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DSMA: an Access Method for MIMO Ad Hoc Networks Based on Distributed Scheduling

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In this work, we analyze the effects of a distributed transmission coordination scheme that is particularly suited for ad hoc networks with the ability to exploit spatially–multiplexed communications over MIMO links. Following previous work where we discussed the performance of this kind of networks and deployed a fast yet reliable approximation for physical layer behavior, we now employ this knowledge to analyze the performance of a different access scheme, meant to outperform previous results by the use of distributed coordination of transmissions and receptions without adding any further redundancy in communications. Furthermore, we analyze the effect of tuning two parameters on the overall network performance.

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C.2.1 [**Computer–Communication Networks**]: Network Architecture and Design, Network Protocols

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Keywords

Ad hoc networks, MIMO communications, distributed MAC, cross–layer design, spatial multiplexing.

1. INTRODUCTION

Wireless networking is deemed to be a core component of the future information technology infrastructure. More specifically, ad hoc networks are experiencing a constantly increasing research interest, because of the growing need for flexible, adaptive and mobile communication techniques. In this sense, ad hoc networks are completely unattended and non-infrastructured, thus providing the flexibility needed. Being formed of wireless terminals, they also enable mobility up to some extent, leaving to the end users the choice of how, when and where to access wirelessly delivered services.

As everyday life penetration of wireless networking becomes stronger, users will require a wide set of services, most probably including multimedia, and thus a high amount of available bandwidth, for the services to be delivered efficiently. Unfortunately, ad hoc networks have proven to be incapable of providing such a high distributely accessed bandwidth, due to a variety of problems, such as the well–known *hidden terminal* [1], the unfairness deriving from collision avoidance methods based on signaling messages exchange with the purpose of reducing interference toward unknown transmissions [2], and the overall achievable throughput per node, which is known to decay proportionally to the square root of the number of nodes [3].

Multiple antennas in ad hoc networks are a promising enabling technology for reaching high rates in wireless point–to–point links. Thanks to the increased number of degrees of freedom offered by multiple radiating elements, terminals may drive radio transmission and reception phases so as to obtain benefits. For example, they can shape the electromagnetic emissions of the antenna array, and confine *beams* into a definable and adaptable portion of space (*beamforming*) [4]. Otherwise, they can manage multiple antennas in a Multiple–Input–Multiple–Output (MIMO) fashion [5], whose benefits have been well studied. For example, we recall that MIMO enables communication protection through Space–Time Coding (STC) [6], which involves the transmission of a group of symbols through different antennas in consecutive time slots, and their exchange and/or phase rotation in each slot, according to a predefined scheme. In recent years, a category of STC, namely Layered STC (LSTC), has attracted an increasing interest. For instance, V–BLAST is part of this category [7]. The V–BLAST scheme involves a special case of LSTC, called Spatial Multiplexing, where each transmit antenna is used to convey a different symbol per time slot. In sufficiently rich scattering environments, each symbol sent undergoes different propagation conditions, and may be separated from other symbols at the receiver using appropriate algorithms [6].

MIMO technologies may be applied with profit in ad hoc networks as well. MIMO strongly enhances the capacity of a single link between two terminals, and allows for superimposed communications to take place in the same neighborhood. This option greatly improves spatial reuse. Anyway, the number of successfully receivable transmissions is limited and depends on the number of available antennas, channel conditions, post–processing SNR, and power differentiation among incoming streams. For these reasons, MIMO techniques endow an ad hoc network to be designed and deployed with a higher degree of flexibility, improved communication reliability and globally higher performance. However, these advantages are conditioned on the implementation of a careful medium access control (MAC) mechanism, that avoids receiver overwhelming. This MAC also has to be distributed in nature, in order to match the completely unattended and decentralized structure of an ad hoc network. This design paradigm is recently emerging in the

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literature, and its application to ad hoc networks is being studied. For example, such an approach is found in [8].

As per the preceding considerations, in this paper we propose Distributed Scheduling for MIMO Ad hoc networks (DSMA). Our scheme is aimed at achieving some coordination among neighboring nodes, so that i) the scheme is completely distributed, ii) nodes do not try to access the channel simultaneously even under heavy traffic conditions, and iii) transmitter and receiver roles are rotated among nodes in such a way that none can continuously achieve transmit privileges. Moreover, the overall network organization is operated in a *cross–layer* fashion, where the physical layer and the medium access control layer exchange directives and information to improve the performance of the decoding process, as detailed further in Sec. 2.2.

The paper is organized as follows. In Sec. 2.1 we briefly describe our physical layer model; in Sec. 2.2 we give more details about the structure of network messaging and data transmission; in Sec. 3 we introduce DSMA, our access scheme for MIMO ad hoc networks based on distributed scheduling; in Sec. 4 we compare DSMA to exponential backoff, and analyze the impact of relevant protocol parameters. Finally, we conclude our paper in Sec. 5.

2. DESCRIPTION OF NETWORK SCENARIO

2.1 Physical Layer Model

Here we give a summary of our physical layer model, in order to justify the rationale behind our protocol choices.

We consider a network in a rich scattering environment, and formed of nodes with multiple embedded antennas. The fading process is exploited by means of Spatial Multiplexing (SM). SM allows for higher node bit rates and for the superposition of multiple simultaneous communications in the same neighborhood. Each user chooses how many antennas to use for transmission, according to a predefined rule (see also Sec. 2.2). At the receiving nodes, a LAyered Space–Time MultiUser Detection technique (LAST–MUD) is used to separate superimposed incoming transmissions [9], equivalently to V–BLAST. In brief, LAST–MUD estimates the channel gain between any transmit and any receive antenna, computes a space correlation matrix, determines the sender antenna whose symbol experiences the highest SNR and obtains a set of weights for extracting this signal using Zero Forcing. The symbol sent is then estimated, and subtracted from the received signal. Finally, the algorithm restarts from the beginning to extract and decode the symbol with the second highest SNR, and goes on until all symbols have been decoded. Note that the algorithm achieves a further degree of freedom for each decoded user, and reduces the interference affecting subsequent users at each decoding step.

As LAST–MUD requires channel knowledge at the receiver, each packet is preceded by a training sequence, which is used to estimate the channel effects undergone by each stream during propagation. Since the amount of scattering is assumed to be high, the experienced fading process may be modeled as Rayleigh. Thus, channel effects can be completely described in terms of gain and phase rotations, and embedded into a channel matrix $\mathbf{H} = (h_{ij})$, where h_{ij}s are zero-mean, unit-variance circularly gaussian entries representing the complex channel gain between the i-th receive and the j-th transmit antenna. Each user estimates this matrix before beginning the decoding iterations.

We stress that users may be forced, or explicitly decide, to leave some of the superimposed signals as part of an unknown interference term, without estimating their channel. This may be due either to network effects (as will be explained later) or to the decision of a terminal to neglect a subset of the incoming signals, for instance in order to reduce the decoding complexity.

As a final remark, for simulation speed up purposes, we employ a faster yet precise approximation of the physical layer behavior, that allows for much shorter simulation times, yet does not compromise the accuracy and statistical significance of our results. In [10], we built a computationally efficient method that estimates how the detection errors in the decoding process propagate and affect the correctness of subsequent detections. Our method scales the SNR at a given detection step by a term that accounts for errors occured on previous steps. Wrong detections are wrongly canceled, doubling the interference produced by the corresponding symbol. Hence, the SNR at each step depends on the transmitted signal power, on space filtering operations on received signals and noise (thus, on channel effects), on unknown interfering contributions and on the propagation of decoding errors.

2.2 Network Description

In this work, we want to exploit the higher potential of MIMO communications. For this reason, transmitters are allowed to use multiple antennas, in order to reach the higher bit rate made available by SM. This allows senders to activate either many links toward multiple destinations at once, or a few links toward a smaller number of destinations (but using multiple antennas), thereby achieving greater data rates. At the receiver side, the existence of multiple transmit links is completely transparent, because it always uses all of its antennas for reception, and treats all incoming data streams as distinct signals to be separately decoded.

Our network is organized as follows. We deploy some nodes in a square grid, and set the distance between nearest neighbors such that the network is fully connected. We choose such an arrangement because it represents a worst case scenario, where a higher amount of interference is created toward receivers by multiple transmitters. In this network, packets are generated according to a Poisson process of rate λ per node. Each packet is assigned a random length (in multiples of a fixed quantity, say 1000 bits), and a random destination. All communications are 1-hop. Nodes keep backlogged packets in a queue which is organized on a First-Come-First-Served basis.

Since the LAST–MUD algorithm must not be overloaded with too many superimposed signals, a signaling phase is initially set up. First, Request-To-Send (RTS) messages are sent for requesting transmissions, then receivers respond with CTSs to communicate their availability. Data streams are sent and, if received correctly, they are acknowledged with ACK messages.

Transmissions are arranged in frames, where first *all* transmitters send out their RTSs, then all receivers answer with CTSs (provided that they received it) and so on for data and ACK, as depicted in Fig. 1. All nodes are assumed to be frame–synchronous. This may seem a major assumption, but we highlight that i) the network is fully connected, so synchronization is easier to obtain and ii) synchronization is currently achievable in MAC protocols for wireless networks, such as 802.11 DCF [11].

RTSs are formed by including one or more *requests,* i.e., pairs declaring the intended destination and the corresponding number of antennas to use for transmission, one antenna per each subset forming the whole packet. Following the aforementioned example, each subset would be composed of 1000 bits. RTSs may be ad-

Figure 1: The sequence of messages inside a frame.

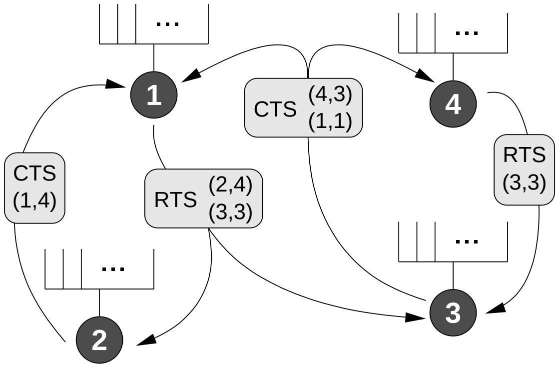

Figure 2: Example of signaling messages exchange between 4 nodes: RTS and CTS phase.

dressed to multiple nodes, enforcing the transmission parallelism allowed by SM. If necessary, RTSs are padded for matching the fixed frame structure.

When forming CTS messages, addressed receivers estimate the amount of traffic they will have to handle upon data reception and compile the CTS message accordingly. There, they specify which transmitters are granted, and how many streams they are allowed to send simultaneously. As a rule of thumb, as more RTSs are sent, more traffic will be present in that portion of the network, and fewer streams are to be granted transmission. This would allow the receiving algorithm to detect all incoming flows with high probability. In Fig. 2, a simple example of how handshaking messages are formed and exchanged is given. The notation (D, A) denotes that the node originating the RTS (CTS) requires (grants) to node D a transmission with A simultaneous streams. Upon compiling RTSs, node 1 asks to send 4 streams to node 2 and 3 further streams to node 3. At the same time, an RTS is sent by 4 requiring the transmission of 3 streams towards node 3. Node 3 receives both RTSs, containing a total of $4 + 3 + 3 = 10$ stream transmission requests, and applies a CTS compiling policy which results in the decision to limit the number of granted transmissions, so as to improve the decoding capabilities of its receiving stage. Thus, it allows node 4 to send all of its 3 streams, but limits node 1 to 1 stream. Node 2, on the other hand, grants node 1 all of its 4 streams.

Data stream transmissions take place following CTS indications. In our sample case, node 3 will apply LAST–MUD to a total of 8 incoming streams, $3 + 1 = 4$ directed to itself, the remaining 4 streams (from node 1 to node 2) being decoded only for interference cancellation purposes.

To describe the handshake operations in further detail, we stress three things. First, control messages are meant to serve primarily as a source of information about the amount of traffic in the network, so they have to be transmitted reliably. We have evidence that, if transmitted with a single antenna, a high number of them can be received without errors even at long distances. This is both because all transmit power is concentrated on a single transmission and because single-antenna communications keep the system fairly unloaded. We do not include this result here due to lack of space. Second, transmissions are ACK'ed *streamwise*. This allows correctly received streams to be signaled, preventing their further retransmission. Third, as a general rule, transmitting far away with too many antennas is not a good strategy. For this reason, we limit the SM depth used toward a certain node depending on that node's distance from the transmitter. The higher the distance, the lower the number of antennas used.

How to create CTS directives based on information acquired from RTSs (a CTS policy) constitutes a design decision. Due to limitations in processing capabilities, nodes cannot estimate the channel of every single transmission within coverage. They can only track a limited number of training sequences, whose source should therefore be carefully chosen. A tradeoff between the reception of wanted streams (thus, *throughput*) and the protection from unwanted interference arises when choosing what channels to track. We deploy the *Follow Traffic* (FT) policy described in order to address this tradeoff.

All requests are evaluated in order of decreasing received power. For each request, e.g. requiring transmission with i antennas, the node reserves processing resources for tracking i streams. If the evaluated request is addressed to the node, it inserts the corresponding grant in the CTS. This process is carried on until all requests have been dispatched or until all available processing resources have been reserved. Care is taken to allocate at least one request directed to the node itself, regardless of its received power. It is worth highlighting that this is a very good example of cross–layer technique. FT bases its decision on detected per–stream power, a measure that can be provided by physical layer to the MAC layer. This enables MAC to decide what streams it is better to grant in the CTS and what are to be canceled for protecting wanted data. Such decisions are then fed back to the physical layer, that spatially de-multiplexes incoming transmissions based on MAC layer directives.

In order to be as resilient as possible to network deadlocks, the system still needs a way to prevent persistency in trasmissions towards congested or unavailable nodes. In [10] we employed a simple destination-wise exponential backoff mechanism. Here we try a different way to rule the network that is based instead on a form of coordination among nodes, which is acquired through the insertion of additional information in signaling messages and which is described in the following section.

3. DSMA CHANNEL ACCESS SCHEME

Here we describe the Distributed Scheduling for MIMO Ad hoc networks (DSMA) algorithm, and motivate its design by a comparison with a previously devised backoff mechanism [10]. DSMA is based on the following consideration: instead of leaving nodes to access the radio medium in a completely uncoordinated manner, as done in typical random radio access standards like the common 802.11 DCF mode [11], we provide a means for receivers to control the state of other nodes in the following frame. This would ensure that a destination node is really listening and ready to operate as a receiver.

More in detail, let us fix the attention over a given frame. Nodes that were receivers in this frame are supposed to send an ACK message to confirm correct data reception. In DSMA, with probability P_{reserve}, receivers scan their backlog queue before composing the ACK, pick the destination of one or more of the head packets (up to a maximum depth d_{max}), and embed in the ACK a *reservation* directed toward those nodes. We recall that ACKs are short signaling messages, and hence are received correctly with high probability, as stated in Sec. 2.2. Nodes receiving the ACKs and recognizing themselves as reserved destinations, refrain from transmission in the following frame.[1]

Note that with DSMA, ACKs reserve only those nodes who were transmitters or idle, because in the final part of the frame, every re-

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[1] Recall that frames are made of synchronized RTS, CTS, DATA and ACK transmissions, so that all ACKs are simultaneously received, and all nodes take on the requested receiver roles accordingly (see Secs. 2.2 and 4).

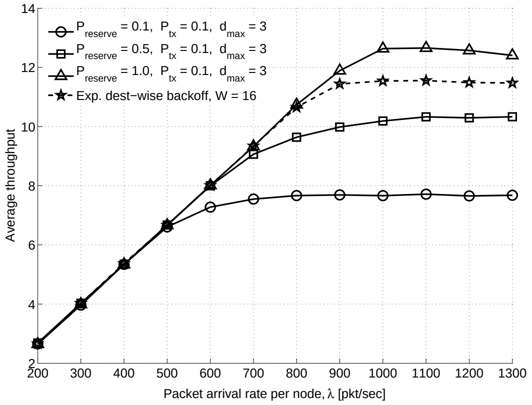

Figure 3: Comparison between average throughput of DSMA and exponential backoff for $P_{\mathbf{TX}} = 0.1$, $d_{\mathbf{max}} = 3$ and varying $P_{\mathbf{reserve}}$. $W = 16$.

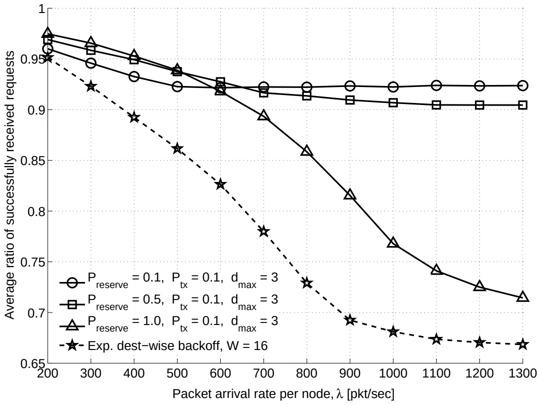

Figure 4: Comparison between success ratio for DSMA and exponential backoff. $P_{\mathbf{TX}} = 0.1$, $d_{\mathbf{max}} = 3$ and varying $P_{\mathbf{reserve}}$. $W = 16$.

ceiver is transmitting its own ACK and is not able to receive other messages. Furthermore, reserving nodes are receivers in a given frame, and will switch to transmit in the following frame, contributing to an overall fairer rotation of transmit and receive roles, and adapting better to local traffic needs.

Idle nodes (i.e., nodes that are neither reserved nor reserving) can decide to act as transmitters in the following frame with probability P_{TX}. When choosing who to transmit to, they privilege reserved nodes and do not send anything to reservers. Thus, they properly exploit the information contained in the previously detected ACKs, which they surely heard.

Unlike previous work in which we ruled the network by a random access policy, we believe that a partially controlled but indeed distributed management of transmissions and receptions could provide benefits to the performance of MIMO ad hoc networks using SM, without introducing any new communication overhead, as reserving information are piggy–backed in control messages that would be sent anyway.

4. RESULTS

4.1 Relevant network parameters

We arrange a total of 25 fixed nodes in a 5×5 grid, with a 25 m distance between nearest neighbors. In this scenario, all nodes are within coverage range of each other. Each node is equipped with 8 antennas to exploit SM benefits. Transmissions are framed as in Fig. 1, so the duration of data transmissions must be limited. For this reason, nodes send a fixed block of 1000 bits per used transmit antenna. For example, a 2000-bit packet may be sent in a single frame using 2 antennas, or otherwise split among multiple frames. Signaling packets are 200 bits long. All nodes share the same frame synchronization. Channel effects are assumed to be constant over the whole duration of a frame. This assumption is reasonable since, e.g., a BPSK modulation with 99% in–band power allows for a bit rate of 7.5 Mbps in the 5.8 GHz ISM band.

Packets are generated according to a Poisson process of rate λ per node. Each packet is assigned a length of $k \times 1000$ bits, with k randomly chosen in the set $\{1, 2, 3, 4\}$. It is also randomly assigned a destination. All communications are 1-hop. The node queue can store up to 120 1000-bit units. Since channel estimation is of paramount importance, each transmission (from *any* antenna) is preceded by a training sequence. Recall that nodes can afford to track a limited number of training sequences, so that a policy is necessary for deciding which channels to lock onto: we use the previously described FT policy.

4.2 Comparison between DSMA and exponential backoff

As a first result, we show in Fig. 3 a comparison between the average throughput for the DSMA and exponential backoff strategies, for varying offered traffic. By throughput, we mean the average number of 1000-bit streams per frame that actually get through. Exponential backoff is intended as the following rule. If a transmission toward a certain destination lacks CTS response, further communications involving *that node* are deferred for a number of frames uniformly distributed between 1 and B_{max}. At each failure, B_{max} is increased exponentially following the equation $B_{\text{max}} = W \cdot 2^{N_{\text{fail}}-1}$. In Fig. 3, we set DSMA parameters by considering a fixed probability of transmission by idle nodes ($P_{\text{TX}} = 0.1$), and fixed queue search depth for reservations ($d_{\text{max}} = 3$). P_{reserve} is varied to be 0, 0.5 or 1. For exponential backoff, we set $W = 16$.[2]

Fig. 3 shows that exponential backoff is outperformed by DSMA if P_{reserve} is sufficiently high. Otherwise, the maximum saturation throughput that can be reached by the DSMA algorithm is inferior, and decreases for decreasing P_{reserve}. A first reason is as follows. For low P_{TX}, if P_{reserve} is also low, a very conservative behavior is set up in the network, because these values limit both the number of reserving nodes and that of idle nodes deciding to transmit. Conversely, a high P_{reserve} maximizes the effects of the DSMA distributed coordination method, achieving a higher throughput than exponential backoff. Hence, the intuition that originates this contribution is confirmed. Note that the maximum throughput (as we defined it) reachable by 802.11 DCF in a completely connected network is 1. Further improvement may be achieved by properly tuning P_{TX} and P_{reserve}, as will be explained in Sec. 4.3, which discusses a high offered traffic scenario.

Besides the higher level of coordination among transmitters and receivers, another reason behind the higher throughput values reached by DSMA is visible in Fig. 4, that shows the ratio of successfully received to sent stream transmission requests, for both DSMA and exponential backoff. The parameters are set as in Fig. 3. The stream

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[2] We have evidence that this is a good value to reach maximum backoff performance, but do not include these results here due to lack of space.

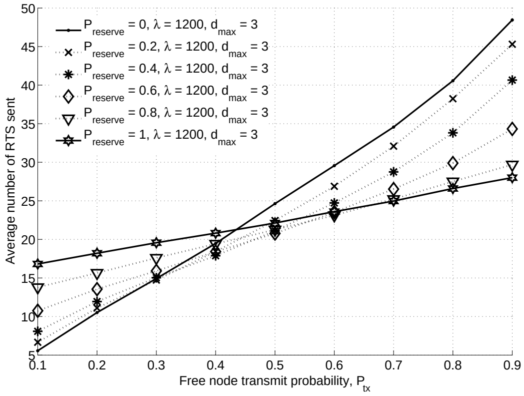

Figure 5: Average number of sent RTSs with DSMA at constant high traffic ($\lambda = 1200$), for varying P_{reserve} and P_{TX}.

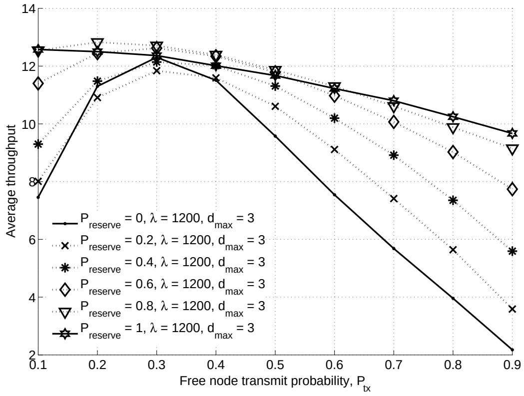

Figure 6: Average throughput with DSMA at constant high traffic ($\lambda = 1200$), for varying P_{reserve} and P_{TX}.

success ratio is a very important metric, because of the way network operations are administered. Recall that the FT policy relies on the knowledge of communications that will superimpose in the next data transfer phase, which is obtained directly from information contained in RTS messages. If an RTS is sent but is not authorized with a CTS by the corresponding destination, it is likely that other neighboring receivers take the request as granted, and spend training sequences to estimate the corresponding channel, even if the transmission does not actually take place.[3] At high traffic loads, this may be a limiting behavior, because important degrees of freedom are wasted for inactive potential transmitters, leaving receivers less protected against other interfering transmissions. DSMA helps solving this problem. Reservations helps to send RTSs to destinations that will be able to grant them with higher probability. This bestows the chance that FT correctly drives the interference cancellation process, thereby increasing the global network throughput. Note that the intersection between the DSMA curves is expected because, at high loads, lower P_{TX} and P_{reserve} allow few nodes to transmit their RTS, hence improving the probability that the few ones getting through are granted.

To sum up, FT needs a higher–level coordination as provided by DSMA in order to correctly exploit channel information, but DSMA also needs FT to reach a good balance between throughput and reliability (obtained through interference cancellation and load bounding).

4.3 Results about P_{reserve} and P_{TX}

In this Section, we describe in deeper detail the effects of tuning the two parameters P_{reserve} and P_{TX} that are part of the DSMA protocol. In Figs. 5, 6 and 7, we give more insights on how the variation of P_{reserve} and P_{TX} affects the behavior of nodes and the network performance. The Figures depict the number of RTSs sent by nodes during handshakes preceding data stream transmissions (more RTSs may be included in a single packet to be sent in the RTS phase), the average throughput (i.e., the average number of 1000-bit streams per frame that actually get through), and the average ratio of successful stream transmissions to the total number of attempts to send data streams, respectively. Results are considered for a large offered traffic ($\lambda = 1200$), so that the system exhibits saturation conditions and the effect of the values of the parameters is better highlighted (e.g., at low traffic P_{TX} has an almost imperceptible influence).

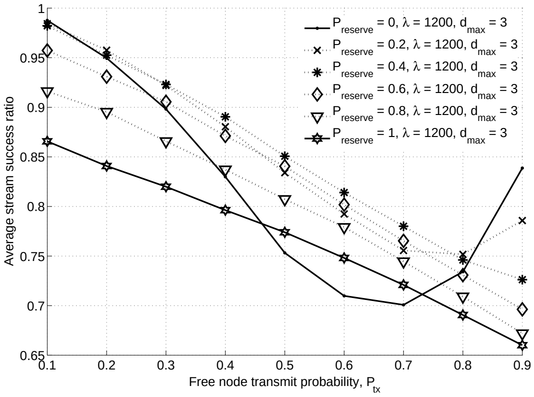

Figure 7: Average ratio of successfully received to transmitted streams with DSMA at constant high traffic ($\lambda = 1200$), for varying P_{reserve} and P_{TX}.

From Fig. 5, we first observe that if $P_{\text{reserve}} = 0$, i.e., nodes are not allowed to reserve any destination, the behavior is quite predictable. In fact, the number of RTSs increases with the probability that an idle node decides to send a packet, P_{TX}. As P_{reserve} is increased, the impact of P_{TX} is reduced, and even if the relationship between the number of RTSs and P_{TX} is still approximately linear, the slope is smaller. This happens because an increasingly higher number of nodes are asked to act as receivers, thereby leaving a smaller subset of terminals per frame. With high P_{reserve}, there is in fact a high probability that transmitters in a given frame are nodes that made a reservation request in the previous frame.

Now let us concentrate on Figs. 6 and 7, representing average throughput and success ratio in a high traffic scenario, respectively. In the case $P_{\text{reserve}} = 0$, at first (low P_{TX}) the number of transmitters per frame is low, and so is the throughput as well. As P_{TX} is increased, the number of transmissions per frame also increases: the system is quickly loaded by senders, thereby experiencing a steep throughput increase. Anyway, nodes inject traffic in the network in a “dumb” way, as they greedily try to send with probability P_{TX} without any coordination. Therefore, throughput first reaches a maximum, but then falls, because receivers are too overloaded to decode incoming transmissions correctly. Success ratio decreases as well, until P_{TX} is so high that almost all nodes try to send data in each frame. In this scenario, they require most probably to transmit

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[3] Clearly, receivers cannot cope with this problem by extrapolating information from CTSs, as they are CTS senders themselves.

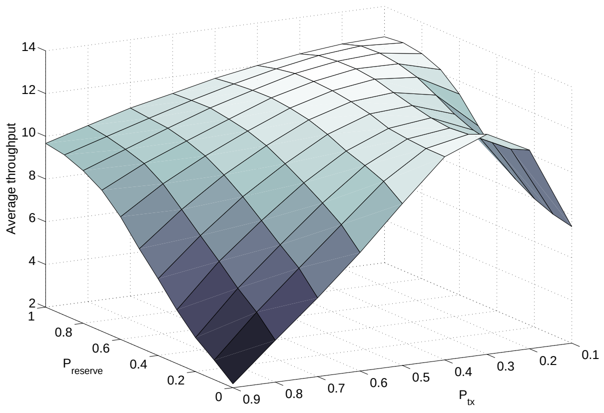

Figure 8: 3D view of throughput with DSMA at constant high traffic ($\lambda = 1200$), for varying P_{reserve} and P_{TX}.

toward nodes that chose to be transmitters themselves, hence causing a failure that forces both to stay silent during the data phase. Therefore, the few handshakes taking place between a sender and an idle receiver succeed almost surely, increasing the success ratio for high P_{TX} and $P_{\text{reserve}} = 0$. Note that, even with a higher success ratio, nodes rarely find a free receiver, so the throughput continues decreasing with P_{TX}.

If the DSMA reservation feature is activated by increasing P_{reserve}, we observe a progressively higher throughput and success ratio, explainable by the deeper level of coordination that is distributely achieved among nodes. In particular, transmitting nodes are more frequently asked to act as receivers. Furthermore, idle nodes choosing to transmit preferably address reserved nodes. This both improves the probability that sent RTSs are granted and reduces the impact of a higher P_{TX}, thereupon achieving a better coordination of traffic flows and a globally higher network performance. Specifically, lower P_{reserve} has a behavior which is very similar to the case $P_{\text{reserve}} = 0$, but with higher success ratio, and thus higher throughput for greater P_{TX}; on the other hand, while proceeding towards the limiting case $P_{\text{reserve}} = 1$, curves show a more linear behavior (due to the smaller influence of P_{TX}), with higher throughput and smoothly decreasing success ratio. In these cases, the level of coordination among nodes is pushed to its maximum depth, obtaining higher throughputs despite the slightly lower success ratios. Such results are due to the very high chance that an RTS is directed toward a node which was asked to be a receiver, improving the likelihood that they are accepted and that more data streams are spatially multiplexed in the network. Of course, the resulting heavier receiver load tends to imply a lower success ratio, but the overall effect is typically a higher throughput nonetheless.

Note that we do not claim at all that increasing P_{reserve} is always the best strategy for achieving higher throughputs: performance depends for instance on traffic and node density, and the best values of P_{reserve} and P_{TX} that allow to maximize dispatched traffic levels are to be tuned adaptively. An in-depth analysis of traffic and density impact on the network is beyond the scope of this paper. For the sake of better understanding DSMA's behavior, we anyway show in Fig. 8 how the maximum allowable throughput is jointly affected by P_{reserve} and P_{TX}. A very interesting thing to note there is the *saddle point* forming at about ($P_{\text{TX}} = 0.3$, $P_{\text{reserve}} = 0.1$), i.e., the intersection of a local maximum in P_{TX} and a local minimum in P_{reserve}. It can be inferred that, at high traffic and for P_{TX} around 0.3, reserving nodes with low probability is worse than not reserving at all, which is in turn worse than reserving with higher probability. In fact, at high traffic, keeping the reservation mechanism too limited has the only net effect of increasing the number of transmissions, whereas the most beneficial effect of DSMA, i.e., the chance to send RTSs to nodes that are ready to listen is still negligible. This sheds some light on the need to set P_{TX} and P_{reserve} jointly, in order to achieve the maximum performance given the offered traffic. In the discussed scenario, with $\lambda = 1200$, this maximum point is found to be around ($P_{\text{TX}} = 0.2$, $P_{\text{reserve}} = 0.8$). Thus, for processing the highest amount of traffic and achieving the maximum throughput, one has to rely on a high probability of reserving receivers in the ACK transmission phase and on a low probability that an idle node decides to initiate a transmission.

5. CONCLUSIONS

In this work we proposed and analyzed DSMA, a radio access method for ad hoc networks with MIMO communications. Our scheme relies on a distributed scheduling and coordination of transmitter and receiver roles, which improves the chance that transmissions are directed towards nodes that are able to receive and process them. We started from a previously studied network structure which achieves good performance results based on cross–layer interaction of MAC and PHY layers. From there, we showed that our policy is able to outperform a random method of coordinating transmissions based on exponential backoff. We also gave further insights on the effect of tuning two relevant protocol parameters. Future work on DSMA includes an analysis of the effect of $d_{\max}$ as well as a more in-depth analysis of the effects of parameter tuning for different traffic values.

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