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In this paper, we highlight some advantages that can be exploited while designing Medium Access Control (MAC) protocols for wireless ad hoc networks with multiple antennas. Our purpose is to trace a connection between network studies and physical layer studies, building a framework for protocol design that stems from an accurate knowledge of the underlying physical behavior. We wish in fact to shed some light on relevant crosslayer design trade-offs, which can be promising for better protocol design. In particular, we analyze the implications that a layered multiuser detection technique at the physical layer has on MAC protocol design for wireless ad hoc networks.

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Some Issues Concerning MAC Design in Ad Hoc Networks with MIMO Communications

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***Abstract*— In this paper, we highlight some advantages that can be exploited while designing Medium Access Control (MAC) protocols for wireless ad hoc networks with multiple antennas. Our purpose is to trace a connection between network studies and physical layer studies, building a framework for protocol design that stems from an accurate knowledge of the underlying physical behavior. We wish in fact to shed some light on relevant cross-layer design trade-offs, which can be promising for better protocol design. In particular, we analyze the implications that a layered multiuser detection technique at the physical layer has on MAC protocol design for wireless ad hoc networks.**

1. Introduction

The recent years have seen an increasing interest in wireless ad hoc networks and in their utilization for office or home purposes. Wireless ad hoc networks are made of nodes which communicate through a shared radio resource by packet transmissions, without any need for pre-existing infrastructures or contracts among the users. Wireless access may be embedded in a number of devices, such as handheld computers, laptops, PDAs, etc., thus increasing the number of users that may access available wireless services, as well as the number of scenarios in which a wireless network may prove to be useful and affordable, i.e., gaming sessions, business meetings, war operations, rescue missions, and so on.

On the other hand, wireless networks are harder to design than wired networks because of problems that arise from the very nature of radio communications. One of these problems, namely the *hidden terminal* [1], is known since the early studies on radio network access, and is the cause of potential data loss as a terminal (say, A) wants to transmit to a given receiver (say, B) while another node in the network has the same intention (say, C). If A does not sense C's communication and vice-versa, for instance because they are out of each other's range, the data packets they send to B will *collide*, superimposing at B and turning out to be mostly undecodable.

To cope with this problem, protocols have been designed that provide a means to inform neighboring nodes of the intention to transmit to a given receiver (Request-To-Send, RTS) and, subsequently, to receive from a given transmitter (Clear-To-Send, CTS). This prevents all nodes that overhear any of the two control messages from radio access. A very well known protocol that follows this concept is found in the IEEE 802.11 standard [2]. This protocol allows to avoid collisions, but some studies have discovered drawbacks of this approach, for instance low spatial parallelism (the RTS/CTS signaling does not allow many communications to take place simultaneously), and unfairness (differences in the ease of channel access as perceived by each of the nodes) [1], [3].

A possible approach to improve spatial parallelism is to embed multiple antennas into wireless nodes. Through *beamforming* techniques [4], these kinds of antennas let transmitters concentrate power in the direction of the receiver, reducing radio interference towards uninterested nodes and letting a communication cover a larger range of distances. Some papers following this approach are [5], [6]: these and other similar papers indeed recognize the usefulness of directional transmissions in ad hoc networks, along with some problems that arise due to directional signal propagation, but are developed assuming too simplified physical behavior models (such as no multipath fading, perfect orientation of antennas' emission, perfect knowledge of each node's position, no mobility).

Another possible way to improve MAC in ad hoc networks is through Multiple-Input-Multiple-Output (MIMO) techniques, which is the approach we take. MIMO techniques allow to exploit the presence of multiple antennas to improve transmission bit rate through spatial multiplexing or to improve the signal decoding efficiency through diversity reception and interference cancellation [7]. We start form this point of view to give some results that explain how a MAC protocol should be designed in order to make full use of the known physical layer specifications and behavior.

In this paper, as a first step towards a fuller understanding of the various issues arising at the MAC layer when MIMO PHY technology is used, we provide some framework and results on the reception performance of MIMO links in a multiuser scenario. The results show that the capture capability introduced by MIMO technology is significant and this should be taken into account when designing MAC protocols.

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2. System Model

We first give a framework of the physical level model we use in our analysis, so that implications and deductions given in Section 3 regarding issues on packet radio access and MAC protocol design are not disconnected from the underlying system structure.

As a general line, consider that nodes are arranged in a network where transmissions take place in a packet radio fashion. Transmitting nodes form streams of bits, that may be convolutionally encoded as needed. We suppose the transmissions to take place in a rich scattering environment, and decide to exploit the available spatial degrees of freedom through spatial multiplexing [7], in order to improve the overall raw bit rate. Each user selects the number of antennas to use for transmission: to simplify the following notation, we assume that, in each packet, the number of bits to be sent *per transmitting antenna* is constant for all users, e.g., 1000 bits per antenna. Hence, each time a multiple transmission has to be decoded, the receiver knows in advance the number of symbols to be simultaneously processed, along with the transmission duration for each of the incoming streams. The following analysis uses the simplifying assumption that all streams on all antennas have the same length in terms of number of symbols. A more general model, taking into account different stream lenghts is anyway easy to build from the given framework.

At the receiver, multi–user decoding is performed symbol-by-symbol, with a decorrelating layered space–time signal processing technique [8]. Let us then fix our attention over a certain symbol interval. The receiver is listening to the signals coming from, say, K different transmitters, indexed by $\ell = 1, \ldots, K$, each using u_ℓ antennas, and is thus handling a total of $U = \sum_{\ell=1}^{K} u_\ell$ incoming streams. Let $\mathbf{b} = [b_1, \ldots, b_U]^T$ denote the U-length symbol vector where each element is a symbol coming from one of the U transmitting antennas, and the superscript ^{T} denotes transposition. Let $\mathbf{S} = [1\ 1 \ldots 1]$ be a vector formed by U ones. We note that in a more general CDMA context [8], $\mathbf{S}$ would be a matrix with columns containing spreading sequences, one column for each stream.

We assume the signals to undergo propagation through a frequency flat fading channel, represented by the channel matrix $\mathbf{H} = (h_{a\ell})$, where $h_{a\ell}$ is the coefficient between the a-th receiver antenna and the ℓ-th of the U transmitting antennas. We denote with $\mathbf{h_a}$ the vector of coefficients between the a-th receive antenna and *all* users. Thus, the received signal at antenna a, assuming perfect channel estimation and symbol synchronization, can be written as:

$$r_a = \mathbf{S}\mathbf{C}_a\mathbf{b} + n_a \tag{1}$$

where $\mathbf{C}_a$ is formed putting channel coefficients for the a-th antenna as its diagonal entries, $\mathbf{C}_a = \mathrm{diag}(\mathbf{h}_a)$, whereas n_a is the noise sample at the a-th antenna, i.e. a zero-mean complex Gaussian random variable with variance σ^2.

After space matched filtering, we obtain the sufficient statistics vector $\mathbf{M}$ as:

$$\mathbf{M} = \sum_{a=1}^{A} \mathbf{C}_a^\dagger \mathbf{S}^T r_a = \mathbf{R}\mathbf{b} + \mathbf{n} \tag{2}$$

where A is the total number of receive antennas, $\mathbf{R} = \sum_{a=1}^{A} \mathbf{Z}_a^\dagger \mathbf{Z}_a$ represents the $U \times U$ space cross-correlation matrix [9], with $\mathbf{Z}_a = \mathbf{S}\mathbf{C}_a$, $\mathbf{n} = \sum_{a=1}^{A} \mathbf{Z}_a^\dagger n_a$ is the filtered Gaussian noise vector with covariance $\sigma^2\mathbf{R}$ and † denotes the complex transpose operator. It has been proven [9] that taking the real part of $\mathbf{R}$ makes the decoding process more robust to noise, though forcing to use real signal constellations. Since this has also been demonstrated not to be a limitation in terms of system capacity, we assume that the real part of $\mathbf{R}$ is always used, and in what follows we shall write $\mathbf{R}$, with the implicit understanding that it means $\mathrm{Real}[\mathbf{R}]$.

In order to be more general, we claim that the receiving node may decide to estimate the channel for only a subset of the transmitting users, limiting the stream detection and cancellation to this subset. Thus, the sufficient statistics vector in (2) becomes a sum of two contributions, the first coming from decoded signals, and the other representing a mere interference term, namely

$$\mathbf{M} = \sum_{a=1}^{A} \mathbf{C}_a^\dagger \mathbf{S}^T (r_a + \mathbf{S}_{int}\mathbf{C}_a^{int}\mathbf{b}_{int}) = \mathbf{R}\mathbf{b} + \mathbf{n} + \mathbf{I} \tag{3}$$

where $\mathbf{I} = \sum_{a=1}^{A} \mathbf{C}_a^\dagger \mathbf{S}^T \mathbf{S}_{int}\mathbf{C}_a^{int}\mathbf{b}_{int}$ is the space-filtered interfering signal, involving the interfering symbols $\mathbf{b}_{int}$ and the channel matrix towards interfering users $\mathbf{C}_{int}$, which the receiver need not know.

The detection algorithm works on a single symbol time span [9] and consists of U iterations. We do not report it entirely here: for our purposes, it is enough to state that it implies pseudoinverse [10] calculus over $\mathbf{R}$ to get $\mathbf{R}^\#$ and reordering of the received symbols according to their post–detection SNRs (including effects deriving from propagation from different distances). Iteration by iteration, the symbol with the maximum SNR is chosen and isolated from spatially multiplexed signals by linearly weighing the suficient statistic vector $\mathbf{M}$ with a set of coefficients extracted from $\mathbf{R}^\#$. The scalar value obtained by this process is fed into a decision block to yield the estimate of the transmitted symbol, and then the sufficient statistics vector $\mathbf{M}$ is updated by cancellation of the resulting estimate. Iterative selection, decoding, and cancellation continues until all U symbols are extracted. Finally, the receiver switches over to the subsequent symbol time. The complete description of the algorithm is available in [9] to the interested reader.

For illustration purposes, in Fig. 1 a graph reporting raw bit error rate behavior for all combinations of 4 and 10 transmitters and 6 and 8 receivers is depicted.

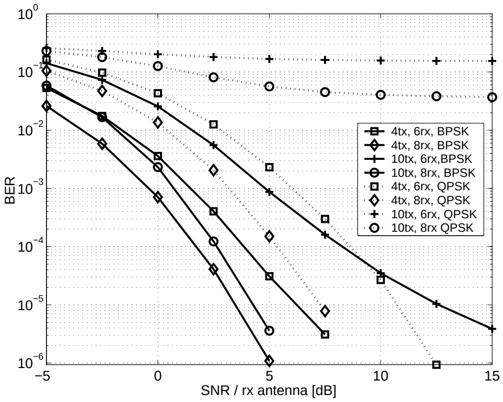

Fig. 1. Comparison of BERs as a function of SNR per receiver antenna for 4 different tx–rx configurations, using BPSK and QPSK modulations.

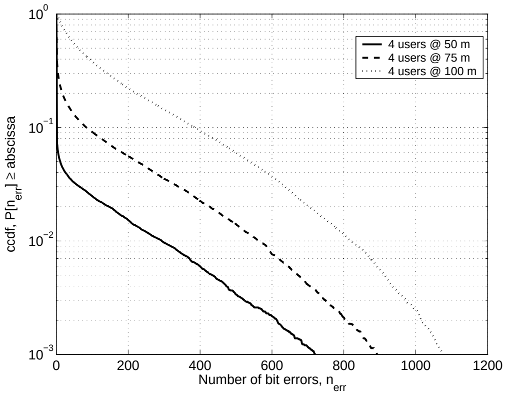

Fig. 2. Complementary cumulative distribution function of the number of errors, 8 rx antennas, 4×4 incoming 1000-bit streams, from 4 users at 50, 75 and 100 meters of distance from the receiver.

The figure contains a performance comparison of a low spectral efficiency Binary Phase Shift Keying (BPSK) modulation processed by taking the real part of $\mathbf{R}$ during the decoding phase along with a Quaternary Phase Shift Keying (QPSK) modulation, which has a double spectral efficiency than BPSK, but requires full complex processing of $\mathbf{R}$.

As can be inferred form Fig. 1, BPSK decoding gives better results. This is not only a consequence of the constellation simplicity, but also of the fact that it is *real*. Real constellation decoding allows for the use of the only $\mathbf{R}$'s real part, while complex constellation decoding requires to take into account $\mathbf{R}$'s imaginary part as well. This brings into the detection process a further uncertainty element, namely the noise affecting the imaginary part, that may impair the decision over symbols in a way that is unpredictable, due to the nonlinearity of the cancellation process. This explains the significant performance difference between QPSK and BPSK $(10;6)$ and $(10,8)$ curves in Fig. 1. It also suggests that the loss in spectral efficiency due to the use of BPSK is easily recovered by the higher decoding performance of the system.

3. Simulation Results

We now show some simulation results which are very useful to understand better what degrees of freedom can be properly exploited during MAC design, taking advantage of some knowledge of the performance and of the inherent multiuser behavior of the signal decoding method at the physical level. These results essentially regard the physical layer behavior in some significant scenarios, but they also have strong implications on preparing the way for the design and optimization of higher level protocols.

We stress that the BER performance of the multiuser detection is very dependent on distance. This is because the interference cancellation operation is effective only if the user being canceled was correctly decoded, and this event is more likely if the received signal possesses a high SNR. Even if we suppose to be decoding two streams at the same distance (i.e., the Signal-to-Interference-and-Noise-Ratio (SINR) approaches zero dB), the rich scattering environment described by the matrix $\mathbf{H}$ as in Section 2 still lets the decoder separate received symbols and reconstruct the original bit sequence correctly with high probability.

This phenomenon is more clearly seen from Fig. 2. The figure contains the complementary cumulative distribution functions (ccdf) of the number of bit errors over a packet (n_{err}), in a high receiver load scenario, when 4 users transmit 4 1000-bit streams each, for a total of 16 streams grouped in 4 4000-bit packets, to be decoded using 8 antennas at the receiver. As the 4 transmitting users are still near the receiving node, their streams are received with a very low probability of error. We stress that in this case transmissions are *not* channel–coded. As the distance increases to 75 meters, the error probability increases, and becomes totally unsustainable at 100 meters.

The first conclusion we can draw is that the error probability at small distances still allows to receive correctly a number of uncoded streams that may even be higher than the number of available receiver antennas, so that a number of packets could be simultaneously received at a single node with no errors. This could have two important MAC implications: in a collision avoidance scenario, for instance, a node could receive multiple RTSs even from distant nodes, and obtain an idea of the congestion situation in the neighboring network portion, as nodes with more packets in the queue would send RTS frames more frequently. We recall that signaling packets are supposed to be shorter than data packets, so that multiple uncoded RTS reception is even easier than multiple data reception. Extensive simulation results show that a receiver with 8 antennas could be simultaneously decode 14 to 18 RTSs, depending on SNR conditions, but we do not include them here due to lack of space. In the considered system, a single CTS

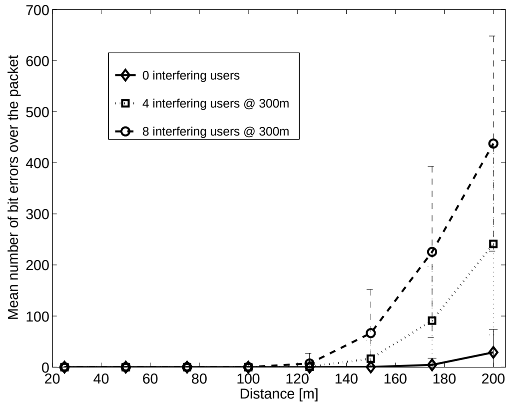

Fig. 3. Average and standard deviation of bit errors over a packet as a function of distance, 8 rx antennas, 4 incoming 1000-bit streams from one user, with 0, 4 and 8 interfering users.

may be used to solicit a single or multiple receivers, depending on perceived traffic conditions. Moreover, if some sort of synchronization in CA signaling is set up between nodes, a station could receive multiple CTSs and decide on its own how many antennas to use for spatially–multiplexed data transmission: as a rule of thumb, as more CTSs are heard, more streams will be sent in that portion of the network, so that more receivers will become overloaded, and fewer streams should be simultaneously sent by each transmitter.

The conclusions drawn so far are also supported by the results of Fig. 3. There, the average number of bit errors over a 4000-bit packet split into 4 streams is shown as a function of distance. We suppose a single user is transmitting 4 1000-bit streams to a receiver with 8 antennas. As we can see, in this low load situation, there are no errors over a large range of distances. The error tolerance is very high up to a distance depending on the number of interfering users, i.e., those whose interference is not eliminated due to unknown channel state. We recall that each of these users is transmitting a total of 4 1000-bit streams, just as all decoded users. Fig. 3 tells us once more that uncoded streams are very likely to be correctly received, and that, in particular, a single tx–rx link may continue to work at distances as far as 120–180 m, depending on the interference level.

Fig. 3 also gives a second insight. During data reception, a user may afford to send uncoded streams at a far distance, even in strong uncanceled interference conditions. Thus, the receiver need not always estimate and cancel interfering components for all signals it hears, but can afford to leave some of them unrevealed, as analytically expressed in (3), reducing the complexity of the decoding process accordingly. This may be of help during both signaling and data packet reception, as a receiver may not require (or not be able) to know every signaling transmission coming from too large a portion of the network, but may eventually afford to take MAC or routing decisions based on the status of only the neighboring nodes, which we recall can be inspected with good accuracy, as short signaling packets have been demonstrated to travel far away without errors.

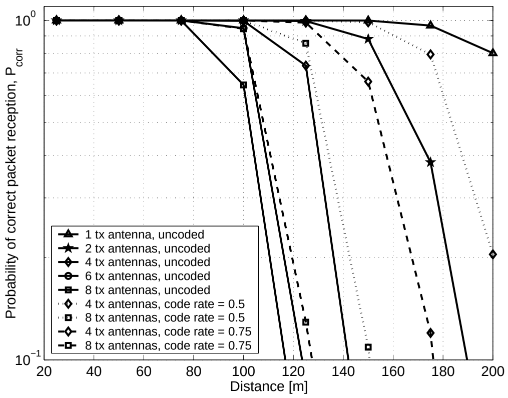

Fig. 4. Probability of correct packet reception, P_{corr}, for a single data transmission as a function of distance, with and without coding, by varying the number of transmitting antennas. 8 receiving antennas, 4 interfering users at 300 meters.

As a next step in drawing MAC layer implications of layered space–time multiuser detection, we inspect the probability of correct packet reception as a function of distance. Following the general rule that the number of bits per transmitting antenna is fixed, as stated in Section 2, we allow some coding to be applied to the data packet, so that if N_D is the number of bits in a data packet and r the code rate, then the number of bits to transmit becomes N_D/r. In order to make a fair comparison between all evaluated configurations, we force the nodes to use more antennas to send more bits, so that the global duration of the transmission is the same in both the coded and uncoded case. As an example, a rate $2/3$ coded flow of 4000 bits becomes 6000 bit long, and is transmitted with 6 antennas to comply with the 1000-bits-per-antenna constraint.

The code used is the rate $1/2$ convolutional code described by the octal coefficients $(133_8, 171_8)$, as specified for instance in the 802.11 standard [2]. A rate $3/4$ version of the code is obtained by puncturing the coded bits according to a predefined scheme.

Fig. 4 shows the correct packet reception probabilty P_{corr} for the case where a single user is transmitting a coded or uncoded flow using the appropriate number of antennas, e.g., 1000 bits with a single antenna, 2000 bits with two antennas, and so on. The receiver always uses all of its 8 antennas. An average interference level is obtained by having 4 users send data from 300 m away. As can be inferred, the distance at which an uncoded transmission becomes excessively error-prone varies as a function of the number of antennas used. The two extreme cases show a maximum reachable distance of about 150 meters (when a single antenna is used) which falls to roughly 75 meters when the complete set of available antennas is engaged in transmission. We only consider the values of P_{corr} ranging from 0.1 to 1, because lower values represent nothing more than a

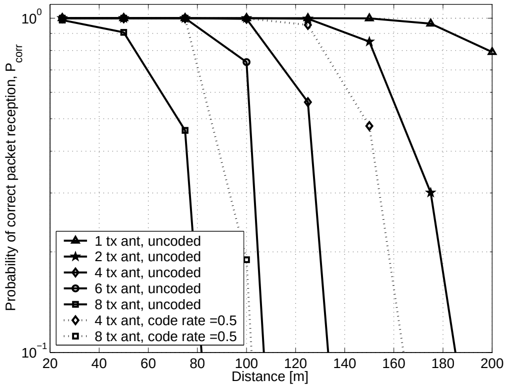

Fig. 5. Probability of correct packet reception, P_{corr}, for 2 simultaneous data transmissions as a function of distance, with and without coding, by varying the number of transmitting antennas. 8 receiving antennas, 4 interfering users at 300 meters.

waste of resources. Again, Fig. 4 tells us that in low traffic conditions and at small distances, a high degree of spatial multiplexing could be used, hence reaching very high transmission bit rates. On the other hand, lower bit rates allow to reach farther destinations. It is interesting to highlight that, for the single user case, a proper encoding of the data stream could translate into a longer covered distance. For example, the curve representing a 2000 bit $1/2$-coded stream (for a total of 4000 bits) sent with 4 antennas outperforms the curve representing a 2000 bit uncoded packet sent with 2 antennas, and the same happens for the 8000 bit $3/4$-coded packet sent with 8 antennas and the 6000 bit uncoded flow transmitted with 6 antennas. This means that, in low traffic conditions, coding makes it possible to reach farther distances at the price of an increased number of transmitting antennas. A MAC protocol should be able to exploit this favorable condition by forcing users to adaptively change their coding and antenna configuration, according to their own bit rate requirements and taking into account the neghboring nodes' status, which could be extrapolated from signaling packets.

The case with 2 transmitting users leads to different observations. Fig. 5 reports the values of P_{corr} following the same concept used in Fig. 4, with the difference that here we consider two users transmitting simultaneously from the same distance, with the same number of antennas and the same coding configuration. The information we draw from this figure is that coding is no longer of help in beating the interference from the other data flow we have introduced, when the objective is to reach a farther distance. The system still has a very high performance even for a high number of transmitting antennas, if the distance from the receiver is kept below 75–80 meters, but when the transmission distance increases, it is better to introduce a smaller overall interference by sending uncoded packets over fewer antennas. Also, we infer it would be preferable for a MAC protocol to fragment longer packets into smaller units, and to transmit these units sequentially using fewer antennas, so as not to increase the system load.

Finally, we stress that graphs like Figs. 4 and 5 are very useful in obtaining the maximum allowable bit rate adaptively as a function of distance and load. For instance, if a node requires that at least an average percentage of its data transmission is correctly decoded, it may estimate (through RTS and CTS overhearing) how loaded its prescribed receiver is, and then "select" on the graphs the appropriate curve which corresponds to the required performance and distance to cover, hence establishing the proper coding and spatial multiplexing scheme that would allow transmission at the desired success probability without overloading the receiver.

4. Conclusions

In this paper, we have explored the use of a layered space–time multiuser detection technique as a means to improve communication efficiency in ad hoc wireless networks, both through the exploitation of multi-antenna signal processing capabilities and through explicit inclusion of physical models in MAC design. We highlighted how a protocol should behave in order to make full use of the available knowledge regarding the underlying physical model. With this paper, we want to make some steps in the direction of a proper cross–layer design of MAC protocols, whose performance we believe can be significantly boosted by properly taking into account the behavior of the receiving and decoding processes.

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