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Energy efficiency and error resilience in coordinated and non-coordinated medium access control protocols

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Abstract

Energy efficiency of a MAC protocol is one of the most important performance metrics, especially in mobile ad hoc networks, where the energy sources are limited. Two key factors in achieving energy efficiency for a MAC protocol are coordination among the nodes and schedule-based channel access. In order to achieve a sufficient level of coordination among the nodes, and hence to achieve energy efficiency, the exchange of control information via control packets is vital. As such, coordinated MAC protocols, which regulate channel access through scheduling, have been shown to achieve very high energy efficiencies when compared to non-coordinated MAC protocols, which do not employ scheduling. However, due to their increased vulnerability to channel errors, the performance of coordinated MAC protocols is affected more by the channel bit error rate (BER) than non-coordinated MAC protocols, which lack such control packets. In this paper, we investigate the energy efficiency and resilience against channel errors for coordinated and non-coordinated MAC protocols. Our results reveal that it is possible to achieve better system performance with coordinated MAC protocols even in lossy channels, provided that the BER level is not extremely high.

Keywords: Energy-aware systems; Distributed networks; Wireless communication; Network protocols; Error resilience; Protocol verification; Algorithm/protocol design and analysis; Mobile communication systems; Access schemes

1. Introduction

In wireless communications, the channel is the common interface that connects the nodes. Like every shared resource, access to the channel needs to be regulated; this resource allocation operation is performed by Medium Access Control (MAC) protocols, which are defined as the second layer of the OSI protocol stack [1]. The objective of controlling access to the channel via the MAC protocol is to avoid or minimize simultaneous transmission attempts (that will result in collisions) while maintaining a stable and efficient operating region for the whole network. Furthermore, the MAC protocol is the key element in determining many features of a wireless network, such as energy efficiency, throughput, Quality of Service (QoS), fairness, stability, and robustness [2].

MAC protocols can be classified into two categories based on the collaboration level of the network in regulating the channel access: coordinated and non-coordinated. A coordinated MAC protocol operates with explicit coordination among the nodes and is generally associated with coordinators, channel access schedules, and clusters. For example, Bluetooth is a coordinated MAC protocol, where channel access within a cluster (i.e., piconet) is coordinated by a coordinator (i.e., piconet Master) [3]. A non-coordinated MAC protocol, on the other hand, operates without any explicit coordination among the nodes in the network. For example, IEEE 802.11 is a non-coordinated MAC protocol when operating in the broadcast mode (i.e., in broadcasting mode, IEEE 802.11 becomes plain CSMA without any handshaking) [4]. Note that IEEE 802.11 channel

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access in unicasting mode is a coordinated scheme (i.e., the four way handshaking between the transmitter and receiver is a special case of a general explicit coordination scheme, such as [5,6]).

Fig. 1 illustrates the channel access mechanism for generic coordinated and non-coordinated MAC protocols. In the coordinated MAC protocol, node N_0 is the cluster-head (coordinator) for the portion of the network consisting of five nodes. Channel access is regulated through a schedule that is broadcast by the coordinator. Upon reception of the schedule, nodes transmit their data at their allocated time, and thus collisions among nodes within the same cluster are eliminated. Furthermore, a node can switch to a low-energy sleep mode during the slots where no transmissions are scheduled or scheduled transmissions are not of interest to a particular node. Time is organized into cyclic time frames, and the transmission schedule is dynamically updated at the beginning of each time frame. IEEE 802.15.3 is a recent example of such a coordinated MAC protocol [7]. In the non-coordinated MAC protocol, each node determines its own transmission time based on feedback obtained through carrier sensing on the channel. Thus, conflicts in data transmission attempts (i.e., collisions, capture) are unavoidable in the non-coordinated scheme. In addition, none of the nodes can switch to sleep mode because future data transmissions are not known beforehand due to the lack of a scheduling mechanism.

Both coordinated and non-coordinated MAC protocols have their advantages and disadvantages.

(i) One of the most important advantages of coordinated MAC protocols is their energy efficiency due to the availability of a schedule that let nodes enter into sleep mode without deteriorating the overall system performance. Thus, the average energy dissipation of nodes in coordinated schemes is significantly lower than in non-coordinated schemes [8].
(ii) Collisions are mostly eliminated in coordinated MAC protocols, while frequent packet collisions are unavoidable in non-coordinated protocols, especially under heavy network conditions, which may draw the network into instability in extreme conditions [9].
(iii) The average packet delay using non-coordinated MAC protocols is lower than the average packet delay using coordinated MAC protocols under mild traffic loads. However, under heavy traffic loads, packet delay in non-coordinated protocols rises to very high levels [10].
(iv) Coordinated MAC protocols are more vulnerable to packet losses than non-coordinated MAC protocols due to their dependence on the reliable exchange of control packets, such as the schedule packet. Mobility, multi-path propagation, and channel noise are the main sources of errors that cause packet losses [11].

Energy efficiency has become one of the predominant platform requirements for battery powered mobile multimedia computing devices. Therefore, the new challenge is to provide QoS in an energy-efficient manner rather than focusing solely on QoS by ignoring the energy dissipation [12]. Consequently, there is a growing interest in energy-efficient design, mainly concentrating on MAC layer energy reduction techniques [8,13,14]. Most of the proposed solutions use TDMA as a MAC scheduling principle in order to utilize the benefits of having a schedule such as fairness, stability, and energy efficiency by regulating the channel access, minimizing collisions, and enabling power saving features, respectively.

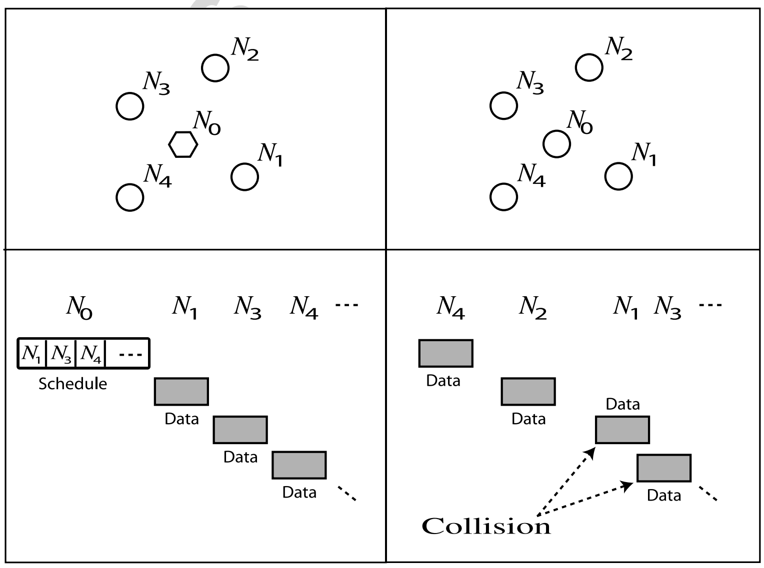

Fig. 1. Illustration of coordinated and non-coordinated MAC protocols. The upper left and right panels show the node distributions for nodes N_0–N_4. The lower left panel shows the medium access for the coordinated scheme, where node N_0 is the coordinator and the channel access is regulated through a schedule transmitted by N_0. The lower right panel shows the channel access for the non-coordinated scheme (e.g., CSMA). Overlapping data transmissions of N_1 and N_3 lead to a collision.

In general, energy-efficient distributed protocol design can be described as creating an appropriate distributed coordination scheme that minimizes a radio's total energy dissipation without sacrificing its functionality, by intelligently switching between the radio's different operating modes. Actually, there are only three modes that a radio can be switched to: transmit mode, active mode (receive, carrier sense, and idle modes), and sleep mode. Although further classification of the energy dissipation modes of a radio is possible (i.e., deep/shallow sleep modes, transient modes, etc.), the aforementioned classification is detailed enough in this context. There is no way to switch between receive, idle, and carrier sense modes: when a node is in the active mode, the actual mode (receive, idle or carrier sensing) is determined by the activities of the node's neighbors, which is not a controllable design parameter. Nevertheless, the ultimate goal is to keep the radio in the low energy sleep mode as long as possible without sacrificing network performance.

The general trend in the evaluation of the performance of network protocols (e.g., energy efficiency) is to ignore channel errors and assume a perfect channel [15]. Although the assumption of a perfect channel is reasonable in the initial design stage, further verification of a proposed protocol should consider error resilience. In this paper, we investigate the performance of two MAC protocols, IEEE 802.11 and MH-TRACE (Multi Hop Time Reservation using Adaptive Control for Energy Efficiency), at different Bit Error Rate (BER) levels by providing an analytical model which is well supported with ns-2 simulations. IEEE 802.11 is a well-known example of a non-coordinated MAC protocol when it is used for broadcasting. MH-TRACE is a recent example of an energy-efficient coordinated MAC protocol that relies on control packet exchanges for its operation. A comparative evaluation of IEEE 802.11 and MH-TRACE for real-time data broadcasting using a perfect channel showed that the energy efficiency of MH-TRACE is much better than IEEE 802.11 [16]. However, due to the relatively complicated design of MH-TRACE, which relies on robust control packet exchange, the advantages of MH-TRACE over IEEE 802.11 are questionable under high BER levels.

In our previous work, we presented a comparative performance evaluation of IEEE 802.11 and MH-TRACE when they are utilized for single hop data broadcasting through mathematical analysis and simulations [17,18]. In this paper, we present an extended analysis of the effects of channel noise for IEEE 802.11 and MH-TRACE for a wide range of parameters that affect the system performance. To the best of our knowledge, a joint analysis of energy efficiency and channel errors is not reported in the literature. Thus, we believe that the results of our work provide a valuable contribution to the better understanding of energy efficiency in mobile ad hoc networks.

The remainder of this paper is organized as follows. Section 2 presents related work. Section 3 presents the IEEE 802.11 and MH-TRACE MAC protocols. In Section 4, we introduce an analytical model for the performance of MH-TRACE as a function of BER. Simulation results and analysis of both protocols under different BER levels are presented in Section 5. Conclusions are drawn in Section 6.

2. Related work

Although performance analysis of ad hoc networks has found some noticeable attention in the literature [19–27], there is little work done to explore the characteristics of different types of MAC protocols (i.e., coordinated and non-coordinated) under varying channel noise. Our work explicitly aims to answer the question of whether a coordinated MAC protocol preserves its superior performance, or whether its higher level of vulnerability due to the dependence on robustness of the control traffic makes it unstable under high BER levels.

A comprehensive survey of MAC approaches for wireless mobile ad hoc networks is presented in [28]. This work individually concentrates on different MAC approaches and tries to identify their problems and discusses possible remedies. One of the important conclusions of [28] is that increased throughput results in increased energy efficiency due to a decrease in the number of retransmissions. However, it is also pointed out that one has to sacrifice some throughput in order to achieve fairness (e.g., reservation based MAC protocols). Another major conclusion is that in order to achieve QoS one has to increase the persistence, which results in decreased throughput stability.

In [8], MAC protocols are compared in terms of battery power consumption in order to emphasize the characteristics of an energy-efficient MAC protocol. They concluded that reducing the number of contentions reduces the energy consumption. Moreover, reservation (i.e., coordination and scheduling) is proposed as a better solution for messages with contiguous packets. However, energy efficiency under channel noise was not explored in this study.

More focused works investigating packet loss and error resilience can be found in [29,30]. These studies concentrated on identifying and characterizing possible sources of packet losses in ad hoc wireless networks. Mobility and congestion are pointed out as the main reasons in mobile ad hoc networks [29]. On the other hand, [30] takes collisions, error in radio transmission and SNR (signal to noise ratio) variation into account as the main reasons for packet losses in mobile ad hoc networks. They both provide simulation results to demonstrate the effects of each individual source of packet losses.

In [31] an adaptive frame length control approach, which is implemented at the MAC layer to compensate for rapidly varying channel conditions of wireless networks, is presented. They showed that by adjusting the frame length, there is much to be gained in terms of throughput, effective transmission range and transmitter power for wireless links. All of their outcomes stem from the assumption that the probability of error for a longer packet is higher than the probability of error for a shorter packet. Therefore, reducing the frame length when the channel conditions are worse will improve the throughput since the effective transmission range is increased. As a result of improved throughput, less energy is consumed due to the reduced number of retransmissions as we discussed earlier. However, in their analysis they did not consider the effects of channel noise on control packets.

However, none of the aforementioned studies provide sufficient insight on the error resilience, in general, and the vulnerability of control traffic to channel noise, in particular, and hence the performance evaluation of MAC protocols under various BER levels. Although the impact of channel errors on the control packets is crucial to the overall performance of coordinated MAC protocols, evaluation of coordinated MAC protocols under realistic channel errors has found little attention in the literature. In this paper, we investigate the effects of channel errors on the control traffic in a coordinated MAC protocol and determine the extent of performance deterioration. Furthermore, we present a comparative performance evaluation of a coordinated and a non-coordinated MAC protocol under a realistic error model. We believe that jointly analyzing the energy efficiency and error resilience of coordinated and non-coordinated MAC protocols and identifying the pros and cons of them will motivate future research to produce more accurate and reliable solutions to MAC related problems.

3. Background

In this section, we present an overview of IEEE 802.11 and MH-TRACE when used for single-hop data broadcasting.

3.1. IEEE 802.11

In broadcasting mode, IEEE 802.11 uses p-persistent CSMA with a constant defer window length (i.e., the default minimum defer period) [4]. When a node has a packet to broadcast, it picks a random defer time and starts to sense the channel (see Fig. 2). When the channel is sensed idle, the defer timer counts down from the initially selected defer time at the end of each time slot. When the channel is sensed busy, the defer timer is not decremented. Upon the expiration of the defer timer, the packet is broadcast.

The IEEE 802.11 standard includes an energy saving mechanism when it is utilized in the infrastructure mode [4]. A mobile node that needs to save energy informs the base station of its entry to the energy saving mode, where it cannot receive data (i.e., there is no way to communicate to this node until its sleep timer expires), and switches to the sleep mode. The base station buffers the packets from the network that are destined for the sleeping node. The base station periodically transmits a beacon packet that contains information about such buffered packets. When the sleeping node wakes up, it listens for the beacon from the base station, and upon hearing the beacon responds to the base station, which then forwards the packets that arrived during the sleep period. This energy saving method results in additional delays at the mobile nodes that may affect QoS. Furthermore, this approach is not directly applicable in multi-hop networks. IEEE 802.11 also supports an energy saving mechanism in ad hoc mode called ad hoc traffic indication message (ATIM) window, which is not an effective method for energy saving in broadcasting.

3.2. MH-TRACE

Multi-hop time reservation using adaptive control for energy efficiency (MH-TRACE) is a MAC protocol designed for energy-efficient real-time data broadcasting [16]. Fig. 3 shows a snapshot of MH-TRACE clustering and medium access. In MH-TRACE, the network is partitioned into overlapping clusters through a distributed algorithm. Time is organized into cyclic constant duration superframes consisting of several frames. Each clusterhead chooses the least noisy frame to operate within and dynamically changes its frame according to the interference level of the dynamic network. Nodes gain channel access through a dynamically updated and monitored transmission schedule created by the clusterheads, which eliminates

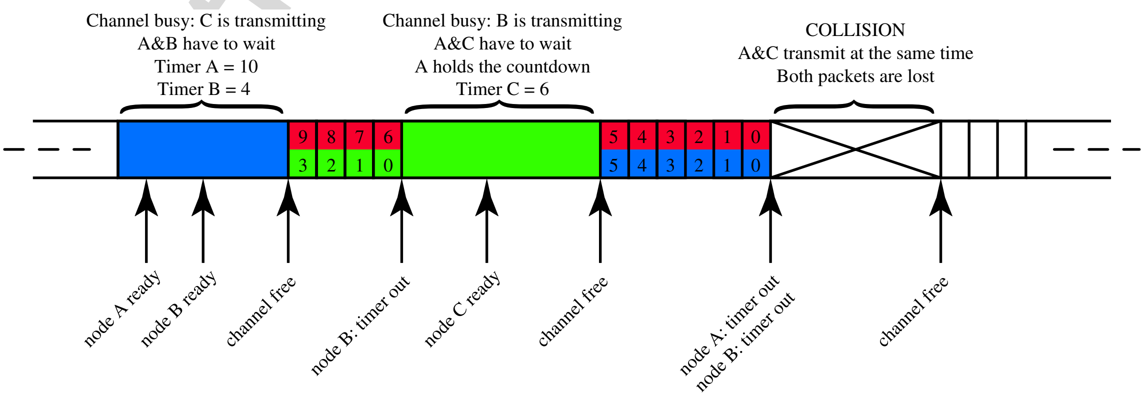

Fig. 2. Illustration of IEEE 802.11 medium access control mechanism in broadcasting.

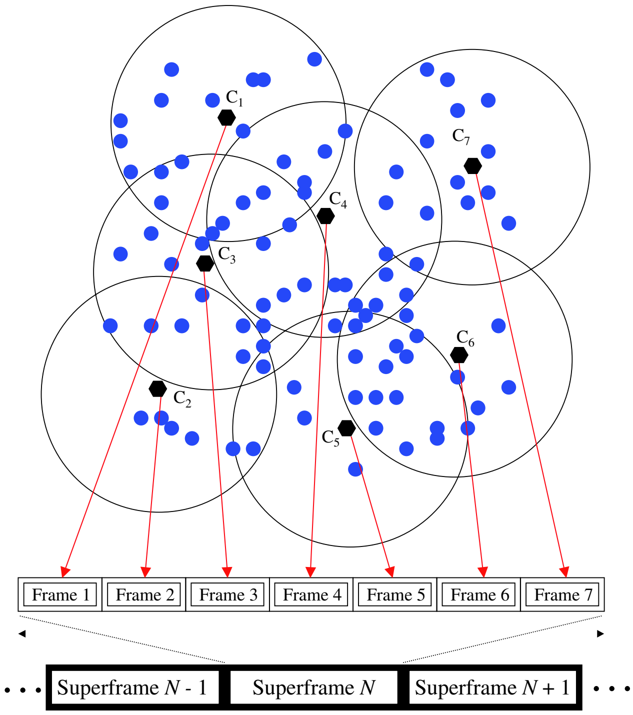

Fig. 3. A snapshot of MH-TRACE clustering and medium access for a portion of an actual distribution of mobile nodes. Nodes C_1–C_7 are clusterhead nodes.

packet collisions within the cluster. Collisions with the members of other clusters are also minimized by the clusterheads' selection of the minimal interference frame. Ordinary nodes are not static members of clusters, but they choose the cluster they want to join based on the spatial and temporal characteristics of the traffic, taking into account the proximity of the clusterheads and the availability of the data slots within the corresponding cluster.

Each frame consists of a control sub-frame for transmission of control packets and a contention-free data sub-frame for data transmission (see Fig. 4). Beacon packets are used for the announcement of the start of a new frame; Clusterhead Announcement (CA) packets are used for reducing co-frame cluster interference; contention slots are used for initial channel access requests; the header packet is used for announcing the data transmission schedule for the current frame; and information summarization (IS) packets are used for announcing the upcoming data packets. IS packets are crucial in energy saving. Each scheduled node transmits its data at the reserved data slot.

In MH-TRACE, nodes switch to sleep mode whenever they are not involved in data transmission or reception, which saves the energy that would be wasted in idle mode or in carrier sensing. Ordinary nodes are in the active mode only during the beacon, header, and IS slots. Furthermore, they stay active for the data slots for which they are scheduled to transmit or receive. In addition to these slots, clusterheads stay in the active mode during the CA and contention slots. Instead of frequency division or code division, MH-TRACE clusters use the same spreading code or frequency, and inter-cluster interference is avoided by using time division among the clusters to enable each node in the network to receive all the desired data packets in its receive range, not just those from nodes in the same cluster. Thus, MH-TRACE clustering does not create hard clusters-the clusters themselves are only used for assigning time slots for nodes to transmit their data.

4. Analytical model

In this section, we develop an analytical model to estimate the performance of MH-TRACE as a function of BER. However, our model essentially models a generic coordinated MAC protocol, thus, it is not necessarily specific to MH-TRACE and it can easily be extended to analyze any coordinated MAC protocol with little modification (e.g., IEEE 802.15.3 [7] and EC-MAC [32]). For example, IEEE 802.15.3 has a similar channel access mechanism to MH-TRACE, where time is organized into cyclic superframes and channel access is granted through a control packet that includes the schedule (i.e., a beacon packet). Therefore, modeling the performance of IEEE 802.15.3 will be essentially the same as our modeling of MH-TRACE. In our analysis, we do not consider any error correction scheme, thus, if there is at least one bit error within a packet, then that packet is discarded. Random packet errors are independently introduced at the receivers.

If a protocol cannot maintain the desired level of performance, then its energy efficiency becomes meaningless. Thus, in order to achieve meaningful energy efficiency, it is absolutely necessary to make sure that a protocol does not deteriorate system performance while saving energy. MH-TRACE is a protocol designed primarily for energy efficiency, and it is obvious that under ideal channel conditions its energy efficiency will be superior to any non-coordinated protocol. However, the question is whether MH-TRACE preserves its performance in the face of channel errors. In this section, we seek the answer to this question through mathematical analysis supported with simulations.

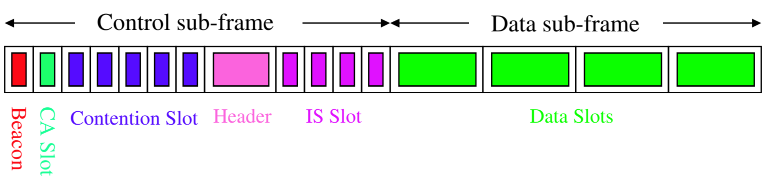

Fig. 4. MH-TRACE frame structure.

4.1. Basic model

To demonstrate our approach clearly and with a simple example, first we consider a fully connected network with a small number of static nodes. The number of data slots in one superframe is high enough to support all of the nodes in the network (see Table 1). When there are no channel errors, all nodes should be able to transmit and receive without any packet drops or collisions. There will be only one clusterhead in the network due to the fact that there cannot be two clusterheads that can hear each other directly.

The number of data packets generated per node per second, (DP_{node}), is equal to the packet rate (R_{packet}) of MH-TRACE (i.e., one packet per superframe time ($1/T_{\mathrm{sf}}$)).

$$DP_{\mathrm{node}} = R_{\mathrm{packet}} = \frac{1}{T_{\mathrm{sf}}}, \tag{1}$$

where DP_{node} represents the number of data packets generated by a single node in the network and can be regarded as the maximum number of packets a node can transmit given that it has full access to a perfect channel whenever it needs. However, a lossy channel will cause packet drops and therefore the throughput of the network will drop accordingly.

In Fig. 5, the corresponding throughput losses due to dropped beacon, header and contention packets are given to illustrate the impact of the particular control packet on overall protocol performance. In these results only the specified control packets are lost due to channel errors and all the other packets are not affected [17].

These results are from our previous work where we simulated a six node fully connected static network to clearly observe the effects of packet losses. When there are no channel errors, all nodes should be able to transmit and receive without any packet drops or collisions. There will be only one clusterhead in the network due to the fact that there cannot be two clusterheads that can hear each other directly. We utilized 1.0%, 3.0%, and 5.0% packet error probabilities. Note that a 5.0% packet error probability represents a harsh environment [11]. We used the *ns*-2 simulator to evaluate the system performance.

Table 1
Simulation parameters

Acronym	Description	Value
T_{SF}	Superframe duration	25.172 ms
T_{F}	Frame duration	3.596 ms
N_{F}	Number of frames	7
N_{DS}	Number of data slots per frame	7
N_{C}	Number of contention slots per frame	6
T_{B}	Beacon slot duration	32 µs
T_{CA}	CA slot duration	32 µs
T_{C}	Contention sub-slot duration	32 µs
T_{H}	Header slot duration	92 µs
T_{IS}	IS sub-slot duration	32 µs
T_{D}	Data slot duration	432 µs
N/A	Data packet size	104 B
N/A	Header packet size	4–18 B
N/A	All other control packet size	4 B
IFS	Inter-frame space	16 µs
T_{drop}	Packet drop threshold	50 ms
T_{VF}	Voice packet generation period	25.172 ms
P_{T}	Transmit power	0.6 W
P_{R}	Receive power	0.3 W
P_{I}	Idle power	0.1 W
P_{S}	Sleep power	0.0 W
D_{Tr}	Transmission range	250 m
D_{CS}	Carrier Sense range	507 m

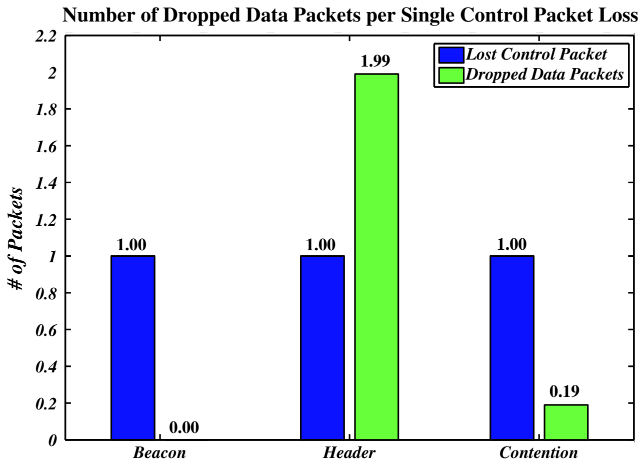

Fig. 5. MH-TRACE performance degradation in terms of dropped data packets for beacon, header, and contention packet losses.

As can be seen from the figure, a lost header packet has the most impact on the performance of MH-TRACE. Loss of contention packets cause 10 times less impact on throughput than loss of header packets (0.19). Finally, for each beacon packet dropped, only 0.0015 data packets are dropped. Like beacon packet losses, losing other control packets (e.g., IS, CA) do not significantly affect the throughput of the network. Thus, we conclude that the header and contention packets are the only control packets whose loss due to channel noise affect the network performance.

Therefore, we can write the equation for the *transmit* throughput of a single node (i.e., transmit throughput per node per second T_{node}) in terms of the data packets dropped before transmission due to lost header packets (DPL_{H}) and contention (DPL_{C}) packets:

$$T_{\mathrm{node}} = DP_{\mathrm{node}} - DPL_{\mathrm{H}} - DPL_{\mathrm{C}}. \tag{2}$$

Both (DPL_{H}) and (DPL_{C}) can be written as the product of three parts. (i) Number of data packets dropped per header or contention packet loss (DPL_{perH} or DPL_{perC}). (ii) Number of header or contention packets sent to a node or clusterhead per second (HP_{node} or CP_{node}). (iii) Probability of dropping a header or contention packet (P_{H} or P_{C}).

As contention packets are relatively short (4 bytes), they are less likely to be dropped than header packets (16 bytes for 6 broadcasting nodes). Furthermore, since the sources are constant bit rate (CBR) and MH-TRACE utilizes automatic channel access renewal, once a node gets channel access, it will not loose it and, thus, will not need to transmit contention packets for the rest of the simulation time. Moreover, the number of dropped data packets per lost header packet is 10 times larger than the number of dropped data packets per lost contention packet, as shown in Fig. 5. Therefore, it is reasonable to assume that the effect of losing contention packets can be neglected. Furthermore, by ignoring the control packets other than the header packet, we focus on a more general model rather than an MH-TRACE specific model. Based on these assumptions, the transmit throughput per node per second becomes:

$$T_{\text{node}} = DP_{\text{node}} - DPL_{\text{H}}, \tag{3}$$

$$T_{\text{node}} = \frac{1}{T_{\text{sf}}} - DPL_{\text{perH}} \times HP_{\text{node}} \times P_{\text{H}}. \tag{4}$$

In Eq. (4), DPL_{perH} is a constant (1.99) and HP_{node} is equal to DP_{node} since each node receives one header per superframe from its clusterhead. Finally P_{H} depends on the length of the header packet L_{H} and is calculated from the Bit Error Rate (BER) of the channel.

$$P_{\text{H}} = \{1 - (1 - \text{BER})^{L_{\text{H}}}\}. \tag{5}$$

Therefore,

$$T_{\text{node}} = \frac{1}{T_{\text{sf}}} - 1.99 \times \frac{1}{T_{\text{sf}}} \times \{1 - (1 - \text{BER})^{L_{\text{H}}}\} \tag{6}$$

$$T_{\text{node}} = \frac{1}{T_{\text{sf}}} \times [1 - 1.99 \times \{1 - (1 - \text{BER})^{L_{\text{H}}}\}]. \tag{7}$$

In order to get the number of received packets per second in the network, we need to multiply the transmit throughput per node per second with the number of neighboring nodes $N - 1$ (note that all the nodes can hear each other in this network). Moreover, each data packet is received with a probability P_{D}, which is the probability that a data packet (with length $L_{\text{D}} = 104$ bytes) goes through the channel with no error at a given BER. Accordingly, the receive throughput per node per second (T) becomes

$$T = (N - 1) \times T_{\text{node}} \times (1 - \text{BER})^{L_{\text{D}}}. \tag{8}$$

Note that the receive throughput per node per second of IEEE 802.11 is simply equal to $\frac{N-1}{T_{\text{sf}}} \times (1 - \text{BER})^{L_{\text{D}}}$ since in CSMA-type protocols such IEEE 802.11 in broadcasting mode, only data packets are sent through the lossy channel and the throughput is determined by the BER of the channel and length of a data packet.

We used the ns-2 simulator to validate the analytical model. The channel rate is set to 2 Mbps, and all nodes have a CBR (Constant Bit Rate) data source with 32 Kbps data rate, which corresponds to one voice packet per superframe. The simulations are run for 1000 s and repeated with the same parameters five times.

In Fig. 6, the analytical model for MH-TRACE and IEEE 802.11 are plotted against increasing BER. Also, the simulation results are included for both protocols to demonstrate the accuracy of the models. The throughput of MH-TRACE drops by almost 50% at a BER around

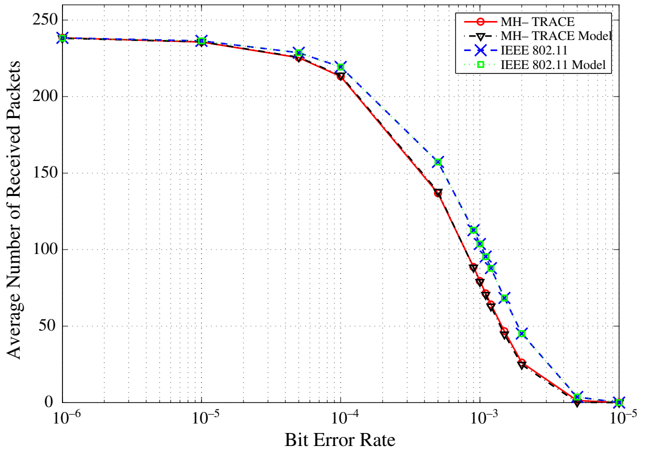

Fig. 6. Average number of received packets per node per second versus bit error rate (BER).

7×10^{-4}. On the other hand, IEEE 802.11 retains almost 55% of its initial throughput at the same BER (note that the initial throughputs of both protocols are the same). This difference can be translated into the fact that IEEE 802.11 performs 10% better than MH-TRACE, which experiences a worse performance degradation due to lost coordination packets [17].

These results show that the analytical model proposed to estimate the throughput of MH-TRACE is quite accurate. The model captures the fact that coordinated MAC protocols are more vulnerable than non-coordinated MAC protocols to channel noise due to their dependence on the robustness of the control traffic. In Fig. 6, MH-TRACE experiences a steeper loss than IEEE 802.11 for BER values greater than 10^{-4}, which is the point where header packet losses become the dominant factor in performance degradation. Our model captures this unique behavior of MH-TRACE. Therefore, our first conclusion is that the increased throughput loss occurs when a coordinated MAC protocol starts to lose its control packets. In our case, header packets are lost first since they are the longest control packet in MH-TRACE (see Table 1).

Before starting to derive a general model for MH-TRACE throughput, we want to mention that in our model, we treated the clusterhead as a regular node inside the network, but in reality, a clusterhead would not drop any data packets due to lost header packets since the clusterhead is the one generating the header packets. Therefore, our model slightly underestimates the throughput of MH-TRACE by treating the clusterhead as an ordinary node.

4.2. General model

In this section, we consider a rectangular field ($L \times H$) in which a certain number of nodes (N), which have a communication radius (r), are randomly deployed. We use a statistical model of Voice Activity Detector (VAD) equipped voice source model that classifies speech into *spurts* and *gaps* (i.e., gaps are the silent moments during a conversation). During gaps, no data packets are generated, and during spurts, data packets are generated at 32 Kbps data rate. Both spurts and gaps are exponentially distributed statistically independent random variables, with means $\eta_s = 1.0$ s and $\eta_g = 1.35$ s, respectively [5]. The reason for using such a statistical voice source is that the transmission schedule will change frequently (i.e., at the end of spurts nodes cease transmitting and their granted data slot will be taken away from them, and they will need to contend for channel access at the beginning of the next spurt), even in the absence of the channel errors, which is necessary to asses the system performance for a coordinated MAC protocol in the face of a dynamically changing transmission schedule.

Our approach to this more complex model will be basically the same as before. We begin by calculating the transmit throughput per node per second (T_{node}) when the channel is perfect. In addition to Eq. (7), we need a term that captures the effect of the voice source model. This term can easily be represented with the ratio of spurts to the whole conversation (η). Therefore, we can write T_{node} as in Eq. (9).

$$\begin{aligned} T_{\text{node}} &= \frac{1}{T_{\text{sf}}}[1 - 1.99\{1 - (1 - \text{BER})^{L_{\text{H}}}\}][\eta] \\ &= \frac{1}{T_{\text{sf}}}[1 - 1.99\{1 - (1 - \text{BER})^{L_{\text{H}}}\}]\left[\frac{\eta_s}{\eta_s + \eta_g}\right]. \end{aligned} \tag{9}$$

After obtaining the expression for the transmit throughput per node per second, we have to find an expression for the average number of nodes within the communication range of a given node (i.e., the average number of neighbors for a given node). In Fig. 7, the rectangular field is partitioned into three different regions according to the coverage characteristic of a node in a particular region. For example, a node inside region 1 (e.g., n_2) has its full coverage within the boundaries of the field. Therefore, any node inside region 1 utilizes 100% of its total coverage. Whereas nodes inside regions 2 and 3 (e.g., n_1 and n_3) have a part of their coverage outside the field of interest and consequently the average percentage coverage for these nodes is less than 100%. Finding the percentage coverage for each region will lead us to the average number of neighbors.

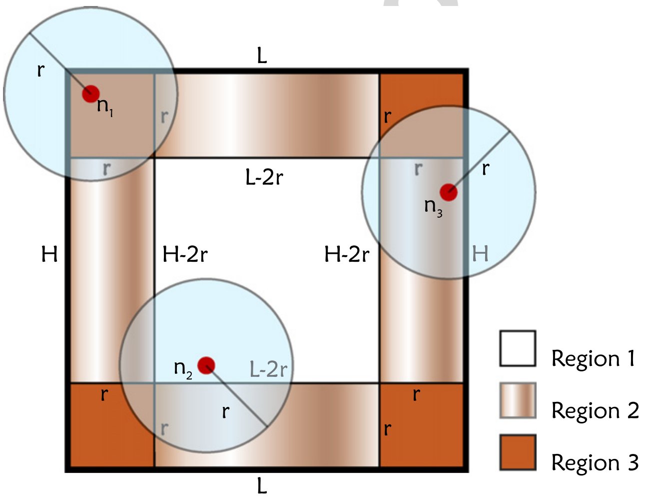

Fig. 7. Rectangular field partitioned into three different regions.

We start the derivation of the percentage with region 2. In Fig. 8 the approach we used for obtaining the percentage is given. The area of the piece of circle shaded in Fig. 8 can be expressed as follows:

$$\begin{aligned} I &= \int_{x_0}^{r} \sqrt{r^2 - x^2}\, dx \\ &= \frac{\pi}{4}r^2 - \frac{x_0}{2}\sqrt{r^2 - x_0^2} - \frac{r^2}{2}\arcsin\left(\frac{x_0}{r}\right). \end{aligned} \tag{10}$$

Thus, the average coverage for region 2 (α_2) becomes,

$$\begin{aligned} \alpha_2 &= \frac{1}{r}\int_0^r A(x_0)\, dx_0 = \frac{1}{r}\int_0^r \left(\pi r^2 - 2I(x_0)\right) dx_0 \\ &= \pi r^2 - \frac{2}{3}r^2. \end{aligned} \tag{11}$$

After obtaining the average coverage as in Eq. (11), we can easily calculate the percentage coverage of region 2 (σ_2).

$$\sigma_2 = \frac{\alpha_2}{\pi r^2} = 1 - \frac{2}{3\pi}. \tag{12}$$

Next we derive the average coverage for region 3 (σ_3). The area in question is divided into three parts (see Fig. 9). According to this partitioning, we have $A = \pi r^2 - (A_1 + A_2 - A_3)$, which is the coverage for a node inside region 3. The integrals for A_1 and A_2 are the same as I given in Eq. (10) and can be expressed as $2I(x_0)$ and $2I(y_0)$, respectively.

$$\begin{aligned} A_3 &= \int_{x_0}^{\sqrt{r^2 - y_0^2}} \left(\sqrt{r^2 - x^2} - y_0\right) dx \\ &= -\frac{y_0\sqrt{r^2 - y_0^2}}{2} + \frac{r^2 \arcsin\left(\frac{\sqrt{r^2 - y_0^2}}{r}\right)}{2} \\ &\quad - \frac{x_0\sqrt{r^2 - x_0^2}}{2} - \frac{r^2 \arcsin\left(\frac{x_0}{r}\right)}{2} + y_0 x_0. \end{aligned} \tag{13}$$

After obtaining A_3, we can calculate the average coverage α_3 by taking the average of A.

$$\alpha_3 = \frac{1}{r^2}\int_0^r \int_0^r A(x_0, y_0)\, dx_0\, dy_0 = \pi r^2 - \frac{29}{24}r^2. \tag{14}$$

Thus, σ_3 becomes

$$\sigma_3 = \frac{\alpha_3}{\pi r^2} = 1 - \frac{29}{24\pi}. \tag{15}$$

This is the last percentage coverage we needed to calculate the overall percentage coverage (σ), or the average number of nodes within the range of a given node inside the rectangular field. Below we give the resulting σ in terms of the communication radius r, the length of the field L and the height of the field H.

$$\sigma = \frac{\sigma_1(L - 2r)(H - 2r) + 2\sigma_2(H + L - 4r)r + 4\sigma_3 r^2}{LH} \tag{16}$$

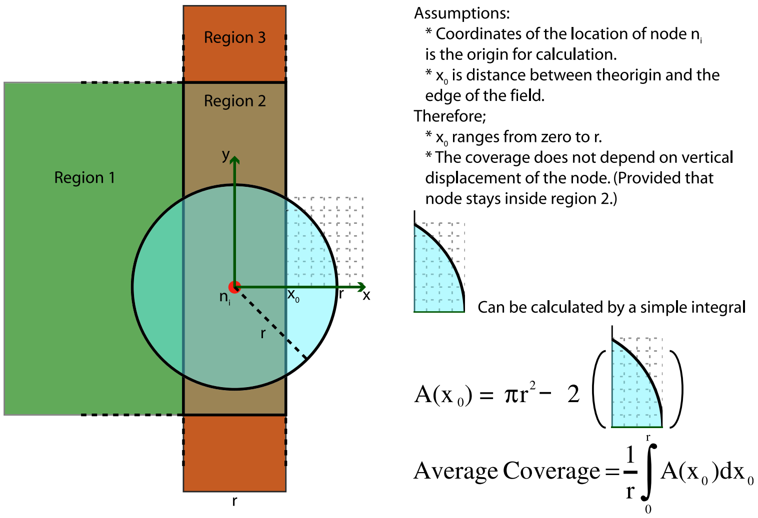

Fig. 8. Calculation of the percentage coverage of a node inside region 2.

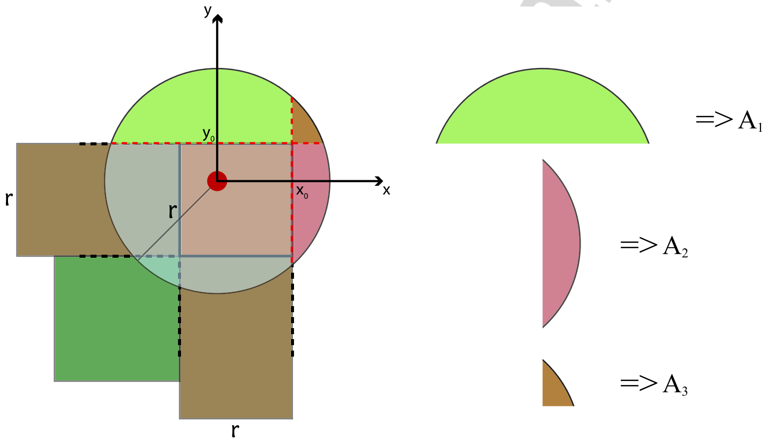

Fig. 9. Calculation of the percentage coverage of a node inside region 3.

This expression can be used to calculate the average number of neighboring nodes (N_{N}) for a node inside of a rectangular field by multiplying σ with πr^2 (i.e., the coverage of a node with communication radius r) and the node density $\left(\frac{(N-1)}{LH}\right)$. Note that there are $N-1$ nodes remaining that can be neighbors.

$$N_{\mathrm{N}} = \frac{(N-1)\sigma\pi r^2}{LH}. \tag{17}$$

Now, we can combine Eq. (17) with Eq. (9) to get the receive throughput per node per second, T.

$$T = N_{\mathrm{N}} \times T_{\mathrm{node}} \times (1 - \mathrm{BER})^{L_{\mathrm{D}}} \tag{18}$$

According to our model, given that we have a constant simulation area and the same traffic model, throughput increases as the number of nodes in the network increases. In other words, the model suggests that throughput increases linearly with increasing node density. However, our previous work showed that throughput per node per second goes into saturation as the number of nodes in the network increases (see Fig. 10). This trend is a result of packet collisions and drops emerging from mobility and increased contention for channel access [9]. According to this fact, we have to modify our initial throughput value (throughput when there is a perfect channel) in order to get a more accurate model for throughput. Since it is extremely challenging to model the dynamical behavior in Fig. 10 analytically, the initial throughput values are calibrated according to feedback from simulation results.

5. Simulations

5.1. Simulation environment

To test the performance of MH-TRACE and IEEE 802.11 with increasing BER levels and to test the validity of our model, we ran simulations using the ns-2 network simulator [33]. We simulated conversational voice coded at 32 Kbps with VAD (see Section 4.2), which corresponds to one voice packet per superframe. The channel rate is set to 2 Mbps and the standard IEEE 802.11 physical layer is employed for both protocols. All the simulations are run

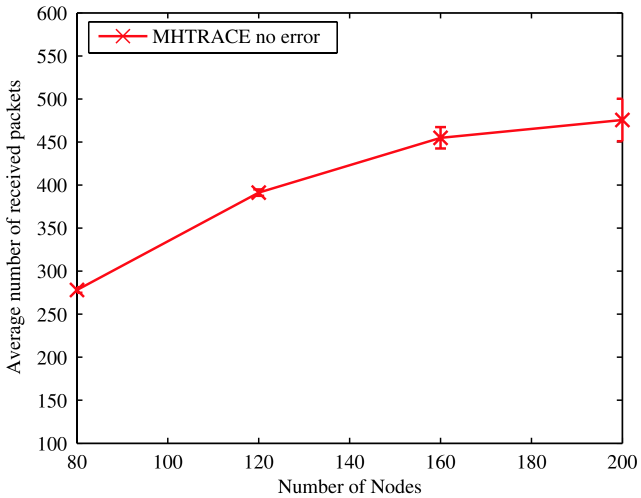

Fig. 10. Average number of received packets per node per second versus number of nodes (mobile).

with 100 or 200 nodes, moving within a 1 km by 1 km area for 100 s according to the random way-point (RWP) mobility model with node speeds chosen from a uniform distribution between 0.0 and 5.0 m/s. In this work, we use 5.0 m/s, which is the average pace of a marathon runner, as our upper limit; however, we have observed that the performance of single-hop broadcasting in MH-TRACE does not change with increased mobility. Pause time is set to zero to avoid any non-moving nodes throughout the simulations. The transport agent used in the simulations is User Datagram Protocol (UDP), which is a best effort service. The simulations are repeated with the same parameters six times, and the data points in the figures are the average of the ensemble. Acronyms, descriptions, and values of the parameters used in the simulations are presented in Tables 1 and 2.

Beacon, CA, contention, and IS packets are all 4 bytes. The header packet has a variable length of 4–18 bytes, consisting of 4 bytes of packet header and 2 bytes of data for each node to be scheduled. Data packets are 104 bytes long, consisting of 4 bytes of packet header and 100 bytes of data. Each slot or sub-slot includes 16 μs of guard band (IFS) to account for switching and round-trip time.

We used the standard energy and propagation models of ns-2 [33] without any modifications. Transmit power, P_T, consists of a constant transmit electronics part and a variable power amplifier part. The propagation model is a hybrid propagation model, which assumes Free-Space propagation for short distances and Two-Ray Ground propagation for long distances. In the simulations, we used

Table 2
Simulation setup

Parameter	Value
Number of nodes	100 & 200
Simulation area	1000 m × 1000 m
Simulation time	200 s
Number of repetitions	6

a constant transmit power, which results in a constant transmission range, D_{Tr}, of 250 m and constant carrier sense range, D_{CS}, of 507 m. Receive power, P_R, is dissipated entirely on receiver electronics. Idle power, P_I, is the power needed to run the electronic circuitry without any actual packet reception. In sleep mode, the radio is just shut down so sleep mode power, P_S, is very low.

In this study, we want to evaluate the performance of the MAC protocols; thus, the scenario we employ is single-hop data broadcasting, which does not require a routing protocol on top of the MAC protocol. Furthermore, in single-hop broadcasting, the overall performance (e.g., energy dissipation, QoS, etc.) is directly determined by the performance of the MAC protocol.

5.2. Throughput

Figs. 11 and 12 present the throughput of MH-TRACE and IEEE 802.11 obtained from analytical models and simulations as functions of BER with 100 nodes and 200 nodes, respectively. Throughput is defined as the average number of received bit error-free data packets per node per second. The analytical model developed in Section 4 (Eq. (18)) for MH-TRACE is in very good agreement with the simulation results presented in the figures. The model for IEEE 802.11 is obtained by using the probability of successful data packet transmission ($(1 - \text{BER})^{L_D}$) and the initial throughput value, which also closely follows the simulation results for IEEE 802.11.

The difference between the initial throughput values of MH-TRACE, where the BER rate is too low to affect the throughput (i.e., BER $<10^{-4}$), for the 100-node network (see Fig. 11) and the 200-node network (see Fig. 12) is due to the fact that both the number of transmissions and receptions are directly proportional to the total number of nodes in the network; thus, when the number of nodes is doubled, in ideal conditions, total throughput should be quadrupled. Hence, the throughput per node should be doubled. However, non-idealities, such as packet drops, keeps the throughput less than the ideal value. IEEE 802.11 throughput for the 200-node network is lower than

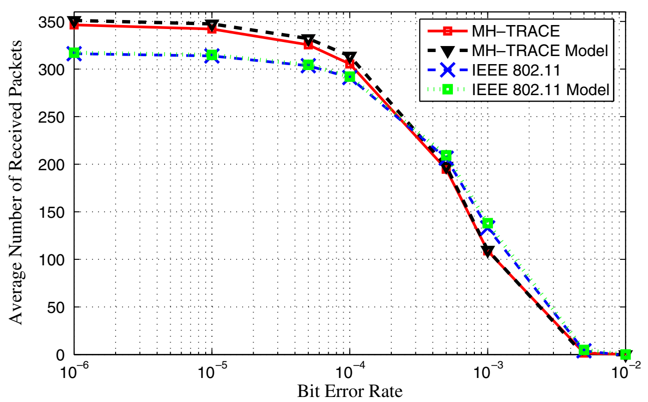

Fig. 11. (100 nodes) Average number of received packets per node per second versus bit error rate (BER).

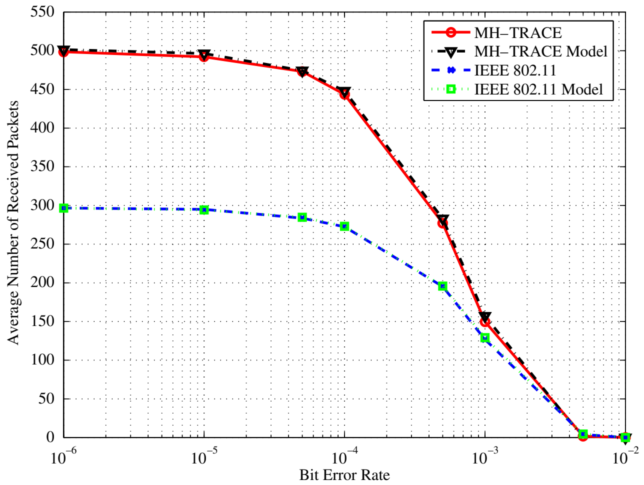

Fig. 12. (200 nodes) Average number of received packets per node per second versus bit error rate (BER).

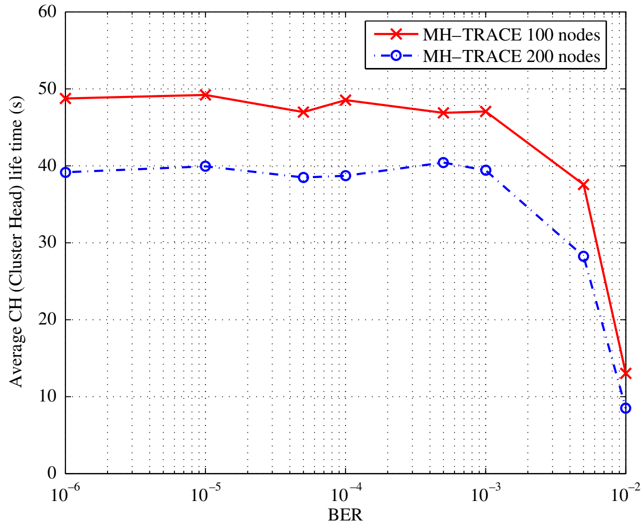

Fig. 13. Average CH lifetime versus bit error rate (BER).

the 100-node network throughput because of a very high collision rate. Note that while IEEE 802.11 collision resolution mechanism (i.e., *p*-persistent CSMA in broadcasting) has a similar performance with MH-TRACE in the 100-node network, it becomes increasingly ineffective with the increasing node density (i.e., IEEE 802.11 throughput is 60% of MH-TRACE throughput in the 200-node network).

There are two mechanisms that decrease the throughput of MH-TRACE with increasing BER: (i) with the increasing BER, more data packets are corrupted, which is also true for IEEE 802.11. Thus, the throughput decreases with increasing BER and (ii) the increase of the corrupted header packets results in unutilized data slots for MH-TRACE, whereas in IEEE 802.11 this is not a problem due to the lack of header packets. This situation creates an interesting tradeoff: while scheduling through header packets results in very high channel utilization in congested networks, it prevents nodes from channel utilization in high BER levels. However, when we examine the figures we see that MH-TRACE throughput is lower than IEEE 802.11 throughput only in low node density networks and only for extremely high BER levels (i.e., the 100-node network and BER $\geqslant 10^{-3}$). Note that at BER $= 10^{-3}$ only 45% of the data packets are non-corrupted, which is not an acceptable operating condition. For all other situations, MH-TRACE throughput performance is better than IEEE 802.11. Furthermore, in the 200-node network MH-TRACE throughput never drops below that of IEEE 802.11 throughput at any BER level. Thus, coordination through header packets is preferable over non-coordination regardless of the BER level of the network, especially in high congestion networks, from a throughput performance point of view.

5.3. Stability

Fig. 13, presents the average clusterhead lifetime for the 100-node network and the 200-node network as a function of BER. Only the clusterheads that have a minimum lifetime of $10T_{SF}$ are counted in order to filter frequent clusterhead changes due to mobility and collisions so that only stable clusterheads are taken into consideration. Average clusterhead lifetime in the 100-node network is higher than the clusterhead lifetime in the 200-node network due the fact that the average number of clusterheads in a denser network is higher than the average number of clusterheads in a sparser network. This is because in sparse networks some areas are not covered by any clusterhead, and in fact, these areas are unpopulated by any node. On the other hand, in dense networks there are barely any uncovered areas. Thus, the total coverage of dense networks is higher, which can be made possible by higher number of clusterheads. A higher number of clusterheads in the same network topology (i.e., 1 km by 1 km network) results in less inter-clusterhead separation on the average, which increases the chance of one clusterhead moving into another's transmission range and resigning (i.e., there cannot be any other clusterhead in the receive range of a clusterhead). Therefore, the average clusterhead lifetime in the 200-node network is lower than the average clusterhead lifetime in the 100-node network.

Clusterhead stability is not significantly affected by the BER level of the network for relatively low BER levels (i.e., BER $\leqslant 10^{-3}$). This is because only 4% of beacon packets are corrupted at BER $= 10^{-3}$, on the average. However, at BER $= 10^{-2}$, more than a quarter of the beacon packets are corrupted, which results in significantly shorter average clusterhead lifetime. Note that a node starts to contend for being a clusterhead if it does not receive a beacon packet for two consecutive superframes. Nevertheless, at BER $= 10^{-2}$, 99.98% of the data packets are corrupted. Thus, maintaining a cluster structure is not a meaningful consideration at such high BER levels.

5.4. Packet delay

Fig. 14 presents the average data packet delay for MH-TRACE and IEEE 802.11 as a function of BER. Data packets are dropped at the MAC layer if the data packet delay exceeds T_{drop}, which is 50 ms. MH-TRACE packet delay is higher than IEEE 802.11 packet delay at all BER levels in both the 100-node network and the 200-node network due to the fact that in MH-TRACE nodes can have channel access only once in a superframe time, whereas in IEEE 802.11 channel access is not restricted. MH-TRACE has comparatively higher packet delays as the BER level increases towards 10^{-3}. The increase in the packet delay in MH-TRACE is mainly due to the header packet losses, as once a node looses a header packet, it loses several frame times before regaining channel access. IEEE 802.11 packet delay is almost constant. Packet delay is not very informative for BER levels higher than 10^{-3}, because the throughput decreases to unacceptably low values. Average packet delay is higher in denser networks for both MH-TRACE and IEEE 802.11 due to the fact that higher channel utilization brings longer delays at the queue. The delay of MH-TRACE for both node densities tends to converge to similar values when BER $>10^{-3}$. Although it is less obvious, the same behavior is also present in IEEE 802.11 case.

5.5. Energy dissipation

One of the most important advantages of MH-TRACE over IEEE 802.11 is its better energy efficiency. Average energy dissipation per node per second for MH-TRACE and IEEE 802.11 with 100 and 200 nodes as a function of BER are presented in Fig. 15. MH-TRACE energy dissipation under all BER levels and node densities is less than 40% of the energy dissipation of IEEE 802.11.

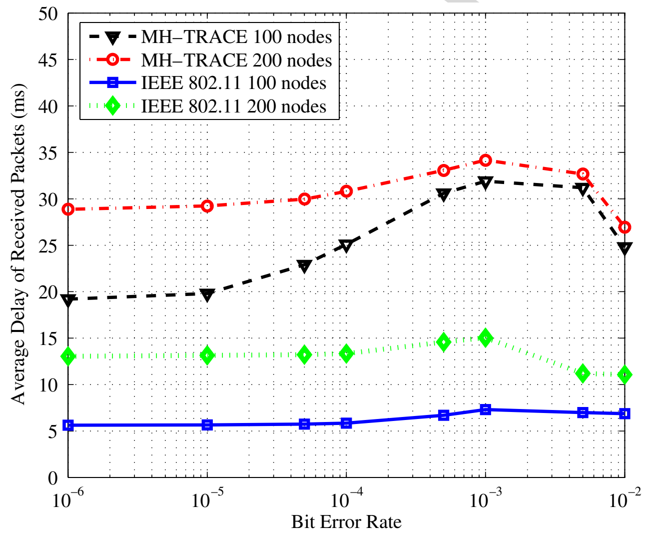

Fig. 14. Average data packet delay versus bit error rate (BER).

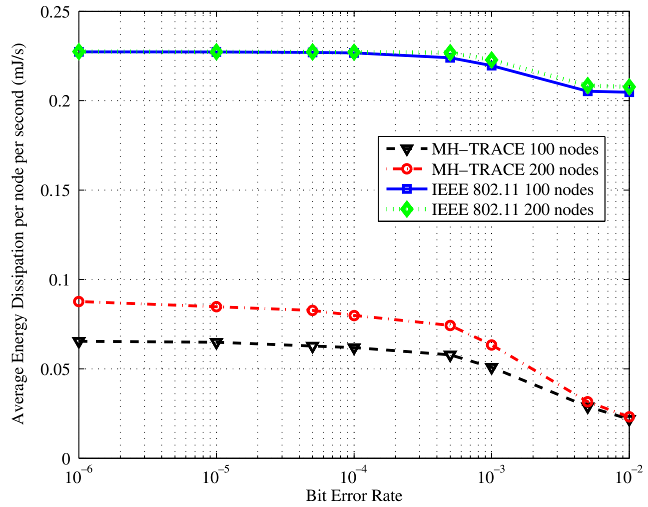

Fig. 15. Average energy consumption per node per second versus bit error rate (BER).

IEEE 802.11 energy dissipation does not show any significant change with increasing BER due to the fact that the dominant energy dissipation terms in IEEE 802.11 are receive and carrier sensing and they are not significantly affected by the BER. This is because the energy dissipated for receiving a non-corrupted packet and a corrupted packet is the same. Furthermore, in carrier sensing only the presence of the carrier is important, which is not affected by the BER level of the network. Packet transmissions are also not related with BER level (i.e., data packets are coming from the application layer and they are not routed). IEEE 802.11 energy dissipations in the 100-node network and the 200-node network are very close because the network is already in saturation conditions in the 100-node network (i.e., full channel utilization) and this situation does not change in the 200-node network (i.e., energy dissipated for a successful reception is the same with energy dissipated on a completely overlapping collision) from an energy dissipation point of view.

MH-TRACE energy dissipation is higher for the 200-node network than the 100-node network, because of the increase in channel utilization. Note that MH-TRACE is not utilizing all of the available bandwidth in the 100-node network (i.e., a significant portion of the data slots are unused). The reason for the sharp decrease in energy dissipation of MH-TRACE for both node densities for BER $> 10^{-3}$ is that the nodes spend most of their time in sleep mode. Since a large portion of the header packets are corrupted, nodes cannot have channel access. Note that in MH-TRACE, a node is only awake if there is a scheduled data transmission. If the header packet is not received, then the corresponding node stays in the sleep mode for the whole frame time.

6. Conclusions

In this paper, we investigated the impact of channel errors on the energy efficiency and QoS performance of

MH-TRACE and IEEE 802.11, which are examples of coordinated and non-coordinated MAC protocols, respectively. We developed an analytical model for the performance of MH-TRACE as a function of network area, number of nodes, and BER of the channel. We presented ns-2 simulations both to demonstrate the validity of the analytical model and to show the degradation in MAC protocols' (i.e., IEEE 802.11 and MH-TRACE) performance with increasing BER. As expected, the impact of channel errors is more severe on MH-TRACE than IEEE 802.11 at extremely high BER levels due to the dependence of MH-TRACE on robust control packet traffic. Nevertheless, as the node density increases, MH-TRACE performs better than IEEE 802.11 (in terms of throughput and energy efficiency) even under very high BER levels due to its coordinated channel access mechanism.

In this study, we explored the performance of coordinated and non-coordinated MAC protocols as stand-alone entities under noisy channel conditions. However, by building upon our current results we plan to extend our analysis to other layers, such as the network layer, as well. Furthermore, we considered only real-time voice communications in ad hoc networks and we will extend this work into sensor networks with different flow models and expiration deadlines.

Lessons learned from the results of this paper are not specific to MH-TRACE or IEEE 802.11. In fact, we developed our model to account for a generic schedule based coordinated MAC protocol, and the analytical model is shown to be in good agreement with the simulations, which are specific to MH-TRACE and IEEE 802.11. Thus, the major conclusion of this study is that the energy efficiency and QoS performance of coordinated MAC protocols are superior to those of non-coordinated MAC protocols. The relatively better QoS performance of non-coordinated MAC protocols at extremely high BER levels is actually deceiving due to the fact that such a low level of QoS is not beneficial to the application layer. Finally, we point out that for higher data rates or node densities coordinated protocols are expected to perform better in terms of initial throughput due to their controlled access mechanisms.

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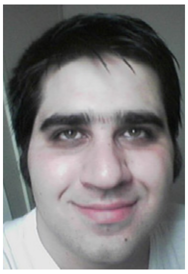

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