive free from collision. The dominating CTS plays the role of a busy tone.

Figure 1 shows how the *CTS dominance* operates in more detail. Station B is sending a CTS while station A is attempting to send its RTS and acquire the floor. Because stations use carrier sensing, A must send its RTS within τ seconds of the start of B's CTS; otherwise one of the stations would detect carrier and back off. Figure 1a) illustrates the case in which B's CTS arrives at A just as A begins its RTS transmission. Because B's CTS is longer than the RTS plus the transmit to receive turnaround time, A hears the overlap as noise (i.e., jamming) and backs off. Figure 1b) illustrates the other possible case, in which A can begin its RTS before B starts sending its CTS. A can start its transmission no earlier than τ seconds before B begins its CTS transmission; otherwise, A would have interfered with the RTS being sent to B and no CTS would have been transmitted by B. In this case, the CTS arrives at A 2τ seconds after A's RTS began. Again, because the CTS is longer than the RTS plus the transmit to receive turnaround time, A hears the end of the CTS as noise and backs off.

Figure 2 specifies FAMA-NCS in detail. The specification assumes that the turn-around times of the radios are longer than the maximum round-trip time between any two nodes that can hear each other, which is the case with existing commercial-off-the-shelf (COTS) radios operating in ad-hoc networks and wireless LANs.

A station that has just been initialized must wait the time it takes to transmit the maximum-size data packet in the channel plus one maximum round-trip time across the channel. This allows any neighboring station involved in the process of receiving a data packet to complete the reception un-obstructed. The initialization time also gives the station the ability to learn of any local traffic in progress. If no carrier is detected during the initialization period, the station transitions to the PASSIVE state. Otherwise, it transitions to the REMOTE state. A station can only be in the PASSIVE state if it is properly initialized (i.e., has no packet to send, and senses an idle channel). In all other states, the station must have listened to the channel for a time period that is sufficiently long for any neighbor involved in receiving data to have finished before transitioning to the PASSIVE state.

A station that is in the PASSIVE state and detects carrier on the channel transitions to the REMOTE state. Alternatively, a station that receives a packet to send in the PASSIVE state transmits an RTS and transitions to the RTS state. The sending station waits long enough for the destination to send the CTS. If the CTS packet is not received within the time allowed, the sender transitions to the BACKOFF state. If the sender hears noise on the channel after its RTS, it assumes a collision with a neighbor's dominating CTS and waits long enough for a maximum-length data packet to be received. Otherwise, upon receiving the CTS, the sender transmits its data packet. Because the CTS could be corrupted at the sender, once the destination station sends its CTS, it only needs to wait one maximum round-trip time to sense the beginning of the data packet from the source. If the data packet does not begin, the destination transitions either to the BACKOFF state (if it has traffic pending) or to the PASSIVE state.

In the BACKOFF state, if no carrier is detected during the entire backoff waiting period computed by the station, the station transmits an RTS and transitions to the RTS state as before. Otherwise, upon sensing carrier the station transitions to the REMOTE state.

For stations in the REMOTE state, FAMA-NCS enforces different waiting periods on passive stations (those stations not directly involved in the current transmission period) based on what was last heard on the channel. Any passive station that detects carrier transitions to the REMOTE state, and after the channel clears the waiting period is determined as follows:

- After hearing an RTS for another station, the station must wait long enough for a CTS to be transmitted by the destination and received by the sender, and the data packet to begin.
- After hearing a CTS from another station, the station must wait long enough to allow the other station to receive its data packet.
- After hearing a data packet, the waiting time is the enforced FAMA waiting period.
- After hearing noise (colliding control packets) on the channel, the waiting period must be long enough to allow another station time to receive a maximum size data packet.

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.

To increase the efficiency of the channel, a station that has successfully acquired the floor can dynamically send multiple packets together in a train, bounded by an upper limit. To allow this to be successful in a hidden-terminal environment, the destination station must alert its neighbors that it has more data packets coming, and for them to continue to defer their transmissions. FAMA-NCS uses a simple handshake mechanism to support packet trains.

If the sending station has multiple packets to send, it sets a MORE flag in the header of the data packet. When the destination receives the data packet and sees the MORE flag set, it immediately responds with a CTS, just as when hearing an RTS. This CTS alerts all neighbors that might interfere with the next data packet that they must continue to defer.

Additionally, stations in the REMOTE state must extend their waiting period after hearing a data packet with the MORE flag set to allow additional time for the sender to receive the CTS from the destination signaling that it can receive the next data packet.

2.3. FAMA-NPS

We present here a variant of FAMA that does not use carrier sensing and which we call FAMA-NPS (for non-persistent packet sensing). It basically amounts to MACA or a single-channel SRMA using ALOHA. Figure 3 specifies FAMA-NPS in detail.

Section 3 shows that, for a FAMA protocol with packet sensing to work with hidden terminals, the CTSs must be transmitted multiple times, which means that floor acquisition can be supported efficiently only in fully connected networks. Accordingly, our specification of FAMA-NPS assumes that it is used in a fully connected network and that a CTS is transmitted only once. RTSs and CTSs have the same duration, which is longer than one maximum round-trip delay.

A station that has a data packet to send and that is not expecting to hear a CTS or a data packet first transmits an RTS to the receiver. When a station processes a correct RTS, it defers transmission of any RTS for an amount of time specified in the RTS. If the RTS is addressed to the station, it sends a CTS and waits long enough for an entire data packet to arrive from the sender. Following the deferment specified by the RTS, a station with a packet to send waits a random waiting period before it transmits an RTS.

MACA and improvements over it are also discussed in detail by Bharghavan et al. [2].

The key aspect of this variant of FAMA protocols that is important to highlight is that, as specified by Bharghavan, et al. [2] and Karn [13], 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 8 illustrates, without proper precautions, data packets can collide with RTSs. Section 3 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 FAMA-NTR, described next.

3. Correct Floor Acquisition

3.1. Using Carrier Sensing

For FAMA-NCS to provide correct floor acquisition, it must ensure that that each new 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.

Theorem 1 below shows that FAMA-NCS provides correct floor acquisition if an RTS lasts longer than the maximum propagation delay and a CTS lasts longer than the time it takes to transmit an RTS, plus a maximum round-trip time and a maximum hardware transmit-to-receive transition time. We make the following assumptions to prove the theorem[1]:

A0) The maximum propagation time between any two stations that are within range of each other (i.e., can hear each other) is $\tau < \infty$.

A1) A packet sent over the channel that does not collide with other transmissions is delivered error free with probability $p > 0$.

A2) A station sends an RTS to the intended destination and receives a CTS in return that does not collide with any other transmission with probability larger than 0.

A3) All stations execute FAMA-NCS correctly.

[1] Similar results can be obtained under different assumptions using a similar approach to the one presented here.

A4) The transmission time of an RTS is $\gamma < \infty$, the transmission time of a CTS is $\gamma' < \infty$, the maximum transmission time of a data packet is $\delta < \infty$, the hardware transmit-to-receive transition time is $2\tau < \varepsilon < \infty$, and the receive-to-transmit transition time is 0.

A5) There is no capture or fading on the channel.

A6) Any overlap by transmissions at a particular receiver causes that receiver to not understand either packet.

Theorem 1. FAMA-NCS provides correct floor acquisition in the presence of hidden terminals, provided that $\gamma > \tau$ and $\gamma + 2\tau + \varepsilon < \gamma' < \infty$.

Proof: Figure 4 illustrates any possible case of hidden terminals with respect to a given pair of source S and receiver R. Station L characterizes any neighbor of S that is hidden from R but can cause interference at S. Station K characterizes any neighbor of L hidden from S that can cause interference at L and can prevent L from following S's dialogue with R. Similarly, Station X is a neighbor of R that is hidden from S but can cause interference at R; and station Y is a neighbor of X that is hidden from R and can prevent X from following R's dialogue with S. The proof must show that, if S sends a data packet to R, no other transmission can collide with it, regardless of the possible transmissions of other interfering nodes.

For S to be able to send data packets to R, it must first receive a CTS from R. Without loss of generality, assume that, at time t_0, S sends an RTS to R.

Because the channel has a minimum propagation delay larger than 0, any neighbor of S (e.g., Station L) must start receiving S's RTS at time $t_0^L > t_0$. If L receives S's RTS correctly, then it must back off for a period of time larger than $2\tau + \gamma'$ *after* the end of S's RTS reaches L, which means that L backs off for $\gamma + 2\tau + \gamma'$ seconds after t_0^L. Alternatively, if the RTS reaches L in error or Station K's transmission interferes with S's RTS at Station L, then, starting with the end of carrier, Station L must back off for a period of time larger than $2\tau + \delta$. The minimum amount of time that L must back off then corresponds to the case in which the end of carrier coincides with the end of S's RTS. Accordingly, L must back off for $\gamma + 2\tau + \delta$ seconds after t_0^L. It follows that the RTS sent by S at time t_0 forces any neighbor of S other than R to back off until time $t_1 > t_0 + \gamma + \gamma' + 2\tau$.

If the RTS is received at Station R with errors or collides with transmissions from other neighbors of R who are hidden from S (e.g., X), then R cannot send a CTS and S cannot send its data packet in return.

Assume that S's RTS is received correctly by R at time t_2. If S receives R's CTS with errors or the CTS collides with transmissions from neighbors of S hidden from R (e.g., L), then S cannot send its data packet.

For the rest of the proof, assume that the RTS that S sends at time t_0 is received error free at station R within one maximum propagation delay, which means that R must start sending its CTS to S at time $t_2 \leq t_0 + \gamma + \tau$ (given that zero processing delays are assumed). This CTS must reach S within one maximum propagation delay after R sends it. Therefore, S must receive R's entire CTS at time $t_3 \leq t_2 + \gamma' + \tau \ = t_0 + \gamma + \gamma' + 2\tau$.

Because $t_1 > t_3$, it follows that any potential interfering neighbor of S (e.g., L), must back off long enough for S to be able to receive R's CTS without collisions.

Station S must start to receive R's CTS no later than τ seconds after R starts its transmission, and must receive R's entire CTS and send its data packet at time $t_4 \leq t_2 + \tau + \gamma'$. In turn, Station R must receive the end of S's data packet by time $t_5 \leq t_4 + \delta + \tau \ \leq t_2 + 2\tau + \gamma' + \delta$.

On the other hand, any station X other than S within range of R must start receiving R's CTS at time $t_2^X > t_2$. If X receives R's CTS with no errors, then it must back off for a period of time larger than $2\tau + \delta$ *after* the end of R's CTS reaches X, which means that X backs off for $2\tau + \delta + \gamma'$ seconds after t_2^X. Conversely, if R's CTS reaches X in error or a transmission from one of its neighbors hidden from R, call it Y, interferes with the CTS, then, starting with the end of carrier, X must back off for more than $\delta + 2\tau$ seconds. The minimum amount of time that X backs off corresponds to the case in which the time when X detects the end of carrier equals the time when X receives R's entire CTS; therefore, X must back off for $2\tau + \delta + \gamma'$ seconds after t_2^X. It follows that the CTS sent by R at time t_2 forces X and any neighbor of R other than S to back off until time $t_6 > t_2 + 2\tau + \gamma' + \delta$.

Because $t_6 > t_5$, it follows that Station X and any other potential interfering neighbor of R must back off long enough for R to be able to receive S's data packet without collisions. Accordingly, it is true that FAMA-NCS allows a station to transmit a data packet only after a successful RTS-CTS exchange and no data packet collides with other transmissions. □

Our assumption that $\epsilon > 2\tau$ is not necessary to make a FAMA protocol be correct, but simplifies our equations and is consistent with the specifications of

COTS radios and IEEE 802.11. In theory, to make the CTS dominance technique applicable to any value of $\epsilon \geq 0$, we would only need to require the sender of a data packet to wait for 2τ seconds after receiving a correct CTS, and for stations that back off to allow a possible data packet to go through to increase the back-off time by 2τ seconds.

3.2. Using Packet Sensing

In FAMA-NPS a station must understand a packet before deferring transmissions and it takes up to τ seconds for a transmission to reach all stations. Therefore, 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. 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 $\epsilon \rightarrow 0$, 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 8 illustrates this situation.

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

Proof: Given a fully connected network of stations, consider a station A sending data to station B, and an interfering station C. If $\gamma > 2\tau$ (as shown in Figure 9), 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 $\epsilon \rightarrow 0$), 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. □

The following example illustrates that a MAC protocol based on an RTS-CTS exchange and no carrier sensing cannot support floor acquisition efficiently in the presence of hidden terminals, because CTSs must be repeated several times to ensure that data packets never collide with other packets. We assume that RTSs and CTSs have the same duration.

Assume that Station S sends an RTS that is received correctly at Station R, then R immediately begins transmission of a CTS to S. Figure 5 shows two cases where the CTSs are not understood by stations in R's neighborhood. In the first case, station X in Rs neighborhood transmits an RTS to R, blocking itself and all other stations in Rs neighborhood from understanding the first and second CTSs. In the second case, a station in the neighborhood of X (and not R or S) transmits an RTS that blocks Rs CTS from X allowing X to transmit an RTS itself blocking additional CTSs. In either case, at least X does not understand the CTS and can transmit an RTS that collides at R with the data packet from S if not enough CTSs are sent by station R.

To resolve the contention in the first case, the receiver needs to send at least three separate CTSs (Figure 5, Case 1). This is necessary, because a station considers the channel clear until any packet transmission is completely received free of error, and until that point there is no detection of traffic on the channel and transmissions are possible. Accordingly, station X can transmit its RTS just before the very end of receiving the CTS from R, and in the process also transmits over the beginning of the next CTS. X waits to get the CTS for it from R and instead sees the CTS to S, and defers further transmission.

In the second case, R must send at least five CTSs (Figure 5, Case 2). Here, the neighbor of X transmits an RTS that can collide with the first and second CTS blocking them from X, allowing it to send an RTS masking the third and fourth CTSs. The fifth CTS will be understood at X forcing it to defer after that point.

As the size of the network increases, any receiver R must send more and more CTSs to ensure that its neighbors are aware of its pending reception of a data packet, which renders the approach inefficient.

4. Comparative Throughput Analysis

4.1. Assumptions and Notations

We present an approximate throughput analysis that assumes the same traffic model first introduced for CSMA [15] to analyze the throughput of CSMA protocols, and the conditions for floor acquisition derived in Section 3.

As we have shown in Section 3, carrier sensing is needed to attain correct floor acquisition without sacrificing performance, which makes FAMA-NCS the only practical floor-acquisition solution; therefore, we analyze the throughput of FAMA-NCS only, and compare it against non-persistent ALOHA, CSMA, and MACA (i.e., FAMA-NPS). The throughput of non-persistent CSMA used in this analysis was reported by Kleinrock and Tobagi [15]. We have reported previously the throughput of FAMA-NPS [9]. We compare these protocols in fully-connected networks and wireless LANs with hidden terminals.

We assume that 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 per unit time. Any station can listen to the transmissions of any other station.

Each station is assumed to have at most one data block to send 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 [13]) or as multiple packets (which is the case of FAMA-NCS). The average size of a data block is δ seconds, RTSs last γ seconds, and CTSs last γ' seconds. The maximum propagation delay in the channel between any two stations that are within range of and can hear each other is τ seconds. Collisions (e.g., RTS packets in FAMA-NCS, 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 [15]

$$S = \overline{U}/(\overline{B} + \overline{I}) \tag{1}$$

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 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 [15]. To reduce the number of variables used, we also consider that the turn-around times (ϵ) are part of the packet times, and still include the propagation delays in our computations. This provides a lower bound on the performance of the protocols we analyze.

Of course, this model is only a rough approximation of the real case, in which a finite number of stations access the same channel, stations can queue multiple packets for transmission, and the stations' transmissions and retransmissions (of RTS or data packets) are correlated (e.g., a failed RTS is followed by another RTS within a bounded time). However, this model is a simple tool that helps us 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 FAMA protocols and the impact of channel speed and propagation delay on the floor acquisition technique.

For the case of non-persistent CSMA, we assume [15] that a separate perfect channel is used for acknowledgments to let a station know when its packet was received free of collisions, and that all acknowledgments are sent reliably Therefore, the throughput of non-persistent CSMA used for comparison with FAMA protocols is only an upper bound.

To facilitate the comparison of the various protocols numerically, the graphs showing average throughput versus traffic load normalize the results obtained for S by making $\delta = 1$ and introducing the following variables:

$$a = \tau / \delta (\text{normalized propagation delay}) \tag{2}$$

$$G = \lambda \times \delta (\text{offered Load, normalized to data packets}) \tag{3}$$

4.2. Throughput in Fully Connected Networks

Fig. 6 shows the transmission periods of FAMA-NCS. 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-NCS, a successful RTS is followed by the CTS response from the destination and the data packet(s) from the source. As Fig. 6 illustrates, because of the enforced waiting times and idle periods discussed in Section 2.2, a FAMA-NCS busy cycle is exactly one busy period in length, either a successful or failed transmission period, followed by an idle period.

Theorem 3. The throughput of FAMA-NCS is given by

$$S = \frac{\delta}{\gamma' + \delta + 2\tau + \frac{1}{\lambda} + e^{\tau\lambda}(\gamma + 4\tau)} \tag{4}$$

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. Accordingly, the time for a successful transmission, T, is

$$T = \gamma + \gamma' + 3\tau + \delta \tag{5}$$

Because FAMA-NCS guarantees that data packets sent after a successful RTS will not collide with any other packet, an unsuccessful transmission consists of one RTS being sent to the channel at time t_0, followed by one or more RTSs transmitted by other stations within a period of time of Y seconds (see Fig. 6), where $0 \leq Y \leq \tau$, plus one final propagation delay. Therefore, as in non-persistent CSMA, the duration of the average failed transmission period is given by [15] $T_{FAIL} = \gamma + \tau + \overline{Y}$. The cumulative distribution function for Y is the probability that no arrivals occur in the interval of length $\tau - y$ and equals [15] $F_Y(y) = e^{-\lambda(\tau - y)}$ (where $y \leq \tau$); therefore, the expected value of Y is [15] $\overline{Y} = \tau - (1 - e^{-\tau\lambda})/\lambda$.

The probability of success for an RTS, P_S, equals the probability that no arrivals occur in τ seconds, because there is a delay of τ seconds across the channel 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 the arrivals of RTSs to the channel are Poisson with parameter λ, we have

$$P_S = \mathrm{P}\{\text{no arrivals in } \tau \text{ seconds}\} = e^{-\tau\lambda} \tag{6}$$

A busy period is successful with probability $e^{-\tau\lambda}$, and its length equals $(\gamma + \tau) + (\delta + \gamma' + 2\tau)$, where $\gamma + \tau$ accounts for the duration of an RTS and one propagation time, and $\delta + \gamma' + 2\tau$ accounts for the corresponding CTS, data packet, and their propagation times. As can be appreciated from Fig. 6, on the other hand, the length of an unsuccessful busy period equals $\gamma + \tau + Y$. Therefore, given that $y = 0$ in a successful busy period, the length of the average busy period is

$$\overline{B} = e^{-\tau\lambda}(\gamma' + \delta + 2\tau) + \gamma + 2\tau - \frac{(1 - e^{-\tau\lambda})}{\lambda} \tag{7}$$

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

$$\overline{U} = \delta \cdot P_S = \delta e^{-\tau\lambda} \tag{8}$$

According to FAMA-NCS's definition, stations always incur a fixed time waiting period of 2τ seconds after each transmission period on the channel before making the transition to the PASSIVE or BACKOFF state (Fig. 2). Therefore, the average idle period can be expressed by

$$\overline{I} = \frac{1}{\lambda} + 2\tau \tag{9}$$

Substituting Eqs. (7), (8) and (9) in (1), we obtain Eq. (4). □

4.2.1. FAMA-NPS

Figure 7 shows the transmission periods in FAMA-NPS under the assumption that $\gamma > 2\tau$. Note that, because a station using FAMA-NPS does not enforce any waiting times after transmission periods (see [2] and Figures 8, 9 and 7), the RTS and CTS specify how long stations should defer [13]. 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 FAMA-NPS busy period is limited to either a single successful transmission period, or a failed transmission period.

Theorem 4. The throughput of FAMA-NPS is given by

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

$$\text{where } F=\left[\frac{e^{\lambda\gamma}-1-\lambda\gamma}{\lambda\gamma(1-e^{-\lambda\gamma})}\right]; P=\left[\frac{e^{-\lambda\gamma}-e^{-\lambda(\gamma+\tau)}}{(1-e^{-\lambda(\gamma+\tau)})}\right] \quad (10)$$

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. (5).

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 FAMA-NPS. 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 10 illustrates in more detail the FAMA-NPS 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 $\overline{f}$ have been previously derived [22] 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

$$T_{FRTS} = \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right] + \gamma + \tau \tag{11}$$

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 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,

$$\begin{aligned} P_{FCR} &= \frac{P\{\text{No arrivals in } \gamma\} \cdot P\{\text{at least one arrival in } \tau\}}{P\{\text{at least one arrival in } (\gamma + \tau)\}} \\ &= \frac{e^{-\lambda\gamma} \cdot (1 - e^{-\lambda\tau})}{(1 - e^{-\lambda(\gamma+\tau)})} \end{aligned} \tag{12}$$

Because the arrival process is Poisson, arrival times during any given time interval are independent and uniformly distributed [26], which implies that, on the average, τ' equals $\tau/2$. Therefore the average length of a failed CTS transmission period is,

$$T_{FCTS} = \gamma + P_{FCR}(\gamma + 2\tau) + (1 - P_{FCR}) \cdot (T_{FRTS} + \tau/2) \tag{13}$$

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,

$$P_S = \mathrm{P}\{\text{No RTS arrivals in } 2\gamma + \tau\} = e^{-\lambda(2\gamma+\tau)} \tag{14}$$

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 FAMA-NPS busy period can be only a single successful transmission, or any of two types of unsuccessful transmission periods. Accordingly,

$$\overline{B} = T \cdot P_S + T_{FRTS} \cdot P_{FRTS} + T_{FCTS} \cdot P_{FCTS} \tag{15}$$

Substituting P_S, P_{FRTS}, P_{FCTS}, T, T_{FRTS} and T_{FCTS} into Eq. (15) we obtain

$$\begin{aligned}\overline{B} = e^{-\lambda(2\gamma+\tau)} \Bigg[\delta + \frac{3\tau}{2} - \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right] \\ - \frac{e^{-\lambda\gamma} \cdot (1 - e^{-\lambda\tau})}{(1 - e^{-\lambda(\gamma+\tau)})} \left(\tau - \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right]\right)\Bigg] \\ + e^{-2\gamma\lambda} \left[\gamma + \frac{\tau}{2} + \frac{e^{-\lambda\gamma} \cdot (1 - e^{-\lambda\tau})}{(1 - e^{-\lambda(\gamma+\tau)})} \left(\tau - \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right]\right)\right] \\ + \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right] + \gamma + \tau\end{aligned} \tag{16}$$

Because all arrivals to the channel, either new or retransmitted, are preceded by an RTS, the average idle period ($\overline{I}$) for FAMA-NPS is equal to the average interarrival time of RTSs, i.e.,$\frac{1}{\lambda}$. As in the case of FAMA-NTR, $\overline{U} = \delta \cdot P_S$. Substituting Eq. (14) in $\overline{U}$ we obtain

$$\overline{U} = \delta e^{-\lambda(2\gamma+\tau)} \tag{17}$$

Substituting $\overline{U}$, $\overline{I}$, and $\overline{B}$ into Eq. (1) we obtain Eq. (10). □

We first compare the throughput of FAMA-NCS with that of non-persistent CSMA and FAMA-NPS in a fully connected network with a rate of 1 Mb/s, using both small data packets of 53 bytes (as in ATM cells) and longer packets of 400 bytes. We assume a network with a maximum diameter of 1 mile,[2] which gives

[2] In practice, much shorter diameters are to be expected.

a one-way propagation delay of approximately 5μs. The minimum size of RTSs is 20 bytes to accommodate the use of IP addresses for destination and source, a CRC, and framing bytes. Fig. 11 shows the throughput (S) versus the offered load (G) for the various protocols under these conditions. These results indicate the importance of using carrier sensing as an integral part of the floor acquisition strategy. FAMA-NCS provides a much higher throughput than FAMA-NPS (i.e., MACA) or slotted FAMA-NPS. Of course, FAMA-NCS is more attractive for small values of $b = \gamma/\delta$ (Figure 12). It is also clear that using MACA (or its derivatives) in low or high-speed channels to transfer a single small packet for each successful RTS-CTS exchange is inefficient.

4.3. Throughput in Wireless LANs

To study the performance of FAMA-NCS in wireless LANs with hidden-terminals, we adopt the same tractable model first used by Tobagi and Kleinrock [23] to analyze the impact of hidden terminals in CSMA. The model includes the same assumptions made in Section 4.1, and a system configuration consisting of a large number of terminals communicating with a single base station over a single channel. All terminals are within line-of-sight and range of the base station, but they may be hidden from one another. The population of terminals is partitioned into N *independent groups* [23], such that all terminals within the same group can hear one another and the base station, and any two terminals from different groups are hidden from each other. All traffic is directed from the terminals to the base station, and each group i consists of a large number of terminals who collectively form an independent Poisson source with an aggregate mean rate of λ_i floor requests per second, such that $\Sigma_{i=1}^{N}\lambda_i = \lambda$. The following theorem provides the throughput of the system as a function of λ_i, the rate of floor requests from a given group.

Theorem 5. The throughput of FAMA-NCS for a system with N independent and identically distributed groups of hidden terminals is given by

$$S = \frac{\delta \cdot \frac{1}{N}\sum_{i=1}^{N}\left(e^{-\lambda_i\tau}\prod_{j\neq i}^{N} e^{-\lambda_j(2\gamma)}\right)}{P_{SE}\cdot\left[e^{-\lambda_i\tau}\cdot(\delta+\gamma'+2\tau)+\gamma+\tau\right]+(1-P_{SE})\left(\left[\frac{e^{\lambda(\gamma+\tau)}-1-\lambda(\gamma+\tau)}{\lambda(\gamma+\tau)(1-e^{-\lambda(\gamma+\tau)})}\right]+\gamma+\tau\right)+\frac{1}{\lambda}+2\tau\cdot\frac{1}{N}\sum_{i=1}^{N}\left(e^{-\lambda_i\tau}\prod_{j\neq i}^{N} e^{-\lambda_j(2\gamma)}\right)}$$

$$\text{where } P_{SE}=\frac{1}{N}\sum_{i=1}^{N}\left(\prod_{j\neq i}^{N} e^{-\lambda_j(2\gamma)}\right) \quad (18)$$

Proof: Consider the time line for the base station; it consists of a sequence of busy and idle periods. Because FAMA-NCS provides correct floor acquisition, collisions can occur only among RTSs. Therefore, because no successful RTS can overlap at all with any other RTS and because a successful transmission period is detected by all groups and forces an idle time of 2τ seconds, a busy period consists of either a single failed transmission period or a single successful transmission period.

An RTS originated from any node s in Group i is successful if no other RTS from any group collides with s's RTS. Within Group i, the vulnerability period of s's RTS is τ seconds, because all nodes in Group i can detect carrier τ seconds after the beginning of the RTS. Accordingly, an RTS is successful within its own Group i with probability $e^{-\lambda_i \tau}$. In contrast, the vulnerability period of an RTS with respect to other groups is 2γ at the base station, because nodes in hidden groups cannot hear s's transmissions and all transmissions take τ seconds to reach the base station. Accordingly, an RTS is successful with respect to a Group j other than its own with probability $e^{-\lambda_j(2\gamma)}$. Because all groups are independent, it follows that an RTS from Group i is successful at the base station with the following probability:

$$P_{S_i} = e^{-\lambda_i \tau} \prod_{j \neq i}^{N} e^{-\lambda_j(2\gamma)} \tag{19}$$

Therefore, the probability that an RTS from any one group is successful equals

$$P_S = \frac{1}{N} \sum_{i=1}^{N} \left(e^{-\lambda_i \tau} \prod_{j \neq i}^{N} e^{-\lambda_j(2\gamma)} \right) \tag{20}$$

It also follows that, the probability that an RTS from any given group is successful with respect to the rest of the other groups at the base station is given by

$$P_{SE} = \frac{1}{N} \sum_{i=1}^{N} \left(\prod_{j \neq i}^{N} e^{-\lambda_j(2\gamma)} \right) \tag{21}$$

A successful transmission period in the time line of the base station lasts T seconds, which is given in Eq. 5.

There are two types of failed transmission periods. If only one of the groups sends RTSs in a transmission period, its average duration in the time line of the base station equals $T_{F_1} = \gamma + \overline{Y}$, where $\overline{Y}$ is the same as in the fully-connected network case. Note that T_{F_1} is not equal to T_{FAIL} of the fully-connected case, because nodes in a given Group i cannot hear RTSs from another group and can transmit at any instant after the end of a failed transmission period that does not involve Group i. Noting that $\overline{Y} \leq \tau$, we use the following bound for simplicity:

$$T_{F_1} \leq \gamma + \tau \tag{22}$$

If more than one group sends RTSs in a failed transmission period, the failed transmission period consists of multiple overlapping transmission periods with average durations of T_{F_1} seconds. Because groups are hidden and independent from each other, the length of the average failed transmission period in this case can be obtained by treating this case as an ALOHA channel with N stations, in which a station i corresponds to Group i and has an aggregate rate of λ_i. 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). The values for $\overline{L}$ and $\overline{f}$ are derived in [22] 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 transmission period collides with other RTSs, the average time of a failed transmission period, T_{FRTS}, equals

$$T_{FRTS} = \left[\frac{e^{\lambda\gamma} - 1 - \lambda\gamma}{\lambda\gamma(1 - e^{-\lambda\gamma})}\right] + \gamma \tag{23}$$

To make use of prior results, we make the simplifying assumption that N is very large. Accordingly, we approximate the average duration of the failed transmission period by substituting the upper bound of Eq. (22) for γ in Eq. (23), which yields

$$T_{F_2} = \left[\frac{e^{\lambda(\gamma+\tau)} - 1 - \lambda(\gamma + \tau)}{\lambda(\gamma + \tau)(1 - e^{-\lambda(\gamma+\tau)})}\right] + (\gamma + \tau) \tag{24}$$

Accordingly, the average busy period lasts

$$\overline{B} = P_{SE}\left(e^{-\lambda_i\tau}(T) + (1 - e^{-\lambda_i\tau})(T_{F_1})\right) + (1 - P_{SE})(T_{F_2}) \tag{25}$$

Substituting Eqs. (21), (22) and (24) in the above Eq., we obtain

$$\overline{B}=\frac{1}{N}\sum_{i=1}^{N}\left[\left(\prod_{j\neq i}^{N}e^{-\lambda_j(2\gamma)}\right)\left(e^{-\lambda_i\tau}(\delta+\gamma'+2\tau)+\gamma+\tau\right)\right]+\left(1-\frac{1}{N}\sum_{i=1}^{N}\left(\prod_{j\neq i}^{N}e^{-\lambda_j(2\gamma)}\right)\right)\left(\left[\frac{e^{\lambda(\gamma+\tau)}-1-\lambda(\gamma+\tau)}{\lambda(\gamma+\tau)(1-e^{-\lambda(\gamma+\tau)})}\right]+\gamma+\tau\right) \quad (26)$$

The average idle period lasts 2τ seconds after every successful data packet transmission plus an average interarrival time of RTSs from all groups; therefore, we have

$$\overline{I}=\frac{1}{\lambda}+2\tau\cdot P_S \quad (27)$$

The average utilization time is simply the proportion of time in which useful data are sent during a successful busy period, and

$$\overline{U}=\delta\cdot P_S \quad (28)$$

Substituting Eqs. 26, 27, and 28 into Eq. 1, we obtain the desired result. □

In the limit, as $N \rightarrow \infty$, we obtain that the average throughput in any given system becomes

$$S=\frac{\delta}{\delta+\gamma'+\gamma+5\tau+(e^{2\lambda\gamma}-1)\left(\left[\frac{e^{\lambda(\gamma+\tau)}-1-\lambda(\gamma+\tau)}{\lambda(\gamma+\tau)(1-e^{-\lambda(\gamma+\tau)})}\right]+\gamma+\tau\right)+\frac{e^{2\lambda\gamma}}{\lambda}} \quad (29)$$

The above result is just what should be predicted from the fact that FAMA-NCS supports correct floor acquisition. Together with Eq. 4, the above result indicates that, as the number of hidden terminals increases with respect to any given group, FAMA-NCS degrades to the case in which the vulnerability period of an RTS becomes twice the length of the RTS, rather than the propagation delay. This is exactly the type of behavior of a packet-sensing FAMA protocol operating in a fully-connected network. Note that, because $\gamma << \delta$, this behavior is far better than the degradation experienced by CSMA, in which the vulnerability period of a packet becomes twice its length, which is the behavior of the ALOHA channel.

To visualize the above results, we compare FAMA-NCS and CSMA in wireless LANs with independent groups hidden from one another, and with one common central station. This type of experiment is similar to the ones used by Tobagi and Kleinrock [23].

Fig. 13 shows the maximum attainable throughput of ALOHA, slotted ALOHA, non-persistent CSMA, and FAMA-NCS versus an increasing number of independent groups (N). The results indicate that, FAMA-NCS's performance under hidden terminals becomes that of a packet-sensing FAMA protocol operating in a fully connected network, which is exactly the desired result. In contrast, as has been reported by Kleinrock and Tobagi [23], CSMA quickly degrades to ALOHA.

Another way to look at the behavior of FAMA-NCS in a wireless LAN with hidden terminals is by considering a complimentary-couple configuration. In this configuration, a fraction of the population is hidden from the rest. We use two independent groups ($N = 2$) and vary the size of one group versus the other, such that $S_1 = \alpha \cdot S$ and $S_2 = (1 - \alpha) \cdot S$. The total average arrival rate of RTSs is set to $G = 5.0$, which corresponds to the arrival rate at which the maximum throughput is obtained when $\alpha = 1/2$. Figure 14 shows the maximum attainable throughput of FAMA-NCS versus α; it is clear from the figure that FAMA-NCS suffers much smaller performance degradation with hidden terminals than CSMA does.

5. Simulation Results

To validate our results on sufficient conditions for floor acquisition, the approximations made in our performance analysis of FAMA-NCS, and to study the performance of FAMA-NCS in ad-hoc networks, we carried out a number of simulations[3]. The simulations ran the actual code used to implement the MAC protocols in embedded systems and, for the case of FAMA-NCS, this code is based on the specifications shown in Figure 2.

In the first set of experiments, we assumed single-channel spread spectrum radios capable of transmitting at 256 Kbs. The stations are within four miles of each other, giving a maximum propagation delay of approximately 20 microseconds. We present results for FAMA-NCS using single packet transmissions as well as packet trains. Figure 15 shows the various topologies used by these simulation experiments. Table 1 show the results for FAMA-NCS as compared to MACAW[4] [2].

To illustrate the importance of carrier sensing, we chose to compare FAMA-

[3] We thank Rooftop Communications Corp. for donating the C++ Protocol Toolkit (CPT) simulator.

[4] We thank Ted Goodman for the use of his implementation of MACAW in CPT for our comparisons.

NCS against MACAW instead of FAMA-NPS because MACAW uses packet-sensing and RTS-CTS handshakes and its performance has been reported before by Bharghavan et al. [2]. The physical parameters of the radio assumed a null transmit-to-receive turnaround time and transmitter ramp-up time, we also assumed transmission preamble and framing of 0 bits. These parameters were chosen in order to obtain the same results for MACAW that have been reported previously [2]. Our results are only meant for comparative purposes.

In configuration (a) of Fig. 15 all stations are within range of all others (no hidden terminals). Traffic was generated at each node (N1 - N6) directed to the base station. Configuration (b) has two groups of five nodes that can hear the nodes in their own group, but are hidden from nodes in the other group. Traffic is generated from each node in each group directed to the central base station, $B1$. Configuration (c) has two base stations each with a group of five nodes sending traffic to it. The two groups cannot hear each other except for two nodes in each group that interfere with corresponding nodes in the other group (represented by the dashed arrows in the figure). Configuration (d) represents a multihop network of eight nodes. The lines between the nodes represent the radio connectivity of the network. The lines with arrows depict the flow of traffic from one node to another. Each node is generating a traffic stream to another node that at least three other nodes can hear, and is hidden from at least two of the other nodes in the network.

The traffic delivered to the nodes was sent at a constant rate with a packet size of 512 bytes on the channel (including all headers and framing). The maximum capacity of the channel at this bandwidth and packet size is approximately 63 packets per second. Table 1 reports the maximum throughput achieved by each of the protocols.

FAMA-NCS achieves a higher throughput than that of MACAW in all cases. For the case of a fully connected network (configuration (a)), FAMA-NCS attains a maximum throughput of 78%, while MACAW achieves a 63% throughput. These results are as predicted by our approximate analysis of Section 4. For the case of MACAW, our simulation leads to a slotted behavior in which a slot lasts the duration of an RTS plus a maximum round-trip time. For the case of two independent groups competing for the same base station, FAMA-NCS has a maximum throughput of 58%, while MACAW's achieves 49% maximum throughput. However, for the case of the two base stations with a small number of interfering nodes (configuration (c)), FAMA-NCS achieves a throughput of nearly twice that of MACAW, and in fact shows very little loss in overall throughput from interference due to hidden terminals (78% without interference, 75% with interference).

In the multihop-network example (d) FAMA-NCS achieves an average throughput of 49%, with the nodes on the corners (N1,N4,N5,N8) reaching 57%, and the inside nodes reaching 42%. In this network MACAW achieves a much lower throughput of 6% on the average, achieving 7% at the corner nodes, and 5% on the inside nodes.

Additionally, fairness is not an issue in FAMA-NCS. Even the simple uniformly distributed backoff scheme gives all stations basically an equal share of the channel without the complex housekeeping suggested in MACAW [2].

As expected, FAMA-NCS with packet trains of up to five packets in a train improves over single-packet transmissions by about 14% in the fully connected network and 17% for the two-base station configuration. In the case of two independent groups sending to one central base station, the improvement is almost 40%. For the multihop network FAMA-NCS packet trains provide an average throughput improvement of about 36%.

The poor performance of MACAW with hidden terminals is a direct consequence of the fact that data packets can collide with other packets, i.e., that it cannot enforce "floor acquisition" in the presence of hidden terminals and emphasizes the benefits of using carrier sensing.

In the second set of experiments, A 1Mb/s wireless network was modeled with stations at one mile from neighbors (propagation delay of approximately 6μs). Data packet size was 500 bytes, and RTS and CTS were 25 and 48 bytes respectively.

In the third set of experiments, we assumed a 1 Mbps network with the same topology of Configuration (d) in Figure 15. However, traffic was only between $N1$ and its neighbors, and between $N4$ and its neighbors. Table 6 lists the results for FAMA-NCS, IEEE 802.11 DFWMAC, and MACAW. In the table, "total input" refers to traffic correctly received and meant for any node; "local input" refers to traffic correctly received and meant for the receiving node. The results illustrate that making the CTSs dominate the RTSs, i.e., enforcing floor acquisition, is important for throughput in ad-hoc networks.

6. Concluding Remarks

We have introduced the FAMA-NCS protocol for single-channel wireless networks with hidden terminals. FAMA-NCS permits a sender to acquire control of the channel in the vicinity of a receiver dynamically before transmitting data packets. The floor acquisition strategy uses an RTS-CTS handshake and is based on a few simple principles: (a) making the senders listen to the channel before transmitting RTSs; (b) implementing a busy-tone mechanism using a single channel and half-duplex radios by making the receiver send CTSs that last long enough for the hidden senders to realize that they must back off; and (c) providing priority to those stations who successfully complete a handshake.

Although many MAC protocols have been introduced in the past based on RTS-CTS exchanges, we prove, 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 carrier sensing. Contrary to the conjectures made in prior work on MAC protocols based on collision avoidance [2,13], our verification and throughput analysis demonstrates that carrier sensing should be used in single channel networks because it substantially improves performance by enabling floor acquisition in the presence of hidden terminals.

We have shown through our analysis and supported by simulations that FAMA-NCS solves the hidden terminal problems of CSMA [23] in wireless LANS with hidden terminals and ad-hoc networks, because it is able to enforce floor acquisition. Our analysis illustrates the performance improvement obtained by allowing the transmission of packet trains in the clear, and a method to enable packet trains even with hidden terminals.

FAMA-NCS has been successfully implemented and demonstrated in actual packet radios for ad-hoc networks [29] built using commercial direct-sequence spread-spectrum radios and controllers.

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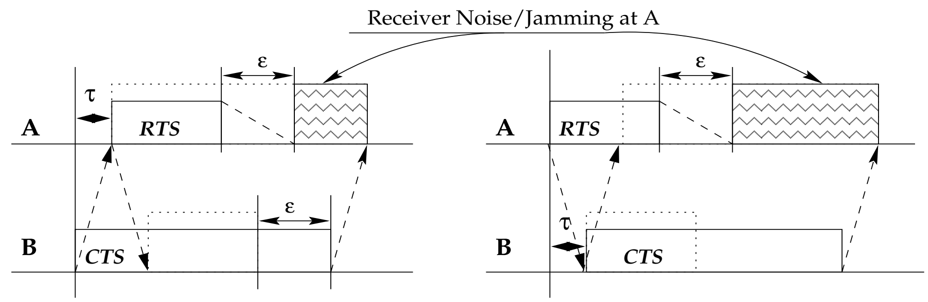

Figure 1.
Dominance of the CTS in FAMA for hidden-terminal:
a) A begins its RTS just as CTS arrives at A
b) A begins RTS τ seconds in advance of the CTS

Configuration	*FAMA-NCS*	*FAMA-NCS train*	*MACAW*
(a)	.78	.89	.63
(b)	.58	.81	.49
(c) B1	.75	.88	.45
(c) B2	.75	.88	.39
(d) average	.49	.67	.06
(d) N1,4,5,8	.57	.81	.07
(d) N2,3,6,7	.42	.54	.05

Table 1
Throughput results for various configurations

Avg. Rate Pkts. Received	*FAMA-NCS* (2KB pkts)	*IEEE 802.11* (2KB pkts)	*MACAW* (1KB pkts)
Avg. Total Input	36.0KB/s	17.0KB/s	–
Avg. Local Input	15.3KB/s	8.4KB/s	1.1KB/s
Avg. at N1 & N4	15.5KB/s	5.5KB/s	2.1KB/s
Avg. for others	15.2KB/s	9.3KB/s	0.8KB/s

```
Variable Definitions
    CD = Carrier Detected
    T_PROP = Maximum channel propagation delay
    T_PROC = Processing time for carrier detection
    T_TR = Transmit to receive turn-around time
    T_WAIT = (2 × T_PROP + T_PROC + T_TR)
    γ = Time to transmit an RTS packet
    γ' = Time to transmit a CTS packet
    δ = Time to transmit a maximum sized data packet
    Burst = Number of packets to send in a burst

Procedure START()
Begin
    Timer ← δ + 2 × T_PROP
    While(¬CD ∧ Timer not expired) wait
    If (CD) Then call REMOTE((δ + T_WAIT),TRUE)
    Else call PASSIVE()
End

Procedure PASSIVE()
Begin
    While(¬CD ∧ No Local Packet) wait
    If (CD) Then call REMOTE((δ + T_WAIT),FALSE)
    Else Begin
        Burst ← maximum burst
        Transmit RTS Packet
        call RTS(T_WAIT)
    End End

Procedure RTS(T_σ)
Begin
    Timer ← T_σ
    While(¬CD ∧ 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 REMOTE((δ + T_WAIT),TRUE)
        End
    End
End

Procedure BACKOFF()
Begin
    Timer ← RANDOM(1,10 × γ')
    While(¬CD ∧ Timer not expired) wait
    If (CD) Then call REMOTE((δ + T_WAIT),FALSE)
    Else Begin
        Burst ← maximum burst
        Transmit RTS Packet
        call RTS(T_WAIT)
    End End

Procedure XMIT()
Begin
    Wait T_TR
    If ((Burst > 1) ∧ Local Packet)
    Then Begin
        Mark MORE flag in header
        Transmit Data Packet
        Burst ← Burst - 1
        call RTS(T_WAIT)
    End
    Else Begin
        Transmit Data Packet
        Timer ← T_WAIT
        While(Timer not expired) wait
        If (Local Packet) Then call BACKOFF()
        Else call PASSIVE()
    End End

Procedure REMOTE(T_σ,dflag)
Begin
    Timer ← T_σ
    While(¬CD ∧ 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:
                If(dflag= TRUE) call REMOTE(T_σ,TRUE)
                If(Destination ID = Local ID)
                Then Begin
                    Wait T_TR
                    Transmit CTS Packet
                    call REMOTE((T_WAIT),TRUE)
                End
                call REMOTE((γ' + T_WAIT),TRUE)
            CTS:
                call REMOTE((δ + T_WAIT),TRUE)
            DATA:
                If(Destination ID = Local ID)
                Then Begin
                    Pass packet to upper layer
                    If (MORE flag set in header)
                    Then Begin
                        Transmit CTS
                    End
                    call REMOTE((T_WAIT),TRUE)
                End
                Else Begin
                    If (MORE flag set in header)
                    Then Begin
                        call REMOTE((γ' + T_WAIT),TRUE)
                    End
                    Else Begin
                        call REMOTE((T_WAIT),TRUE)
                    End
                End
            ERROR:
                call REMOTE((δ + T_WAIT),TRUE)
        End
    End
End
```

Figure 2. FAMA-NCS Specification

```
Variable Definitions
    T_PROP = Maximum channel propagation delay
    T_RTS = Transmission time of an RTS packet
    T_CTS = Transmission time of a CTS packet
    T_DATA = Transmission time of a DATA packet
    T_TR = Time to transition from transmit to receive

Procedure START()
Begin
    Timer ← T_DATA + T_TR + 2T_PROP
    While(Timer not expired) wait
    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 + T_TR + 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
    Timer ← RANDOM(1,10 × T_RTS)
    While(Timer not expired ∧ No Packet Received) wait
    If(Timer expired) Then call PASSIVE()
    Else call REMOTE(received packet)
End

Procedure XMIT()
Begin
    Wait T_TR
    Transmit Data Packet
    call PASSIVE()
End

Procedure REMOTE(packet)
Begin
    DO CASE of (packet type)
    Begin
        Local RTS:
            Wait T_TR
            Transmit CTS
            timer ← T_DATA + T_TR + 2T_PROP
        Other RTS:timer ← T_CTS + T_TR + 2T_PROP
        CTS:      timer ← T_DATA + T_TR + 2T_PROP
        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
```

Figure 3. FAMA-NPS Specification

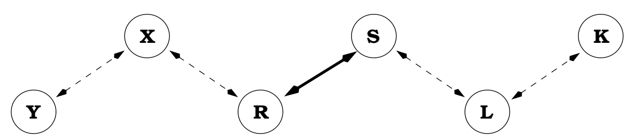

Figure 4. Stations involved in interference of the exchange between S and R

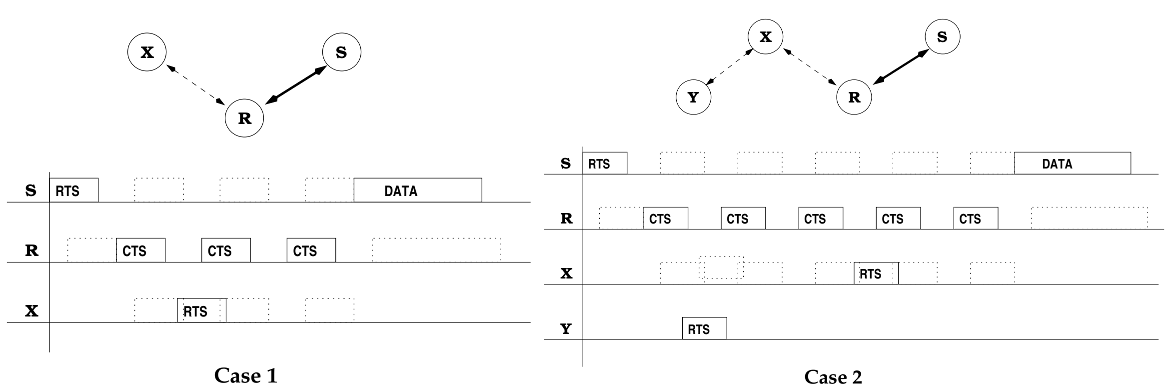

Figure 5. Non-persistent Packet Sensing with hidden terminals

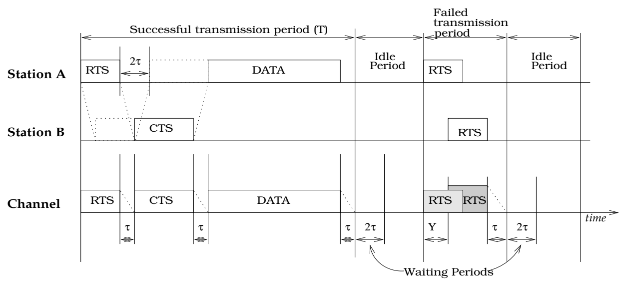

Figure 6. FAMA-NCS transmission periods

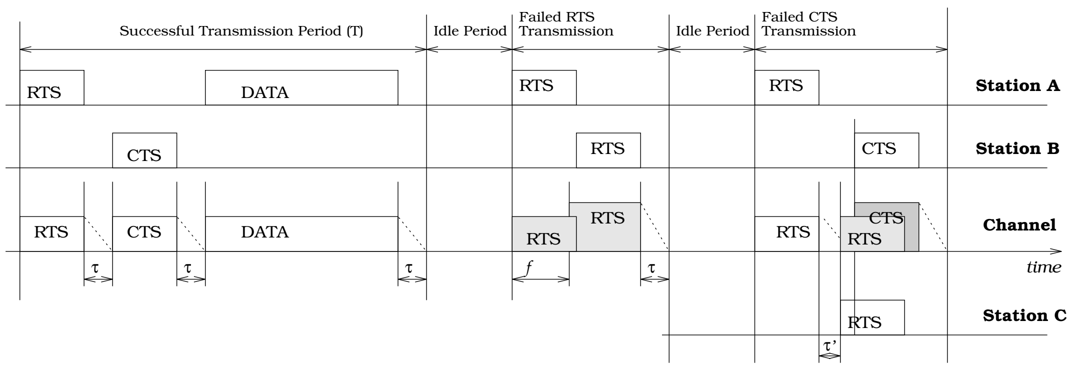

Figure 7. FAMA-NPS transmission periods

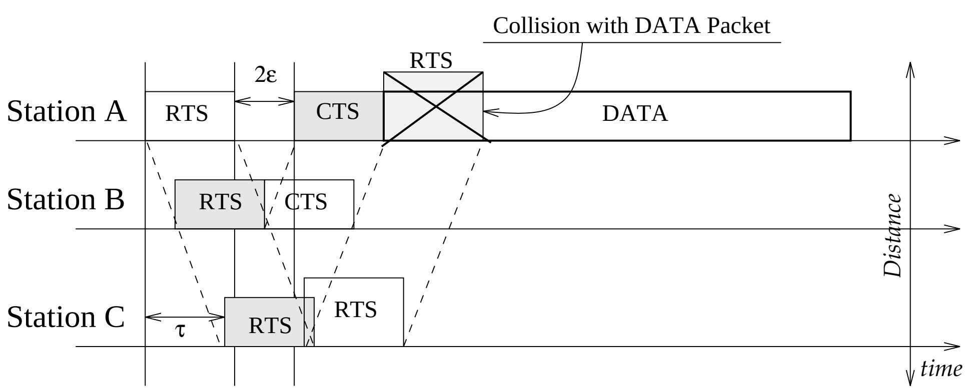

Figure 8. MACA unsafe transmission:
An RTS from C collides with A's data packet due to differences in propagation time from A to B and from A to C and the length of RTS and CTS packets.

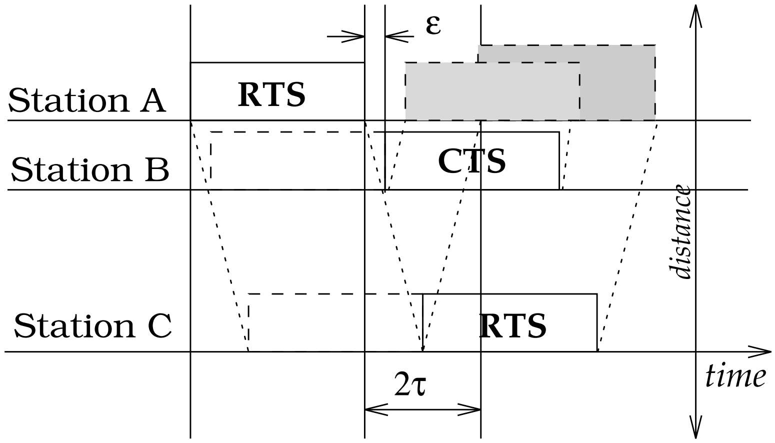

Figure 9. MACA RTS/CTS collision

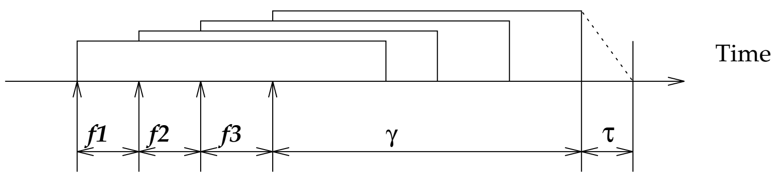

Figure 10. A failed RTS transmission period in FAMA-NPS

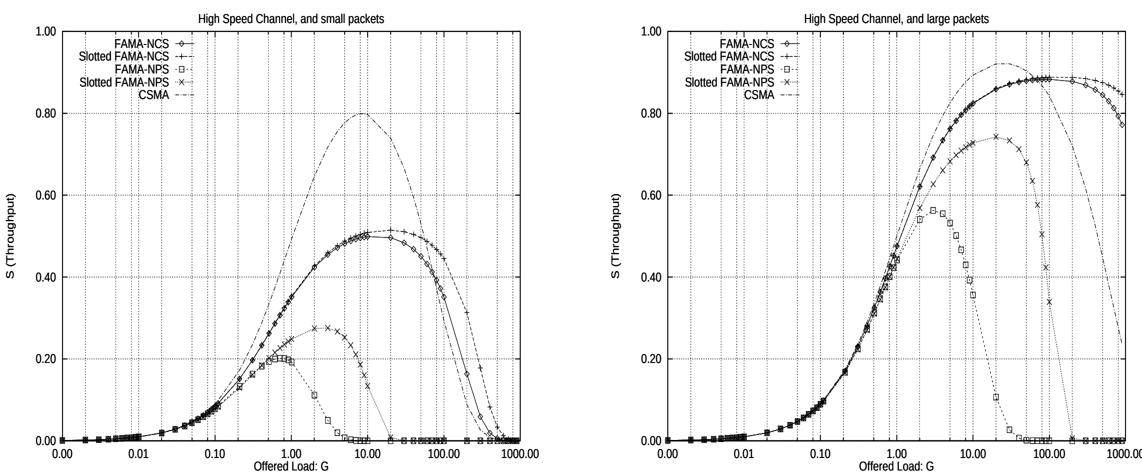

Figure 11. Throughput of FAMA-NCS, MACA (FAMA-NPS), and CSMA in a fully-connected network.

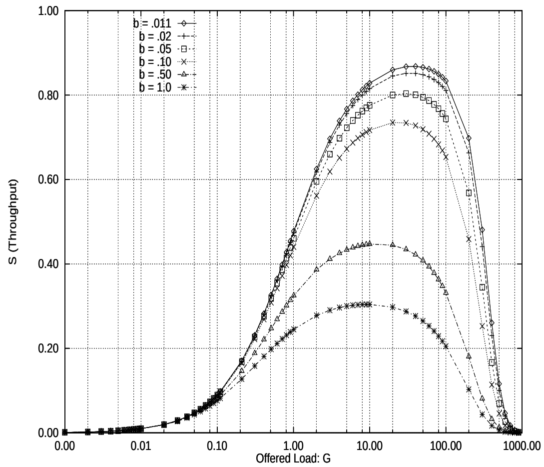

Figure 12. Throughput of FAMA-NCS versus traffic for different values of $b = \gamma/\delta$ and $a = 0.01$.

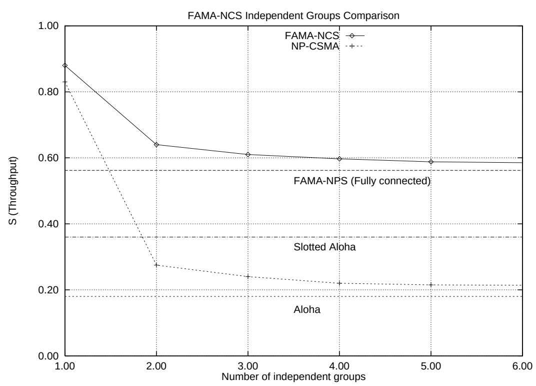

Figure 13. Throughput of FAMA protocols for increasing numbers of independent groups

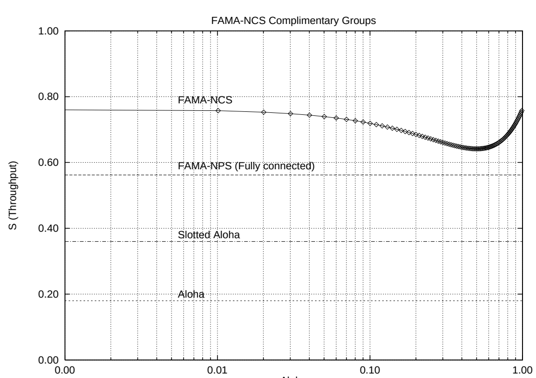

Figure 14. Throughput of FAMA-NCS in the complimentary couple configuration

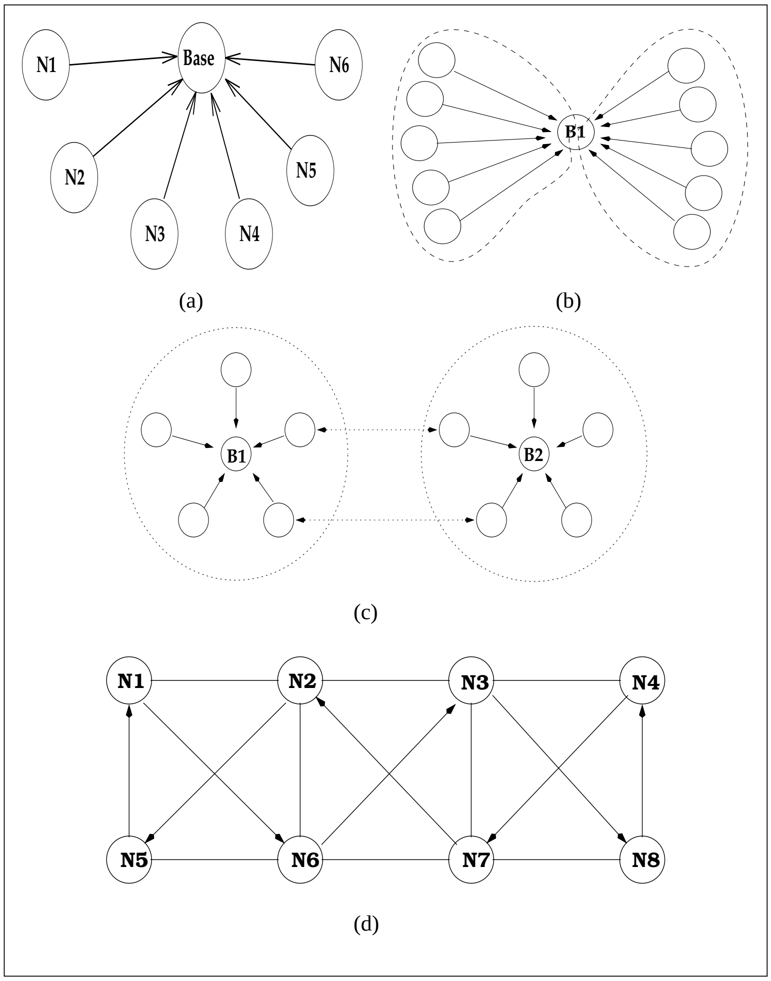

Figure 15. Simulation topologies used in testing FAMA-NCS protocols in hidden terminal environments