Hindawi Publishing Corporation
EURASIP Journal on Advances in Signal Processing
Volume 2009, Article ID 156247, 14 pages
doi:10.1155/2009/156247

Research Article

Medium Access in Spread-Spectrum Ad Hoc Networks with Multiuser Detection

Katsutoshi Kusume,[1] Robert Vilzmann,[2] Andreas Müller,[2] Christian Hartmann,[2] and Gerhard Bauch[1]

[1] *DOCOMO Euro-Labs, Landsberger Straße 312, 80687 Munich, Germany*
[2] *Institute of Communication Networks, Munich University of Technology, Arcisstraße 21, 80290 Munich, Germany*

Correspondence should be addressed to Katsutoshi Kusume, kusume@docomolab-euro.com

Received 15 February 2008; Revised 6 June 2008; Accepted 22 July 2008

Recommended by Shinsuke Hara

Conventional medium access control protocols are designed to avoid simultaneous transmissions, based on a simple collision model in the underlying physical layer. Recently, strong physical layer capabilities, enabled by multiuser detection techniques, have been studied in connection with simple medium access control protocols, for example, slotted ALOHA. We think that neither of these extreme approaches is optimum, particularly in general scenarios where network nodes with different signal processing capabilities coexist. Instead of dealing with interferences in either of the two layers alone, both medium access control and physical layer functionalities should be designed to cooperate and complement each other. We discuss several key aspects for designing such a protocol, especially with an emphasis on iterative multiuser detection, which can provide a good tradeoff between performance and complexity. We propose a new protocol called MUD-MAC which satisfies these key aspects. We analyze its throughput bound and also perform numerical simulations. The simulation results show excellent throughput improvements. It is also demonstrated that the MUD-MAC protocol provides certain fairness among network nodes with different signal processing capabilities.

1. Introduction

Traditionally, *medium access control* (MAC) protocols in ad hoc networks are designed to avoid simultaneous transmissions based on a simple collision model in the *physical* (PHY) layer. A well-known protocol of this kind is used in the IEEE 802.11 standard [1]. It blocks all neighboring nodes by exchanging so-called *request-to-send* (RTS) and *clear-to-send* (CTS) messages in order to protect a single communication link. Today, this protocol is widely used, but due to the blocking mechanism, it has a poor spatial utilization of resources.

There are a number of research activities trying to improve the spatial utilization of the IEEE 802.11 protocol, mostly by using multiple antennas. Some of the work exploit antenna gains of directional antennas (e.g., [2–6]) while the other focuses on spatial multiplexing gains (e.g., [7]). In this paper, we take a different approach that does not rely on the use of multiple antennas.

While the IEEE 802.11 protocol and its variants attempt to block simultaneous transmissions, they might not be necessarily avoided if we recall recent advances in multiuser communications at the PHY layer, as also discussed in [8]. Compared to MAC protocols providing strict collision avoidance, a better spatial utilization may then be realized. Spread-spectrum communications, such as *code division multiple access* (CDMA) (e.g., [9]) and *interleave division multiple access* (IDMA) (e.g., [10]) are suitable choices in this context. Unfortunately, it is not straightforward to apply spread-spectrum communications in ad hoc networks [11]. Most importantly, the near-far effect has to be carefully taken into account, as we discuss in the following.

One way to combat the near-far problem is power control (e.g., [12–14]). However, in contrast to the uplink of cellular networks, power control in ad hoc networks may be impractical because the required power level can be completely different at different receiver locations. To clarify this argument, let us consider the scenario illustrated on the left-hand side of Figure 1, where the two transmitters T_1 and T_2 have data to send to the receivers R_1 and R_2 using the signatures S_1 and S_2, respectively. These transmissions are in general nonorthogonal. Even if orthogonal codes are employed for S_1 and S_2, orthogonality cannot be maintained due to imperfect synchronization among nodes and channel frequency selectivities. Thus, the transmission from T_1 to R_1 also causes interference to the reception of data from T_2 at R_2. Now, a power control mechanism faces the following dilemma: if T_1 increases its power to satisfy a certain *signal-to-interference and -noise ratio* (SINR) requirement at R_1, the SINR of the reception at R_2 will severely degrade due to this increased power. A similar argument holds for the power control at T_2. Consequently, one of these transmitters might have to be silent and spatial utilization cannot be improved.

Another possible approach to cope with the near-far problem is *multiuser detection* (MUD) at the PHY layer (e.g., [7, 8, 15–19]). Power control is then not necessary. Let us again consider the scenario shown in Figure 1. Depicted on the right-hand side is the receiver at R_1 which detects and decodes not only the desired signal from T_1, but also the interference from T_2. The latter is canceled out from the received signal in order to obtain an interference-free transmission from T_1, and it is eventually discarded. The existing works focus mainly on such an improved detection capability over conventional receivers. Simple MAC protocols such as ALOHA are often considered in research on MUD in ad hoc networks (e.g., [8, 15, 16]). That is because, with MUD, the role of medium access control is to *encourage* simultaneous transmissions, in contrast to strict collision avoidance. ALOHA may be the simplest MAC protocol of this kind. However, this solution is not entirely satisfactory, in particular, when many transmitters contribute to the interference level. Then, the decoding process becomes highly complex, as pointed out but not further studied in [20].

In unison with the authors of [11], we emphasize that the question is *not* simply whether interference should be handled at the MAC *or* at the PHY layer. Instead, both MAC and PHY layer functionalities should be designed so as to cooperate and complement each other. This is particularly important in general scenarios where network nodes with different signal processing capabilities coexist. Such an integrated design of MAC and PHY functionalities is the main goal of this article. Our initial ideas were presented in part in [21, 22]. In this article, we add a more-detailed analysis and show simulation results investigating further aspects.

Besides the near-far problem, which we discussed above, there are several other practical issues which need to be addressed to make spread-spectrum communications competitive in ad hoc networks. This article discusses such issues, in particular, signature exchange and synchronization.

The remainder of this article is organized as follows. In Section 2, the PHY layer technique is briefly recalled. This is a necessary step before we proceed with an integrated design of MAC and PHY functionalities. As a means of dealing with interference, we have chosen (but not limited

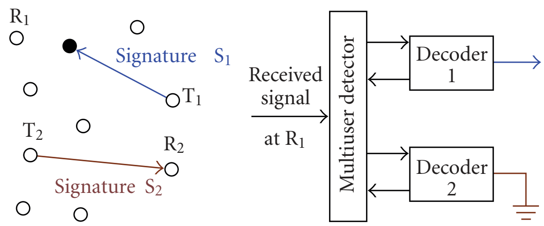

Figure 1: Multiuser detection is exploited as a means of interference cancellation in a wireless ad hoc network.

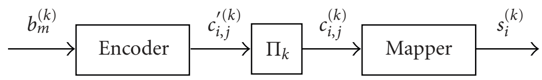

Figure 2: Transmitter structure.

to) an iterative multiuser detection since it can provide a flexible tradeoff between performance and complexity. Then, Section 3 discusses several key requirements for designing such an integrated MAC protocol on top of the PHY layer functionalities presented in Section 2. We propose a new MAC protocol called MUD-MAC which satisfies these key requirements and give some analysis on its achievable overall throughput gain over the IEEE 802.11 protocol. Some cross-layer aspects are covered in Section 4. Section 5 provides numerical simulation results. This article is concluded in Section 6.

2. Iterative Multiuser Detection

In this section we describe the iterative multiuser detection and decoding technique which is implemented for the bit-level simulations presented later. Moreover, the description in this section will also serve as a basis for the discussions on cross-layer implications in the subsequent sections.

The general transmitter structure is shown in Figure 2. At the transmitting node $k \in \{1, \dots, K\}$, information bits $b_m^{(k)}$, $m \in \{1, \dots, N_b\}$, are encoded using either a convolutional code, linear block code, repetition code, turbo code, or any combination thereof to obtain a code word $c_{i,j}^{\prime(k)}$. The code word is permuted by the interleaver Π_k. After interleaving, $c_{i,j}^{(k)}$ is then mapped onto the complex symbols $s_i^{(k)}$ which are elements of a QAM/PSK signal constellation $\mathcal{S}$ with cardinality $|\mathcal{S}| = 2^M$, where $c_{i,j}^{(k)}$ denotes the jth bit of symbol $s_i^{(k)}$, with $j \in \{1, \dots, M\}$.

The channel is modeled by an order L (possibly time-variant) finite length impulse response filter. Thus, the received signal may be expressed as

$$y_i = \sum_{k=1}^{K} \sum_{\ell=0}^{L} h_\ell^{(k)} s_{i-\ell}^{(k)} + n_i, \qquad (1)$$

where n_i is additive white Gaussian noise. Note that the channel taps $h_\ell^{(k)}$ are defined general enough to also include path-loss and transmission delay resulting from imperfect network synchronization as well as a node-specific spreading code (convolved with the multipath channel) in case of CDMA.

The receiver structure is shown in Figure 3. The number of decoder branches K' determines the capability of cancelling out interferences as well as the complexity of the receiver. Usually, most of the gain is achieved by just canceling one or perhaps two dominant interferences [11, 23]. Then, the introduced complexity and latency are limited.

A conventional receiver with only single-user detection capability is a special case where only one decoder branch is available (i.e., $K' = 1$).

Without loss of generality, the first transmitting node ($k = 1$) is considered as the intended transmitter of the receiver, the second to K'th nodes as interferers whose signals are to be cancelled out, and the rest (from $K' + 1$ to K) as remaining interferers. The multiuser detector and the decoders are soft-in-soft-out modules which cooperatively exchange soft values in order to improve the estimate $\hat{b}_m^{(1)}$ in an iterative manner. The iterative processing is concisely outlined in the following.

The multiuser detector considered here is based on the sliding window model (e.g., [24]). The received signals,

$$\mathbf{y}_i = \sum_{k=1}^{K}\sum_{\ell=-L}^{L} \mathbf{h}_\ell^{(k)} s_{i-\ell}^{(k)} + \mathbf{n}_i, \tag{2}$$

in a sliding window are used for estimating $s_i^{(1)}$, where $\mathbf{y}_i = [y_i, \ldots, y_{i+L}]^{\mathrm{T}}$, $\mathbf{n}_i = [n_i, \ldots, n_{i+L}]^{\mathrm{T}}$, and $(\cdot)^{\mathrm{T}}$ denotes transposition. The channel vector $\mathbf{h}_{\ell,i}^{(k)}$ of dimension $L+1$ can be found accordingly (e.g., [24, 25]).

Since the interferences from the $(K' + 1)$th to Kth transmitting nodes cannot be handled due to the limitation of the available decoder branches K', the iterative processing described in the following is only applied to $k = 1, \ldots, K'$.

The MUD attempts to cancel out the interferences by making use of the estimates from the decoders. This is called *soft interference cancellation*:

$$\tilde{\mathbf{y}}_i^{(k)} = \mathbf{y}_i - \sum_{k'=1}^{K'}\sum_{\ell=-L}^{L} \mathbf{h}_\ell^{(k')} \tilde{s}_{i-\ell}^{(k')} + \mathbf{h}_0^{(k)} \tilde{s}_i^{(k)}, \tag{3}$$

where the channels for $k = 1, \ldots, K'$ transmitting nodes are assumed to be known. Later, we will discuss how the channel estimation can be performed under practical assumptions in our approach. The soft symbol estimates $\tilde{s}_i^{(k)}$ are computed as

$$\tilde{s}_i^{(k)} = \sum_{s\in\mathcal{S}} sP\left\{s_i^{(k)} = s\right\} = \sum_{s\in\mathcal{S}} s\prod_{j=1}^{M} P\left\{c_{i,j}^{(k)} = c\right\}, \tag{4}$$

where $c \in \{+1, -1\}$,

$$P\left\{c_{i,j}^{(k)} = c\right\} = \frac{1}{2}\left(1 + c\tanh\left(L_{\mathrm{a}}^{\mathrm{M}}(c_{i,j}^{(k)})/2\right)\right), \tag{5}$$

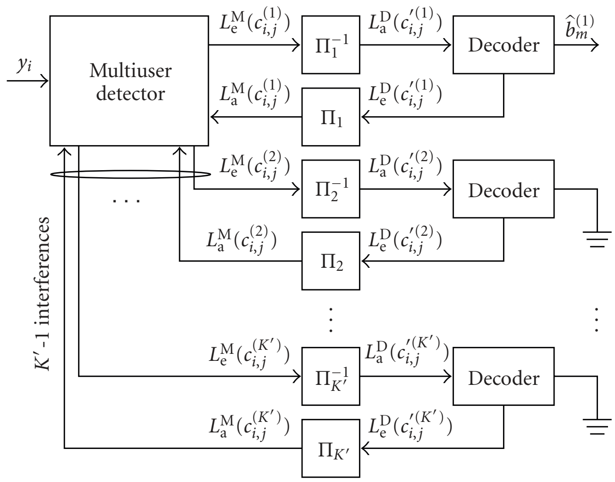

Figure 3: Receiver structure with K' decoder branches.

and the a priori *log-likelihood ratio* (LLR), sent from the decoder, is defined as

$$L_{\mathrm{a}}^{\mathrm{M}}\left(c_{i,j}^{(k)}\right) = \log\frac{P\left\{c_{i,j}^{(k)} = +1\right\}}{P\left\{c_{i,j}^{(k)} = -1\right\}}, \tag{6}$$

which is initialized to 0 before the first iteration, that is, $c_{i,j}^{(k)}$ is equally likely to be +1 and −1. The signals $\tilde{\mathbf{y}}_i^{(k)}$ after the soft interference cancellation are used for computing the a posteriori LLR:

$$L^{\mathrm{M}}\left(c_{i,j}^{(k)}\right) = \log\frac{P\left\{c_{i,j}^{(k)} = +1 \mid \tilde{\mathbf{y}}_i^{(k)}\right\}}{P\left\{c_{i,j}^{(k)} = -1 \mid \tilde{\mathbf{y}}_i^{(k)}\right\}}. \tag{7}$$

The MUD computes the extrinsic LLR: $L_{\mathrm{e}}^{\mathrm{M}}(c_{i,j}^{(k)}) = L^{\mathrm{M}}(c_{i,j}^{(k)}) - L_{\mathrm{a}}^{\mathrm{M}}(c_{i,j}^{(k)})$, which is sent to the decoder after deinterleaving by Π_k^{-1} (cf. Figure 3). The computation of $L^{\mathrm{M}}(c_{i,j}^{(k)})$ is beyond the scope of this article, and interested readers are referred to [24, 25], for example, for CDMA as well as for IDMA.

Each decoder receives the a priori LLR,

$$L_{\mathrm{a}}^{\mathrm{D}}\left(c_{i,j}'^{(k)}\right) = \log\frac{P\left\{c_{i,j}'^{(k)} = +1\right\}}{P\left\{c_{i,j}'^{(k)} = -1\right\}}, \tag{8}$$

which is the deinterleaved version of $L_{\mathrm{e}}^{M}(c_{i,j}^{(k)})$, and computes the a posteriori LLR $L^{\mathrm{D}}(c_{i,j}'^{(k)})$. This computation is done by a standard function [26] and will not be further discussed here. Similar to the MUD, the extrinsic LLR is computed as $L_{\mathrm{e}}^{\mathrm{D}}(c_{i,j}'^{(k)}) = L^{\mathrm{D}}(c_{i,j}'^{(k)}) - L_{\mathrm{a}}^{\mathrm{D}}(c_{i,j}'^{(k)})$, and it is sent to the MUD as the a priori LLR $L_{\mathrm{a}}^{M}(c_{i,j}^{(k)})$ after interleaving by Π_k (cf. Figure 3).

Repeating the above procedure can improve the performance. If the soft estimates become perfect after some iterations (i.e., $\tilde{s}_i^{(k)} = s_i^{(k)}, k \in \{1, \dots, K'\}$), then from (2) and (3) we get

$$\tilde{\mathbf{y}}_i^{(1)} = \mathbf{h}_0^{(1)} s_i^{(1)} + \sum_{k'=K'+1}^{K} \sum_{\ell=-L}^{L} \mathbf{h}_\ell^{(k')} s_{i-\ell}^{(k')} + \mathbf{n}_i \quad \text{if } \tilde{s}_i^{(k)} = s_i^{(k)}, \quad \forall k \in \{1, \dots, K'\}, \ \forall i. \tag{9}$$

This means that the intersymbol interference ($k = 1, \ell \neq 0$) as well as multiple access interference ($k = 2, \dots, K'$) are completely cancelled out, but some interference ($k = K' + 1, \dots, K$) still remains. Later, we will come back to this point for the discussion on crosslayer aspects in Section 4.2.

After a sufficient number of iterations, the decoder also computes the a posteriori LLR of the information bits (not only for code bits $L^{\mathrm{D}}(c_{i,j}^{\prime(k)})$) and taking its sign gives the estimates of the information bits:

$$\hat{b}_m^{(1)} = \operatorname{sign}(L^{\mathrm{D}}(b_m^{(1)})). \tag{10}$$

3. Medium Access Control Protocol Design

3.1. Requirements to support multiuser detection. The following items are identified as essential requirements for the MAC protocol design on top of various multiuser detection capabilities in the underlying PHY layer that are discussed in Section 2. We elaborate each aspect below.

Requirements.

(R1) frame level synchronization,

(R2) signature exchange,

(R3) adaptive control of interference level.

The multiuser detector introduced in the previous section is a block processing scheme, that is, multiple data blocks are transmitted simultaneously by multiple nodes within a certain finite duration and are processed at the same time. Completely asynchronous transmissions may introduce dependencies among multiple packets, as illustrated in the upper part of Figure 4. Due to the detection and cancellation of mutual intra- and interframe interference, these dependencies can cause unacceptably long delays. Moreover, since new interference can arise at any point of time during the decoding of the desired signal due to the lack of synchronization, the decoding and channel estimation tasks can become highly complex in the PHY layer. Therefore, frame level synchronization as illustrated in the lower part of Figure 4 is a desired requirement (R1). A finer level of synchronization in a chip or bit level is not necessary, as discussed in Section 2. Such a frame or slot level synchronization is also assumed in conventional systems like slotted ALOHA [27] or in more recently proposed systems such as [28, 29]. Network synchronization (R1) may be realized by [30–32], for example, and will not be further discussed in this article.

Spread-spectrum communications support simultaneous transmissions by applying user-specific signatures such

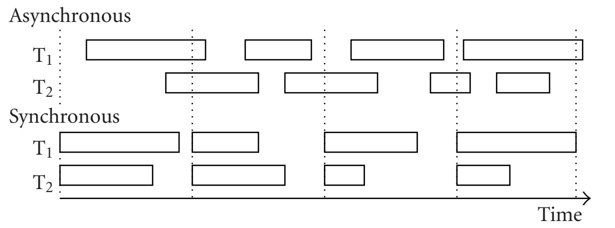

Figure 4: An example of asynchronized and synchronized transmissions.

as spreading codes and interleavers for CDMA and for IDMA, respectively. To enable receivers to separate the signals, signature exchange is clearly required (R2). Two kinds of overhead for satisfying this requirement are generally well recognized. First, distinct signature sequences have to be assigned to different nodes without a central control unit and the assignment has to be updated according to topology changes. Second, network nodes have to keep monitoring the channel to identify when and which nodes start transmitting their data. In order to be able to cancel incoming interference, receiving nodes must monitor the activity on the whole set of signature sequences as potential interference sources. Furthermore, the required channel estimation can become quite complex as well. Unlike the first overhead, the second one is not a direct crosslayer overhead, but it is nevertheless inherent to spread-spectrum communications in ad hoc networks *in general* and can be significant in terms of hardware requirement or battery consumption. In the next subsection, we present our new protocol that is designed such that these two kinds of overhead are avoided.

The adaptive control of the interference level (R3) is often neglected in the literature. Conventional approaches, which are often based on the ALOHA protocol, obviously do not satisfy (R3) since any transmission takes place independently of the amount of interference in the current medium. The other extreme is the IEEE 802.11 protocol which may be too pessimistic about the signal processing capability in the PHY layer. To satisfy (R3), a tighter cooperation between the MAC and PHY layers than conventionally considered is necessary. The interference level has to be controlled by the MAC layer so that not too many transmitters send at once beyond decoding capabilities at receivers, as pointed out but not studied in [20]. That is particularly important for simpler receivers like sensors, which would, otherwise, face tremendous difficulties to decode any message on the medium.

3.2. A new medium access control protocol: MUD-MAC. In this subsection, we introduce our new MUD-MAC protocol that is designed to fulfill the afore-discussed requirements (R1)–(R3) for multiuser detection aware MAC protocols.

In MUD-MAC, each data packet is split into several blocks as shown in Figure 5. Here, packet is a maximum resource unit which can be allocated at a time. The reason why we split a packet into blocks will become clear later.

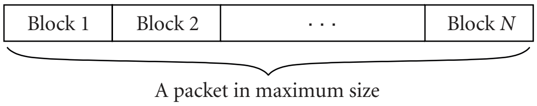

FIGURE 5: A packet in maximum size is split into N blocks to convey N_b information bits. N is the design parameter. Generally, $n \in \{1, \dots, N\}$ blocks can be allocated as a packet.

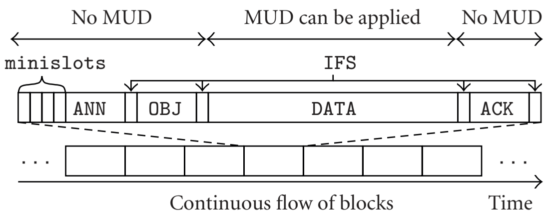

FIGURE 6: Frame structure of new medium access control protocol: MUD-MAC.

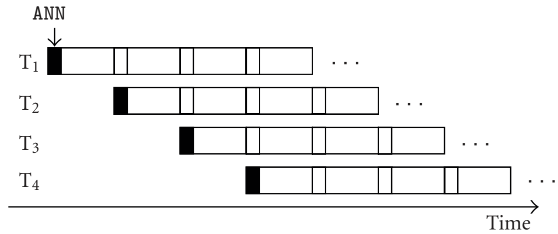

FIGURE 7: An example of initiating parallel transmissions ($n = 4$).

The maximum number of blocks N for conveying N_b information bits is a design parameter and will be discussed in Section 3.3. At this moment, it is sufficient to remember that block is a minimum data unit for resource allocation and $n \in \{1, \dots, N\}$ successive blocks can be allocated as a packet at each medium access.

Data transmissions are organized in a continuous flow of blocks as shown in Figure 6 where network nodes are assumed synchronized to be able to follow the slotted structure as we discussed in Section 3.1(R1). Each block comprises minislots, announcement message `ANN`, objection message `OBJ`, data payload `DATA`, acknowledgment message `ACK`, and interframe spacing `IFS` as a guard time to separate these messages. We note that basic ideas of MUD-MAC are similar to the BeamMAC protocol [33], but the latter neither necessarily requires network synchronization nor splits packets into blocks.

The channel access control mechanism is based on the signaling messages `ANN` and `OBJ` [33]. Each packet transmission using n successive blocks has to be announced by the transmitter using the `ANN` slot prior to the data transmission, and any surrounding nodes, which listen to it, may object to the announcement in the following `OBJ` slot, depending on the interference level and the receiver capability. If no `OBJ` is received, the transmitter proceeds with the packet transmission using n successive blocks. We note that only one `ANN` is transmitted for each packet of n blocks and the remaining $n - 1$ `ANN` slots within the packet may be utilized by other surrounding nodes to initiate new transmissions in parallel to that packet. An example ($n = 4$) is illustrated in Figure 7.

In contrast to the IEEE 802.11 MAC protocol, where both RTS and CTS messages block neighboring nodes, only receiving nodes can block a transmission request with MUD-MAC. Therefore, no exposed terminal problem is caused, which is inherent to the IEEE 802.11 protocol. The hidden terminal problem does not occur, either, since any node must send an `ANN` giving all surrounding nodes a chance to object to the prospective data transmission. Furthermore, an actively receiving node does not block all simultaneous transmissions, but only those which would cause unacceptable interference to the current own data reception are blocked. This mechanism has, thus, a potential for achieving higher network load, reflecting signal processing capabilities of individual network nodes. Consequently, the interference level is adaptively controlled (R3).

Since the exchange of control signaling messages (`ANN`, `OBJ`, and `ACK`) has fundamental importance, the protocol is designed such that the detection of signaling messages does not demand strong signal-processing capabilities (cf. Figure 6). Simultaneous transmissions of control signaling messages are, therefore, regarded as collisions. The min`islots` are introduced to reduce the probability of `ANN` collisions. Each node, which intends to transmit an `ANN`, randomly selects one of the `minislots` and starts transmitting the `ANN` in that slot, unless it detects any `ANN` from other nodes before the chosen slot. If the node loses this `ANN` contention resolution, it backs off for a randomly chosen duration. This mechanism provides simple nodes with an opportunity to understand control signaling messages, even if surrounding nodes are multiuser-detection-capable. In other words, the medium access is not completely dominated by strongly multiuser-detection-capable nodes. That is not possible for conventional approaches with multiuser detection (e.g., [7, 8, 15, 16]) where not only data but also control signaling messages are transmitted in parallel.

Upon receiving an `ANN`, each receiver has to make its own decision whether an `OBJ` has to be issued. The following three cases are considered:

(1) `ANN` is not sensed,

(2) `ANN` is sensed, but cannot be decoded, or

(3) `ANN` is decoded.

The receiver obviously does not need to object in the first case. In the second case, the new incoming transmission will cause additional interference to `DATA` and, therefore, the receiver issues an `OBJ` if the resulting overall interference level in `DATA` becomes intolerable. The third case has to be treated most carefully. The receiver issues an `OBJ` if the interference cannot be handled according to its interference cancellation capability. Since this decision involves quite some crosslayer aspects, we will further discuss it in Section 4.2. It should be noted that the receiver will also issue an `OBJ` in case that the ANN is addressed to itself while it is already busy receiving some data. The protocol may be extended to allow simultaneous receptions from different transmitters, but this is not considered in this article.

After transmitting an ANN, the transmitter listens for OBJs. There are those three cases, similar to the reception of ANNs. The transmitter proceeds with data transmission only if no OBJ is *sensed* (whether or not it can be decoded), otherwise, it backs off because the sensed OBJ indicates that at least one node has sent an OBJ. Multiple receivers can issue OBJs that may be corrupted at the transmitter.

A transmitter uses a signature sequence for the transmission of DATA. The signature has to be exchanged (R2) among the transmitter and the intended receiver as well as unintended neighboring nodes that wish to cancel the interference caused by the transmission. The signature exchange without a central control unit must not introduce large overhead [11]. We adopt a transmitter-based signature exchange instead of a receiver-based one (for detailed discussions, see [12]). We propose using the transmitter's unique address which has to be carried anyway as a part of the ANN message (analogous to RTS of IEEE 802.11 protocol containing two addresses of transmitter and receiver). An address as a scalar value can be used as seed of a pseudorandom generator to generate a unique spreading code or interleaver. More specifically speaking, the UMTS uplink long scrambling codes [34] and the cyclically shifted interleavers, [25, 35, 36], can be used for CDMA and IDMA, respectively, just as examples.

In this way, the signature exchange (R2) is implicitly realized via an exchange of the ANN message. Therefore, the MUD-MAC does not require the additional crosslayer overhead for exchanging and maintaining a whole set of distinct signatures, that is, however, generally inherent to spread-spectrum approach in ad hoc networks, as we discussed in Section 3.1. Moreover, the MUD-MAC does not need the monitoring overhead for the whole set of signatures, since only one ANN is allowed at a time. Each network node does not need continuous control message monitoring, but only the ANN message has to be periodically checked. It should be also noted that this mechanism simplifies channel estimation because new interference arises one after another, rather than multiple new interference sources at the same time. Since ANN transmission is interference-free, it can be easily exploited for channel estimation. That is, anyway necessary for the decoding of the ANN, and the estimated channel can be used for the reception of the subsequent DATA.

If the data transmission is successful, the data packet is acknowledged by the receiver (ACK). It should be noted that only one ACK has to be transmitted per packet although one packet is generally split into multiple data blocks.

3.3. Overall throughput bound analysis. In this subsection, we analyze the overall throughput bound of MUD-MAC and the protocol. We are interested in the bound in dense network topologies. In particular, our analysis here assumes that all network nodes are within communication range. In such topologies, the 802.11 protocol prohibits any parallel transmission. The overall throughput bound for the 802.11 excluding contention resolution overheads can be computed as

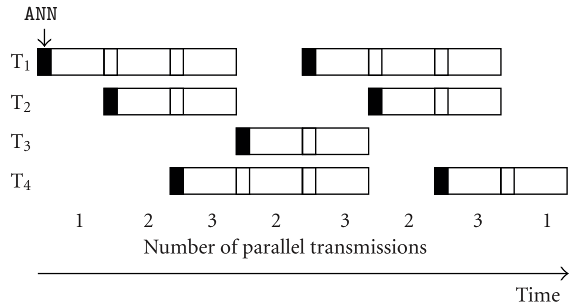

Figure 8: An example of $N = 3$ blocks per packet in maximum size (cf. Figure 5) and each transmitter can send a packet using $n \in \{1, 2, 3\}$ blocks. It demonstrates that the number of parallel transmissions in a contention area (in this example, 4 transmitters can listen to each other) is limited to $N = 3$.

$$R_{802.11} = \frac{N_b}{t_{\text{CTRL},802.11} + t_{\text{DATA}}},$$
$$t_{\text{CTRL},802.11} = t_{\text{RTS}} + t_{\text{CTS}} + t_{\text{ACK}} + t_{\text{DIFS}} + 3 \cdot t_{\text{SIFS}}. \tag{11}$$

The slot durations are summarized in Table 1. We denote by R_c and R_d transmission rates of control signalling and data, respectively. The number of information bits per packet is denoted by N_b.

In case of MUD-MAC, parallel transmissions are possible. The number of parallel transmissions is limited to N, which is the maximum number of blocks per packet. This is because the ANN/OBJ exchange mechanism preceded by the contention resolution using minislots allows only one new incoming ANN message at each ANN slot. While one packet is being transmitted, at most $N - 1$ ANN slots are available for neighboring nodes to initiate new transmissions. Thus, the number of maximum-parallel transmissions in a contention area is bounded by N. That may be better understood by an example of $N = 3$ blocks per packet illustrated in Figure 8 where at most $N = 3$ parallel transmissions can take place.

Assuming a maximum number of N parallel transmissions, the overall throughput bound for MUD-MAC reads as (cf. Figure 6)

$$R_{\text{MUD-MAC}} = \frac{N \cdot N_b}{N \cdot t_{\text{CTRL,MUD-MAC}} + t_{\text{DATA}}},$$
$$t_{\text{CTRL,MUD-MAC}} = t_{\text{ANN}} + t_{\text{OBJ}} + t_{\text{ACK}} + t_{\text{minislots}} + 4 \cdot t_{\text{IFS}}. \tag{12}$$

From (12), we see the N-fold increase in the overall data transmission, while the control signaling overhead is also increased by the factor N. Clearly, the bound in (12) is a monotonically increasing function of N.

This is illustrated in Figure 9, where the overall throughput bounds in (11) and (12) are plotted versus R_d, when $R_c = 1$ Mbit/s, $N_b = 8192$, and $N = 1$, 4, 8. The limit for $R_{\text{MUD-MAC}}$ is $N_b / t_{\text{CTRL,MUD-MAC}}$ as $N \to \infty$. Therefore, larger values for N seem to be reasonable. On the other hand, choosing an arbitrarily large N obviously does not make sense since a huge bandwidth expansion is necessary to support a large number of multiple transmissions in spread-spectrum communications. Moreover, a large N would result in significant control signaling overhead and delays if the multiplexing gains cannot be exploited because of sparse topologies or low traffic patterns. The short block length due to a large N could also have a harmful impact on the performance for iterative processing. That will be further discussed in Section 4.1.

4. CrossLayer Aspects

In this section, we discuss crosslayer aspects which have not been covered in Sections 2 and 3.

4.1. Data block size. In Section 3.3, it was shown that the overall throughput $R_{\text{MUD-MAC}}$ in (12) grows with N in dense network topologies. A large N (the number of blocks splitting packet, cf. Figure 5) results in a short block size which is, however, unfavorable for iterative MUD.

Let us consider an IDMA system with 4 equal power users, where $N_b = 8192$ information bits are split into N blocks and each block of N_b/N bits is encoded by a rate 1/4 memory 4 standard nonrecursive convolutional code, interleaved by a randomly generated user-specific interleaver, mapped on QPSK symbols, and then transmitted. The receiver applies the multiuser detection as explained in Section 2. The PER performance versus E_b/N_0 on an AWGN channel is plotted for different block sizes in Figure 10. The performance is averaged over 4 users and the result is obtained after 8 iterations. For short block sizes, severe performance degradations in high E_b/N_0 values can be observed. Therefore, the number of blocks N must not be too large.

We also note that IDMA might have an advantage over CDMA as far as the choice of N is concerned. For an equal bandwidth efficiency, larger interleaver is guaranteed for IDMA than for CDMA because CDMA spreads the signals *after* the interleaver while for IDMA, all bandwidth expansion is exploited *before* the interleaver. As we observed in Figure 10, larger interleavers can be better exploited by iterative processing. It means that MUD-MAC might achieve higher overall throughput in (12) with IDMA than with CDMA by choosing a larger N that may not cause significant performance degradation in practical systems. IDMA also opens new opportunities for complexity reduction [37] that are of particular interest in ad hoc networks.

4.2. Objection criteria and effective SINR. The objection criteria constitute an essential building block of MUD-MAC protocol. Upon receiving an `ANN` message, a receiver must decide whether an `OBJ` should be issued. The decision should depend on the signal processing capability.

Let us have a look at performance examples of an IDMA system using a rate 1/2 memory 4 standard nonrecursive convolutional code followed by a rate 1/4 repetition code. The code bits are interleaved by a user-specific interleaver and then QPSK modulated. Figure 11 shows the PER performance of a desired user perturbed by an interferer, whose relative strength is varied to observe various near-far scenarios. The performance before iteration (Figure 11(a)) corresponds to a simple node without multiuser detection capability. We see that the performance degradation becomes severe as the interference level goes up. The interference is almost completely removed after 4 iterations (Figure 11(b)), and single-user performance is approached over the whole range of interference levels.

The analysis is more complex in a general setup with more than one interferer. Nevertheless, it is a reasonably good assumption in many cases that the multiuser detection can cancel out most of the interferences when the access parameters (such as processing gain, coding rate, and block size) allow, and when the number of available MUD branches is sufficient. Thus, we introduce the notion of an effective SINR which is used for the objection criteria. Denoting the power of desired signal, noise, interferences to be cancelled, and interferences to remain by P_S, P_N, $P_{I\text{c}}$, and $P_{I\text{r}}$, respectively, the SINR is written as

$$\text{SINR} = \frac{P_S}{P_{I\text{c}} + P_{I\text{r}} + P_N}, \tag{13}$$

where from (1) and under the assumption that the signals of different transmitting nodes ($k \neq k'$) are mutually uncorrelated, we can write

$$\begin{aligned} P_S &= \sigma_s^2 \sum_{\ell=0}^{L} |h_\ell^{(1)}|^2, \qquad P_N = \sigma_n^2, \\ P_{I\text{c}} &= \sigma_s^2 \sum_{k=2}^{K'} \sum_{\ell=0}^{L} |h_\ell^{(k)}|^2, \\ P_{I\text{r}} &= \sigma_s^2 \sum_{k=K'+1}^{K} \sum_{\ell=0}^{L} |h_\ell^{(k)}|^2, \end{aligned} \tag{14}$$

and we define the signal and noise power as $\sigma_s^2 = \text{E}\{|s_i^{(k)}|^2\}$ and $\sigma_n^2 = \text{E}\{|n_i|^2\}$, respectively. Since we assume that $K' - 1$ interferences ($k = 2, \dots, K'$) can be canceled out by multiuser detection after some iterations as we discussed in Section 2, the *effective SINR* ,

$$\text{SINR}_{\text{eff}} = \frac{P_S}{P_{I\text{r}} + P_N}, \tag{15}$$

is considered as the objection criteria: if SINR_{eff} is smaller than a certain threshold, an `OBJ` should be issued.

In practice, the values in (14) have to be estimated. That may be difficult if we have to estimate them from the received signal in (1) because there might be too many channels to be estimated at once. However, if we recall the `ANN` and `OBJ` mechanism of the MUD-MAC protocol as explained in Section 3.2, each `ANN` transmission is made interference-free due to the preceding contention resolution in minislots (cf. Figure 6). Therefore, if we denote some known pilot

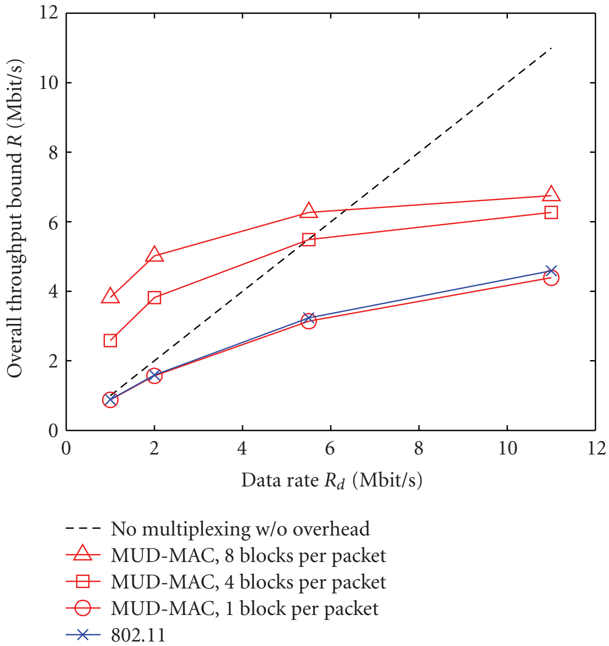

Figure 9: Overall throughput bound versus data rate R_d computed from (11) and (12) with $N_b = 8192$ and $R_c = 1$ Mbit/s.

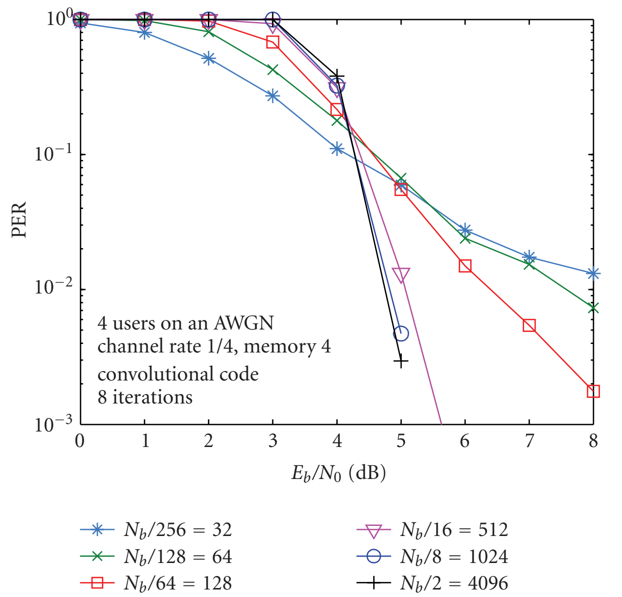

Figure 10: PER versus E_b/N_0 for different block sizes. A packet of N_b information bits are split into $N \in \{2, 8, 16, 64, 128, 256\}$ blocks and each block of N_b/N information bits is encoded and decoded separately.

sequence by p_i, which may be used in a preamble part of the ANN message, the receive signal may be expressed as

$$y_i^{\text{ANN}} = \sum_{\ell=0}^{L} h_\ell^{(k)} p_{i-\ell} + n_i, \tag{16}$$

which can be used for estimating the channel by exploiting the pilot sequence. Consequently, we can compute the estimation of the new interference power:

$$P_{I\text{new}} = \sigma_s^2 \sum_{\ell=0}^{L} |h_\ell^{(k)}|^2, \tag{17}$$

which is much simpler than estimating K channels from (1) at once. Then, $P_{I\text{new}}$ is added to $P_{I\text{c}}$, if the new interference can still be handled, otherwise, it is added to $P_{I\text{r}}$. This is how the interference power $P_{I\text{c}}$ and $P_{I\text{r}}$ can increase in a successive manner. On the other hand, an ongoing packet transmission might terminate in the previous block. In that case, the respective interference level decreases. Figure 8 can be reused to observe how the interference level changes over time. At each ANN slot, the power of an incoming interference (only one at a time) is evaluated, and if it is not objected, either $P_{I\text{c}}$ or $P_{I\text{r}}$ is increased at each node, while either of these is decreased when ongoing transmission terminates. In this way, network nodes can keep track of the SINR as well as SINR_{eff} .

Before closing the discussion on the objection criteria, let us give an extreme example in order to demonstrate the need for more advanced objection criteria as a future work. Figure 12 illustrates the PER performance of an IDMA system where the difference from the previous example is that no repetition code is applied and code bits are mapped onto 16-QAM symbols instead of QPSK. Thus, the system is operating at 8 times higher rate than the previous example. It can be observed that some interference cannot be canceled out even after 10 iterations when the interference level is intermediate: weak interference is obviously harmless, strong one is good in the sense that the multiuser detector can detect and subtract it reliably, and something in between causes a problem. Such a very high spectrally efficient scenario can be also considered by increasing the number of simultaneously transmitting users while keeping the coding and modulation parameters constant. This article will not consider such a very high spectrally efficient scenario. Nevertheless, it is worth mentioning here that more advanced objection criteria alternative to the effective SINR are necessary in order to achieve higher network efficiency, that is our current ongoing work.

4.3. Physical layer abstraction for efficient simulations. We have implemented an event-based simulator for 802.11 and MUD-MAC in C++. At runtime, the simulator calls the PHY layer implementation in MATLAB according to Section 2, which performs bit-level simulations. The bit-level simulations, however, require a long simulation time. Therefore, we introduce an optional simple PHY layer implementation. It computes the SINR_{eff} in (15) that is used for determining a PER. In Section 5, we will present the results obtained by using both of these two implementations, which seem to agree well. Therefore, a tremendous reduction in complexity can be realized without significant degradation of simulation accuracy.

Table 1: Slot durations (microseconds).

802.11		MUD-MAC	
t_{RTS}	$192 + 160/R_c$	t_{ANN}	$192 + 160/R_c$
t_{CTS}	$192 + 112/R_c$	t_{OBJ}	$192 + 112/R_c$
t_{DATA}	N_b/R_d	$t_{DATA\text{-}BLOCK}$	$N_b/N/R_d$
t_{ACK}	$192 + 112/R_c$	t_{ACK}	$192 + 112/R_c$
t_{SIFS}	10	t_{IFS}	20
t_{DIFS}	50	$t_{minislots}$	$20 \cdot n_M$

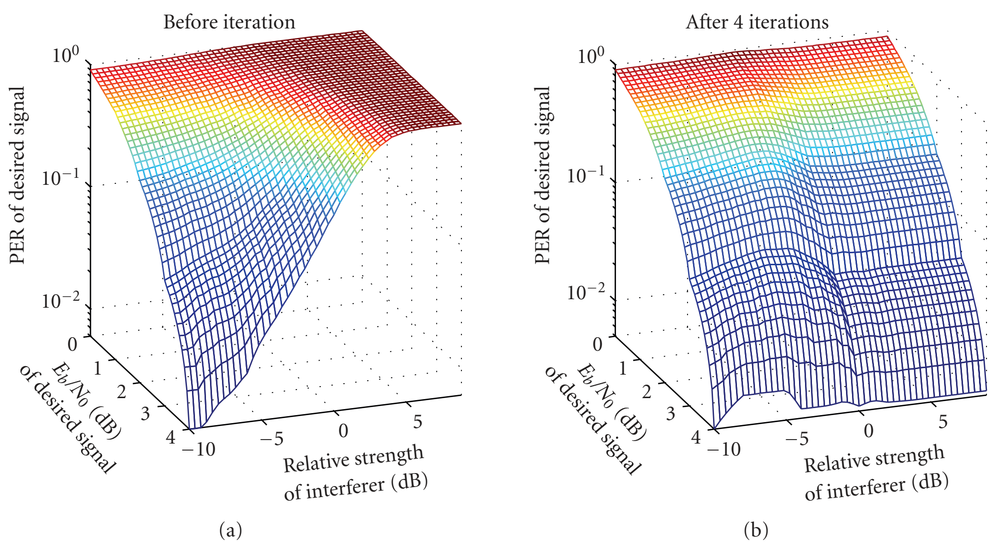

Figure 11: PER versus E_b/N_0 of the desired signal over different interference power. PER is plotted before iteration (a) and after 4 iterations (b).

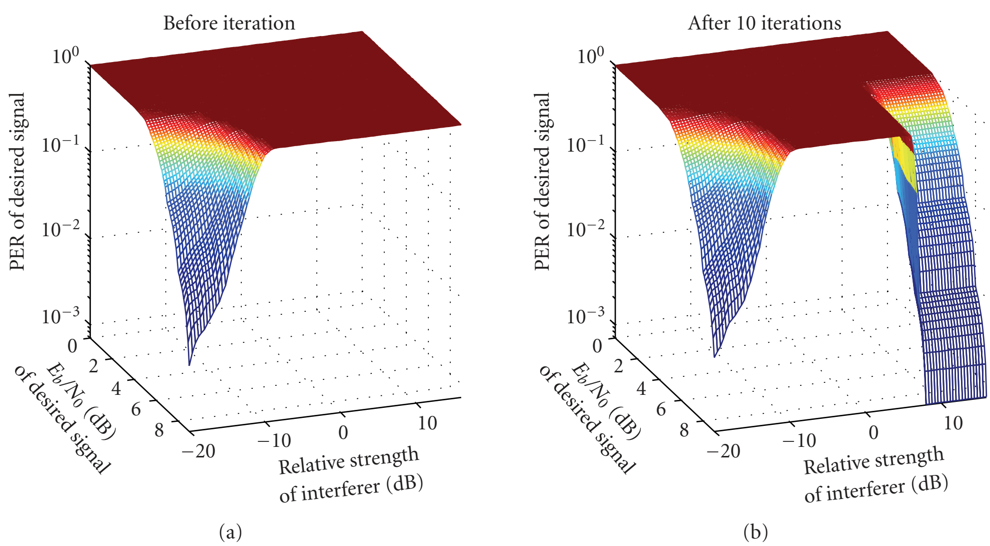

Figure 12: PER versus E_b/N_0 of the desired signal over different interference power. PER is plotted before iteration (a) and after 10 iterations (b). The system operates at 8 times higher rate than the system of Figure 11.

Furthermore, we introduce an SINR threshold, above which any transmission is considered error-free. This threshold is applied to both of the above-mentioned PHY layer implementations and is valid for SINR and $\mathrm{SINR}_{\mathrm{eff}}$ in (13) and (15).

5. Numerical Results

Numerical simulations are performed to evaluate our new MUD-MAC protocol in comparison to 802.11. The main simulation parameters are taken from [1] and are summarized in Table 2. The channel is assumed to be line-of-sight with a modified free space path loss. Although our implementation is not limited to the simple model, more realistic channel models including fading or shadowing effects are not considered in this article. Power control is by no means performed.

Several access schemes are defined for 802.11. In this article, we adopt the direct sequence spread-spectrum transmission mode where an 11-chip Barker sequence is used for spreading [1]. To be comparable to 802.11, an IDMA system with a rate 1/11 repetition code is considered for MUD-MAC. Both are uncoded systems, and bits are mapped on QPSK symbols.

Since each packet is split into $N = 4$ data blocks (2048 bits each), the maximum number of parallel transmissions is limited to 4 for the MUD-MAC as discussed in Section 3.3 (also cf. Figure 8), although more parallel transmissions can be easily supported with the rate 1/11 repetition code.

The traffic model assumes Poisson-distributed arrivals of equally sized packets.

5.1. A topology with 8 nodes. We start our study using a simple topology with 4 communication pairs as illustrated in Figure 13. Each communication pair is separated by a distance of 75 m. By varying the distance d, the protocols are confronted with different interference levels. The overall offered traffic is fixed at 8 Mbit/s.

Figure 14 shows the resulting overall throughput. In the case of 802.11, the overall throughput decreases as the radius d gets smaller and saturates at about 1.6 Mbit/s. This is expected by the analysis (cf. Figure 9 at $R_{\mathrm{d}} = 2$ Mbit/s). For large values of d, the communication pairs are independent of each other, and up to $1.6 \times 4 = 6.4$ Mbit/s can be achieved (cf. Figure 14).

In the case of MUD-MAC, two PHY layer implementations explained in Section 4.3 are tested. Since the bit-level simulations require excessive time, only a few points are simulated. The two results agree quite well. In contrast to 802.11, the overall throughput is constant regardless of the distance d due to the strong interference cancellation capability. The observed overall throughput of about 3.8 Mbit/s also agrees with the analysis (cf. Figure 9 at $R_{\mathrm{d}} = 2$ Mbit/s, 4 blocks per packet). It is higher than with 802.11 in dense topologies due to the better spatial reuse enabled by MUD. In sparse topologies, constant control signaling overhead due to the slotted structure results in lower overall throughput.

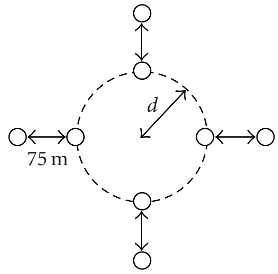

Figure 13: A topology with 4 fixed communication pairs. d is varied.

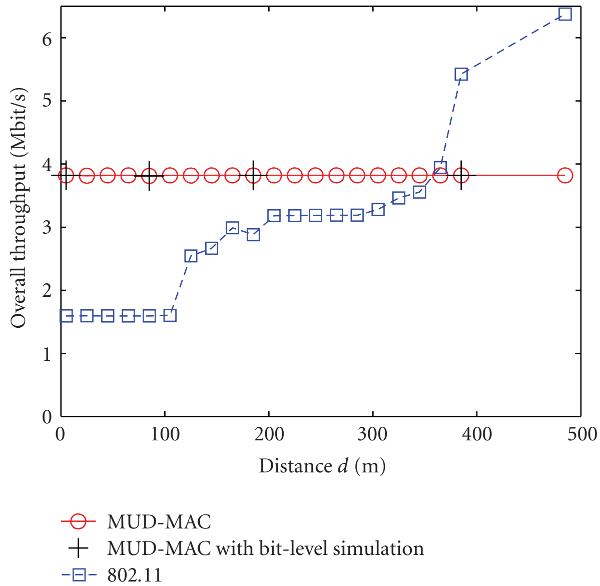

Figure 14: Overall throughput versus distance d in 8 nodes topology of Figure 13.

From the good agreement between analysis and numerical results, an even higher overall throughput in dense topologies is expected to be achievable by choosing a higher number of blocks per packet N (cf. Figure 9).

5.2. Random topologies with 50 nodes. We simulated random networks with 50 nodes in order to challenge the MUD-MAC protocol with a large variety of traffic relationships and transmission-reception constellations, and also for the multiuser detector to face a large variety of near-far scenarios. The overall throughput is averaged over many randomly generated topologies. At the beginning of each simulation run, 50 nodes are randomly placed on a $500 \times 500\,\mathrm{m}^2$ square area according to a uniform distribution, resulting in a scenario where not all nodes are in communication range. In order to provide for a clear notion of throughput, traffic relationships are restricted to single hops, and each node randomly chooses one of its neighboring nodes as sink. The offered traffic is varied by changing the mean packet

Table 2: Simulation parameters.

Control signaling bit rate R_c	1 Mbit/s	Decoding sensitivity	−81 dBm
Data bit rate R_d	2 Mbit/s	Carrier sensing sensitivity	−91 dBm
Packet size N_b	8192 bit	Carrier frequency	2 GHz
Data block size	2048 bit	Bandwidth	22 MHz
Number of minislots n_M	4	Path loss exponent	3.0
Transmission power	100 mW	SINR threshold	10 dB

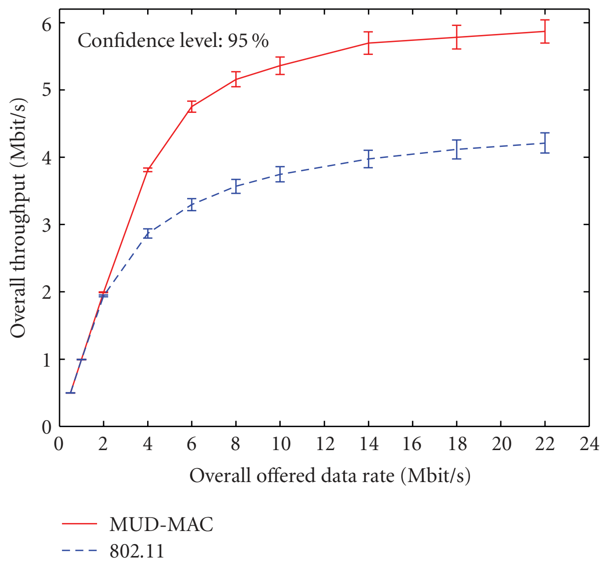

Figure 15: Overall throughput versus offered traffic in random topologies of 50 nodes on a 500 × 500 m^2 rectangular area.

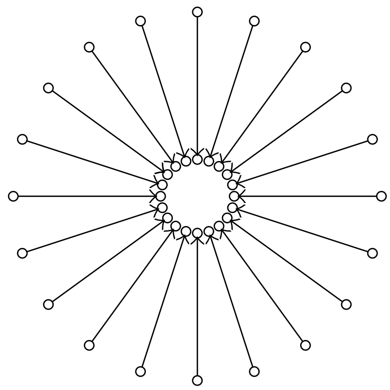

Figure 16: A topology with 20 fixed unidirectional communication pairs. All the nodes are within communication range. The 20 transmitters are located on an outer circle with radius 50 m and the respective 20 receivers on an inner circle with radius 10 m. All the nodes are within communication range.

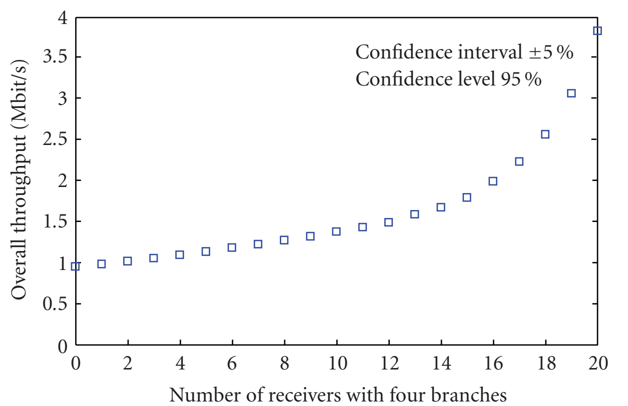

Figure 17: Overall throughput versus the number of receivers with four decoder branches. The rest is assigned only one decoder branch (no MUD).

interarrival time. Figure 15 shows the superior performance of MUD-MAC over 802.11 at high traffic loads.

5.3. Topology with 40 nodes having heterogeneous MUD capabilities. In this subsection, we shed light on the distinguishing feature of MUD-MAC of enabling a network operation with nodes having different MUD capabilities. In such a heterogeneous scenario, not only the overall network throughput is our main focus, but we are also interested in the throughput of individual nodes. Does a node with a powerful signal processing capability dominate the medium access whereas a simple node has little chance? To answer this question, we performed simulations using a topology with 40 nodes as illustrated in Figure 16. The 20 transmitters are located on an outer circle with radius 50 m and the respective 20 receivers are placed on an inner circle with radius 10 m. The traffic relationships are fixed and indicated by the arrows. We note that all the nodes are within communication range. The overall offered traffic is fixed at 4 Mbit/s. In contrast to the simulations in the previous sections, 20 receivers are assigned different numbers of decoder branches that reflect a variety of interference cancellation capabilities.

We start our investigation with a scenario having two types of receivers: simple receivers with only one decoder branch, that is, without MUD capability, and MUD-capable receivers with four decoder branches. Figure 17 shows the overall throughput when the number of MUD-capable receivers is varied from 0 to 20. It can be observed that the larger number of MUD-capable receivers contributes to the overall throughput increase since higher number of transmissions can take place simultaneously. When all the receivers are assigned four branches, the overall throughput ends up with about 3.8 Mbit/s which is expected from the analysis in Figure 9 when $R_d = 2$ Mbit/s and packets are split into $N = 4$ blocks.

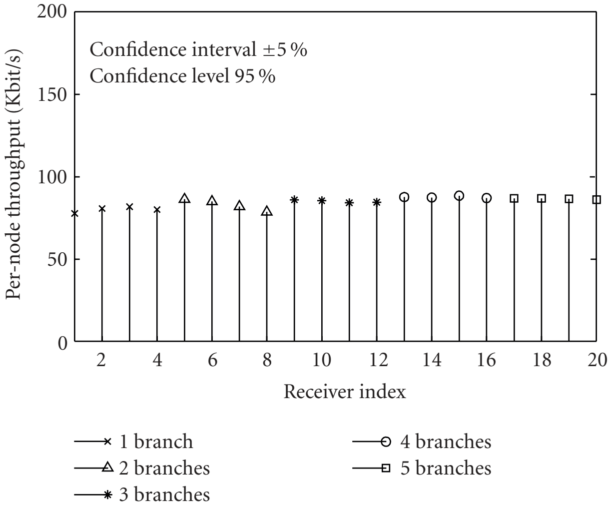

Figure 18: Per-node throughput of receivers in Figure 16 which are assigned different numbers of decoder branches between one (no MUD) and five.

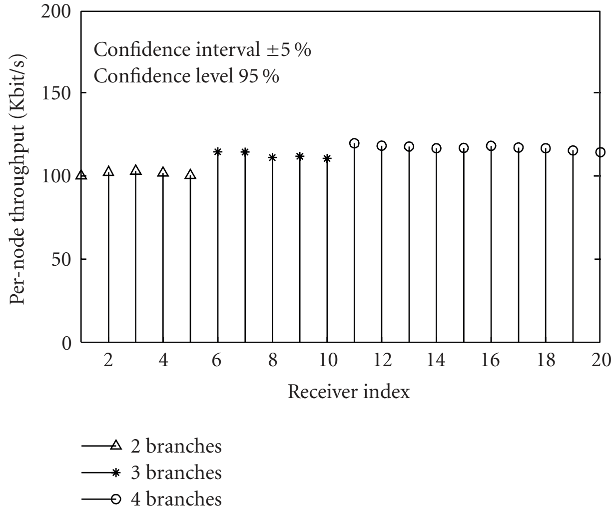

Figure 19: Per-node throughput of receivers in Figure 16 which are assigned different numbers of decoder branches between two and four.

Our next investigation focuses on throughput of individual nodes. Two scenarios are considered in the following. In the first scenario, the 20 receivers are divided into five groups, each of which has four receivers and is assigned one, two, three, four, and five decoder branches. The simulated per-node throughput is plotted in Figure 18. It can be seen that all the nodes obtain similar throughput which slightly increases with the number of decoder branches. Therefore, we conclude that certain fairness is provided by MUD-MAC protocol. The lowest throughput of the simple receivers with one decoder branch is roughly 75 Kbit/s. It is higher than $1000/20 = 50$ Kbit/s, that is, the per-node throughput computed from the overall throughput in Figure 17 where all the receivers have one decoder branch. Thus, the throughput of simple receivers is not suffered by MUD-capable neighbor nodes, but it is even increased.

In the second scenario, which is slightly different from the first one, we consider that five receivers have two decoder branches, another five receivers have three branches, and the remaining ten receivers have four branches. In Figure 19, very similar observation as in the first scenario can be made except that the per-node throughput of every node is considerably increased. This is due to the fact that there is no receiver which cannot accept any interference and block any simultaneous transmission.

6. Conclusions

We addressed key requirements and crosslayer aspects for the design of a MAC protocol which copes with interference by tightly cooperating with the PHY layer, with an emphasis on iterative multiuser detection as a flexible means for interference cancellation. We proposed the MUD-MAC protocol which satisfies these requirements. Its overall throughput bound was analytically studied and was confirmed by simulation results. A significant increase in the overall throughput as compared to the IEEE 802.11 has been observed.

It was also demonstrated that the MUD-MAC protocol provides certain fairness among nodes with different MUD capabilities. Simple receivers do not suffer from neighboring nodes having more powerful signal processing capabilities. On the contrary, such simpler nodes even benefit from MUD-capable nodes. Advanced signal-processing capabilities that are available at some nodes in the network are, therefore, beneficial not only to these nodes themselves, but also to much simpler nodes located in the interference range. These are desired and distinguishing properties of the MUD-MAC protocol.

Encouraged by the initial promising results, we are investigating further aspects that include delay, fairness, QoS issues, multihop scenarios, channel estimation, and more advanced objection criteria towards higher spectral efficiencies.

Acknowledgments

The authors would like to thank J. Widmer, I. Aad, and L. Loyola for various fruitful discussions. The authors would also like to thank V. Janardhanam for his programming efforts. This paper was presented in part at the International Workshop on Cross Layer Design, September 2007 and at the IEEE Global Telecommunications Conference, November 2007.

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