SPCwMD: Towards Uplink Superposition Coding and Multi-User Diversity in Wireless Networks

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***Abstract*—In recent years wireless mesh networks (WMN) gained lots of attention in research and industry. Especially, the use of WMNs for community networks proved their ability to provide a high performance Internet access while demanding little deployment planning or operational management [5]. However, one problem became apparent. Network congestion, especially around gateway nodes, can dramatically decrease the overall performance of the entire network. We present a novel approach to efficiently decrease network congestion while maintaining fairness. To achieve that goal, we combine two modern techniques, namely uplink superposition-coding and multi-user diversity to create a MAC protocol that can dramatically improve the network throughput around gateway nodes, hence extending the capabilities of the entire mesh network. We will present two distributed protocols, which are suitable for ad-hoc networks without any centralized infrastructure. Extensive analysis and simulations will be presented, that show a network throughput increase of up to 88% over the use of 802.11 with the OAR rate selection algorithm. In a fading environment an additional gain of 5-13% from multi-user diversity was observed.**

***Index Terms*—Wireless Networks, Uplink Superposition Coding, Multi-User Diversity, Medium Access Control, Mesh**

I. Introduction

Wireless mesh networks are not only a popular research area; today they also play an important role for sensor networks as well as community networks [1]. In contrast to fixed networks, a well-known problem in wireless networks is the existence of channel fading and undesired interference. A very promising wireless communication idea that inherently considers radio aspects is the notion of multi-user diversity [15] (MUD). The idea here is to communicate with users at good instances, generally interpreted as exploiting channel variations and then selecting the best user(s). At any time in a network with multiple users scheduling the user with the best channel condition increases the throughput significantly. An illustration is depicted in Fig. 1. With increasing number of users the MUD also increases. Moreover the greater fading variation the higher the gain from MUD.

Lots of work was done to improve the throughput in wireless mesh networks. However, the focus was more on traditional forwarding techniques. In recent years newer techniques became available. According to one approach the received signal does not have to come from a single transmitter. Instead, multiple distinct nodes may transmit simultaneously to a common node, and the mixed signal is processed at the receiver.

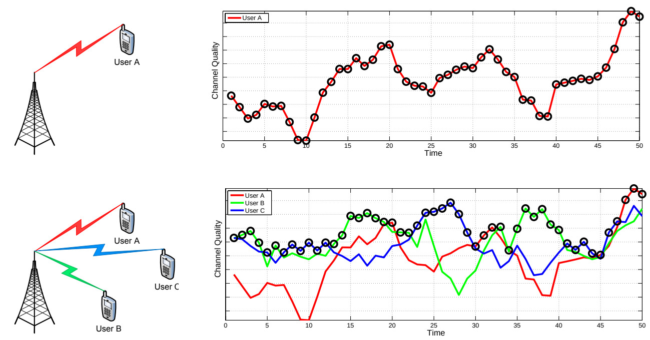

Figure 1. Wireless network with only one user (above) and multiple users (below) and a fading channel.

One such technique is uplink superposition coding [26] (UL-SPC). Fig. 2 illustrates an example. Here both users are transmitting different signals at the same time spreading their signal across the entire bandwidth. The QPSK constellation of user 2 is superimposed on that of user 1. On the receiver side a successive interference cancelation (SIC) receiver is needed. The receiver decodes the incoming signal y in two stages. First, the constellation of the primary user with the stronger signal $\tilde{x}_1$ is decoded, treating the superimposed additional signal as interference. Thereafter the receiver re-encodes the decoded constellation, and then subtracts it from the original signal y. The receiver then decodes the remaining signal of the secondary, weaker user $\tilde{x}_2$. This process is referred to as successive interference cancelation. To allow both signals to be decoded it has to be assured that the signal strength from the primary user is higher than that of the secondary user; that is, the two channels should either be asymmetric or the power-level of the secondary user has to be adjusted accordingly. In this paper, for simplicity, we restrict ourselves to the two-sender case, in which two senders simultaneously transmit a message destined to the same receiver. The common receiver receives two messages and performs successive interference cancelation to retrieve both messages. We refer to the signal of the stronger sender as the first or upper layer (UL), and the signal of the weaker sender as the second or lower layer (LL). However, it would be trivial to extend this method to higher numbers of simultaneous transmitters through iterative application of SIC.

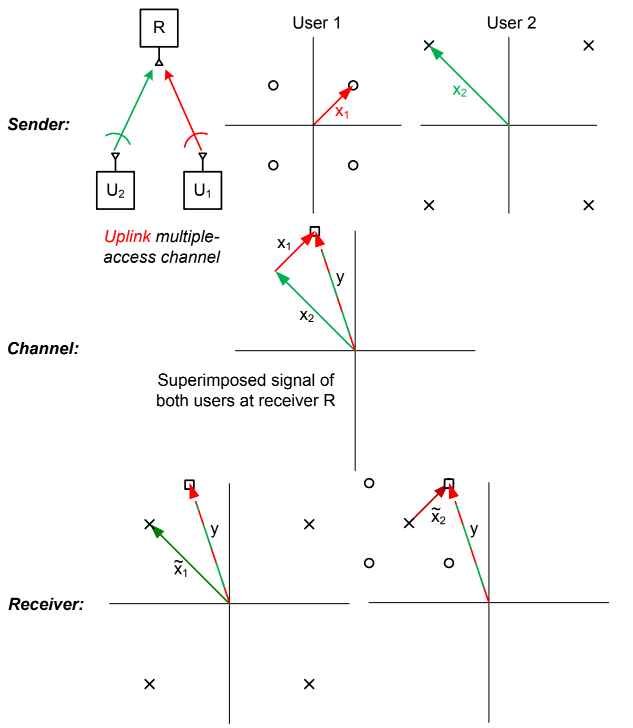

Figure 2. (Uplink) Superposition example. Here a QPSK constellation is used.

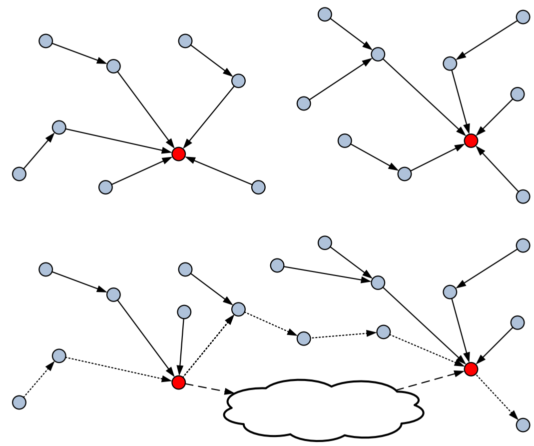

Figure 3. Wireless community mesh network with pure mesh nodes (blue) and gateway mesh nodes (red). In the first scenario (upper) gateway nodes are used to provide Internet access whereas in the second scenario (lower) the gateway nodes are connected by a backbone network (e.g. Internet) thus allowing traffic to be directed through the backbone (dashed line).

A. Motivation

Wireless community mesh networks are often used to provide Internet access on the last hop. Therefore special gateway nodes are used to connect the mesh network to the Internet. In result, community networks are not flat but often structured. In such networks most of the traffic is destined to the Internet and therefore directed to a nearby gateway node (Fig. 3, upper). A number of studies like [8] and [11] have shown that this results in a congested area around gateway nodes and thereby limiting the performance of the whole system. Another advantage of using gateway nodes in a mesh network is the possibility to use the backbone network as a shortcut for routing, therefore reducing the number of end to end hops and thus improving overall performance (Fig. 3, lower). This, however, increases congestion around the gateway nodes even further.

In this paper we propose a MAC protocol that makes use of two novel techniques, namely uplink superposition coding (SPC) and multi-user diversity (MUD), to reduce congestion around gateway nodes and thereby increasing the performance of the whole system. Unlike previous studies, which focus on physical layer issues we will focus only on MAC issues.

The rest of the paper is organized as follows. In Section II, we review related work on MUD and SPC. In Section III, we give a detailed presentation of our protocols. In Section IV, using extensive evaluations in a packet simulator, we demonstrate the throughput gains of our protocols. Our conclusions and future work are in Section V.

II. Related Work

A. Multi-User Diversity

Lots of work was done in the area of mesh networks and multi-user diversity (MUD). A first protocol, which exploits MUD was presented by Larsson with its Selection Diversity Forwarding (SDF, [21]). The main idea of SDF is that, instead of selecting a single node to be the next-hop forwarder for a packet, multiple nodes can potentially act as the next-hop forwarder. The problem with SDF is its expensive 4-way MAC handshake. Other authors like Valenti [27] and Biswas et al. [6], [7] propose improvements to SDF, which replaced the 4-way by a shorter 2-way handshake consisting of data multicast and slotted acknowledgment. Later Larsson et al. propose an improved version of SDF called Multiuser Diversity Forwarding (MDF, [22]). The basic idea of MDF is as follows: The transmitter multicasts a probe to a set of candidate relay nodes, which evaluates the instantaneous channel quality (channel quality indication (CQI)) based on the received probe. The CQI is then reported back to the transmitter that, based on the CQI information, opportunistically determines a next hop relay (out of one or more relays), a flow (out of one or more flows), and a rate (out of one or more rates). MDF assumes that the protocol duration is shorter than the channel coherence time.

Besides the optimization of the choice of forwarder from those nodes that received a transmission, MUD can be used to combine the bits received at different nodes to recover from wireless errors [17], [24], or allow all nodes that overheard a transmission to simultaneously forward the signal acting as a multi-antenna system [18], [19].

B. Superposition Coding

Lots of work was done to improve the throughput in wireless mesh networks. In recent years the focus shifted away from traditional forwarding techniques. Instead, new multiple access methods were proposed that enable multiple distinct nodes to transmit simultaneously to a common node. The mixed signal is processed and/or further relayed to increase spectral efficiency [3]. Examples of such approaches include relay channels [16], physical network coding [28], analog network coding [14], and uplink superposition coding [26].

The idea of superposition coding (SPC) was first introduced by Cook in 1970 [10]. In recent years, especially the downlink was subject to further studies. Potential issues, however, with receiver-based approaches to SPC are the substantial receiver complexity and synchronization requirements for the participating stations. Especially for sensor networks this can be an issue. Uplink-SPC (UL-SPC) can take this load off of the terminals in a network and move it into the base station (BS). The BS can instruct terminals to transmit at different power levels and data rates according to the current channel requirements. The BS then handles the complexity of decoding the different superimposed signals. It has been shown that UL-SPC can be completely transparent to terminals [20]. UL-SPC can also be used in cellular networks to decrease inter-cellular interference while keeping throughput high. This can be achieved by choosing a terminal with a high expected inter-cellular interference as the weak station (LL) and a terminal with low expected interference as the strong station (UL) in an UL-SPC transmission [20]. This way, the terminal that is expected to cause a lot of interference can transmit with reduced power while it is still possible to keep the network throughput high by superimposing one or more further transmissions.

The focus of this paper is UL-SPC where multiple senders transmit simultaneously to a common receiver. However, it is also possible to use SPC in the downlink. Downlink superposition coding (DL-SPC) enables a sender to transmit simultaneously different messages to multiple receivers. There are numerous studies and implementations that show promising results for DL-SPC. Examples include [23], who have shown up to 1.5 times improvements in network throughput for some settings. The main downside however, is the requirement that every station in the network has to have the complex SIC receiver. Another drawback to DL-SPC is the required power split. A station cannot use more power to transmit than a certain P_{max}. This P_{max} has to be split between the different receivers, thus effectively limiting the available power per transmission ($P_1 + P_2 \leq P_{max}$). This split is not necessary for UL-SPC. Each sender may use P_{max}, resulting in a higher SNIR at the receiver when compared to DL-SPC. Specifically, for two superimposed transmissions the accumulated power of all transmitters can be up to $2P_{max}$.

III. Superposition Coding with Multi-User Diversity

In this section we present our proposed MAC protocol called SPCwMD. We developed two versions each with advantages and disadvantages compared to each other. The medium access of both protocols is contention-based like in IEEE 802.11, i.e. they are suitable for ad-hoc networks without any centralized infrastructure.

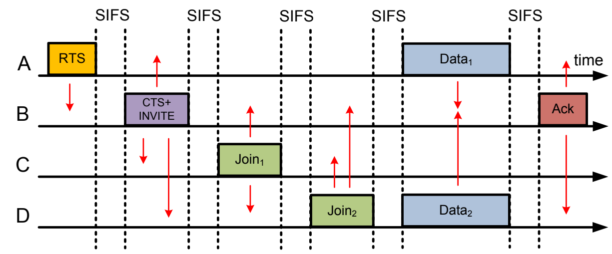

Figure 4. Illustration of the MAC operation in the basic version of SPCwMD.

A. Basic Version

The basic version of SPCwMD, in the following called SPCwMDBasic, works as follows. Consider the illustration of the medium access depicted in Fig. 4. Having data packets destined to B, node A sends an RTS packet with maximum transmission power. On receiving the RTS packet node B replies with a CTS packet. This is similar to IEEE 802.11 with the difference that it also invites other nodes, therefore CTS+Invite, to transmit their data packet synchronized resulting in a superimposed packet on the receiver side (B). To provide MUD, node B sends an invitation (CTS+Invite) not only to one node but to multiple nodes - the so-called candidate-set (here $\{C,D\}$). On receiving such an invitation the selected candidates calculate the expected sum throughput when joining this transmission by simulating a SIC reception at node B (see Listing 1). The invitation contains the received signal strength and noise of the RTS (S_{S1-R}, N_{S1-R}). Upon receiving the invitation, nodes also receive signal strength and noise from the common Receiver B (S_{R-S2}, N_{R-S2}). With those values an accurate simulation of the SIC reception at node B is possible. The calculation of the packet delivery ratio (pdr) assumes a packet size of 1500 Bytes[1]. The calculated value is communicated with a Join packet back to the originator of the CTS+Invite packet as well as to the other nodes in the candidate-set in a time division manner. After the completion of the Join phase all candidates agree on the best candidate, i.e. the one with the highest expected sum throughput (here D), which will take part in the upcoming data transmission towards node B. In the data phase two nodes (here A and D) transmit at the same time resulting in a superimposed signal at B for the duration of a transmission opportunity (TXOP, a concept known from 802.11e). Thereafter, node B tries to decode packets from both sender with the help of a SIC receiver. A subsequent Ack packet acknowledges the successfully decoded packets, similar to block acknowledgements (block Ack) in 802.11e.

In the following, the required steps in the MAC operation of SPCwMDBasic are described in thorough detail.

1) Candidate Selection: The reception of an RTS packet is replied with a CTS+Invite packet. In contrast to 802.11 RTS/CTS a CTS+Invite packet has an additional function. It invites potential candidates to participate in the upcoming data transmission. Only nodes with buffered packets towards the

[1]The distribution of packet size in IP based networks is bimodal. The majority packets are either small or large. Only the large ones are relevant to the calculation.

destination of the RTS packet are considered. To keep the signaling overhead low only a subset of potential candidates can be selected. The algorithm for the candidate selection has to make sure, that:

- Each candidate has at least one packet destined to the common receiver (originator of the CTS+Invite),
- If the number of potential candidates is greater than the allowed maximum, candidates having a better channel (higher SNR) towards the receiver are preferred,
- The candidates agree on the best candidate in a distributed manner. Therefore to guarantee that a Join packet is received by all candidates we have to make sure that the candidates are well connected, i.e. the packet error rate of the links between the candidates is smaller than 10%[2].

One additional problem needs to be solved, namely how a node, in particular a gateway, may find out whether a neighboring node has buffered packets destined to it. Here we distinguish between two cases. First, a node is the source of a packet flow. Second, a node is relaying the packets from another node. In a typical mesh network case two is more common, because there are only a few packet flows and most of the packets are relayed. Therefore we only consider the common case for which the following simple solution is used. Consider the illustration depicted in Fig. 5. Let node A be our gateway node. Here node C transmits a data packet to B, which acknowledges the successful reception with an acknowledgement packet. The Ack packet contains the information about the next hop recipient of the data packet being acknowledged (here A)[3]. By overhearing that Ack packet node A knows that B has a buffered packet to be transmitted to A. Although we have to treat this information as binary, it is sufficient to select a candidate set.

The passive overhearing of Ack packets is robust since Ack packets are very small and do not participate in a SPC transmission. However, it is still possible that the recipient of an RTS packet (gateway node) is unable to construct a valid candidate set. This may happen because none of its neighbors has a buffered packet destined to it. It is also possible that the node missed an acknowledgment packet of neighboring nodes. In such a situation a regular CTS will be send out and therefore no SPC will be used for the ongoing transmission. In this case, we neither benefit nor lose anything compared to regular 802.11 without SPC. An additional benefit of our approach is the fact, that the Ack can be used to measure the channel quality and therefore improving the selection of candidates by choosing those with a strong channel.

2) Join: All nodes whose address is enlisted in the CTS+Invite packet have to reply with a Join packet. With the help of the Join packet a candidate informs the other candidates about the expected sum throughput when participating in the upcoming data transmission. During the slotted join phase each candidate passively overhears the join packets of all other candidates. After the join phase the candidate with

[2]This information is also available from Link-Probing.

[3]The information about the next hop recipient is available when a Source-Routing (e.g. DSR [13]) is used since the entire route is known a-priori and attached to each packet. However, we believe that such an approach is also possible with other routing protocols like AODV or OLSR.

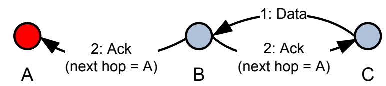

Figure 5. By overhearing the acknowledgment packet of an ongoing packet transmission ($C \rightarrow B$) node A can find out the next hop recipient of that data packet (here A).

the highest expected sum throughput will participate in the upcoming data transmission. All other candidates will cancel their scheduled transmission. Therefore the join phase is a distributed agreement among the candidates on the candidate, which will participate in the ongoing SPC transmission.

The following specifics have to be considered. One of the sender ($S1$, originator of the RTS) is not aware of SPC[4]. Therefore, $S1$ assumes an orthogonal medium access (no SPC) and selects the rate for the data transmission according to the RBAR/OAR rate selection algorithm[5]. Furthermore, $S1$ will send with maximum transmission power. That means that the candidate ($S2$) has no influence on the bit rate as well as power selection of $S1$. In addition, because of a lack of available information in SPCwMDBasic we have to assume that the channel is symmetric. With the help of the RTS we are able to measure the channel from A to B. However for the upcoming data transmission we are also interested in the quality of the channel from C to B and D to B. With the help of the CTS packet, we can only measure B to C and B to D; hence channel symmetry has to be assumed. Note, that the Join packet does not provide this information, as it is only send after the SIC simulation has already been performed.

Again, the candidate with the highest expected sum throughput will participate in the ongoing SPC transmission. The algorithm is depicted in Listing 1. Each candidate (referred as $S2$) executes the SIC simulator. Here it loops over all available bit rates and power allocations to find a solution with the highest expected sum throughput. To be able to calculate the highest expected sum throughput accurately, each candidate has to know about the buffered packets on $S1$ as well as about its own buffered packets. This information is required because in SPCwMD the medium is reserved for the duration of TXOP and not only for a single packet (section III-C). Now it is possible that a given candidate cannot utilize the whole TXOP duration because of insufficient buffered packets towards the destination. Consider the following example. Here, we have 2 candidates. Candidate 1 is able to transmit at a higher rate than candidate 2 because of a better channel. However, candidate 1 has only a single packet buffered. In contrast candidate 1 has lots of packets and therefore is able to fully utilize the TXOP. Despite its higher rate, candidate 1 will have a lower expected sum throughput. Therefore, candidate 1 will be preferred. To take this into account, node $S1$ and $S2$ have to calculate the

[4]The power as well the bit rate of the sender $S1$ cannot be changed by a candidate, because we cannot guarantee that the Join packet will be successfully received by the $S1$.

[5]In Receiver Based Auto-Rate (RBAR) the bit rate for the data packet is estimated on the receiver side with the help of the SNIR value of the received RTS packet. With the help of the CTS packet the sender is informed about the estimated bit rate to be used for the data packet.

number of bits, they can send at a given rate r during a given duration of TXOP and compare this with the number of suitable packets enqueued. Therefore we declare a function $b(r)$: $b(r) \leftarrow min(\sum p_i, r \cdot \text{TXOP}), 1 \leq i \leq \text{buffer\_size}$ where p_i is the size of the i-th packet in queue. This function yields the maximum number of bits a node can send at a certain rate during TXOP. From the technical point of view, node $S1$ calculates $b(r)$ for each available bit rate. This information is included in the RTS as well as CTS+Invite packet[6]. The latter is required to inform the candidates about that value.

Algorithm 1 SIC simulator is executed by each user (S2) enlisted in the CTS packet as candidate.

```
procedure BasicSICSimul    ▷ S1 = originator of the RTS packet; S2 is the current node; R is the common receiver
    (S_{S1−R}, N_{S1−R})    ▷ signal/noise received in RTS
    (S_{R−S2}, N_{R−S2})    ▷ signal/noise measured by CTS
    R_{S1−R} ← getDataRate(S_{S1−R}, N_{S1−R})    ▷ RBAR
    thr_best ← ∅
    for r ∈ Rates × p ∈ (0, p_max) do
                            ▷ Permutations of rate and power of S2
        if S_{S1−R} > S_{R−S2} + p − p_max then
                            ▷ S1 is the primary user.
            S_UL ← S_{S1−R}, S_LL ← S_{R−S2} + p − p_max
            N_UL ← S_LL + N_{S1−R}, N_LL ← N_{R−S2}
            R_UL ← R_{S1−R}, R_LL ← r
        else                ▷ S2 is the primary user.
            S_UL ← S_{R−S2} + p − p_max, S_LL ← S_{S1−R}
            N_UL ← S_LL + N_{R−S2}, N_LL ← N_{S1−R}
            R_UL ← r, R_LL ← R_{S1−R}
        end if
        PDR_UL ← pdr(S_UL, N_UL, R_UL)
        PDR_LL ← pdr(S_LL, N_LL, R_LL)
        thr ← PDR_UL · b(R_UL)/TXOP + PDR_UL · PDR_LL · b(R_LL)/TXOP
        if thr > thr_best then
            thr_best ← thr, R_best ← r, p_best ← p
        end if
    end for
    return (thr_best, R_best, p_best)
end procedure
```

3) Ack: Ack packet enlists the originator address of all successfully received data packets. Multiple packets from the same source are acknowledged with the help of a bitmap (block ack). In addition, as already mentioned, the ack contains the address of the next hop forwarder (section III-C). If the receiving node is either a gateway or the last hop of a flow, there is no next hop and thus the Ack is shorter in this case. The Ack packet is transmitted at the lowest available rate to increase reliabilty.

[6]To keep this information compact we propose the following coding scheme: $\forall r \in R : \lceil b(r)/(r \cdot \text{TXOP}) \cdot 100 \rceil$. This yields a compressed, yet meaningful result between 1 and 100, which can be encoded in just 7 bits per rate. For the 8 available rates in 802.11a/g, this amounts to a reasonable overhead of 7 Bytes per packet.

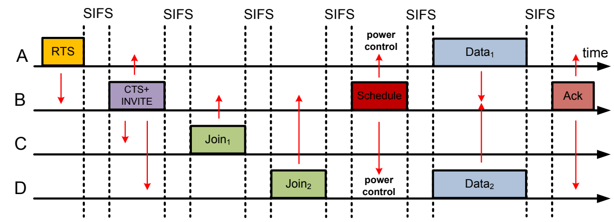

Figure 6. Illustration of the MAC operation in the advanced version of SPCwMD.

B. Advanced Version

In the following we present the advanced version of SPCwMD called SPCwMDPlus. SPCwMDPlus is similar to SPCwMDBasic with the difference that after the Join phase the participating nodes are explicitly scheduled by the common receiver of the data packets. Consider the illustration depicted in Fig. 6. After receiving the Join packets from all candidates node B has enough information to simulate a SIC reception. In the advanced version it is able to control the transmission power as well as the bit rates of all participating nodes ($S1 = A$ and $S2 = D$). With SPCwMDBasic it is only possible to adapt the transmission power and rate of the invited transmission.

The contents of the CTS+Invite and Join packets are different in both versions of SPCwMD. For SPCwMDPlus the CTS+Invite carries less information. So it is no longer necessary to inform the candidates about the buffered packets on $S1$ as well as about the channel quality between $S1$ and the common receiver. In addition, there is no need to put information about the best candidate in the Join packet because the best candidate is explicitly scheduled by the destination. However, the candidates have to inform the common destination with the Join packet about their buffered packets.

1) Candidate Selection: The candidate selection is similar to SPCwMDBasic except that a connectivity between candidates is no longer required. This is because power control as well as rate selection are determined by the receiver, which informs both participating nodes by an explicit schedule packet.

2) Join: With the help of the Join packet a candidate informs the common receiver about its buffered packets, i.e. $b(r)$ for each available bit rate. It is necessary to include the results in the Join packet. Otherwise, the receiver would not be able to calculate the expected sum throughput accurately.

3) Schedule: With SPCwMDPlus there is an additional phase. After the slotted-Join each candidate listens for the Schedule packet, which explicitly selects the best candidate to participate in the SPC transmission. Due to the scheduling phase both participating nodes ($S1$ and $S2$) are aware of SPC. That means that the common receiver is able to adjust the bit rates and the power control of $S1$ as well as $S2$. For all candidates that replied with a Join packet the SIC simulator is executed (Listing 2). In contrast to SPCwMDBasic we have to loop over all possible rates and power adjustments for both participating nodes. Again, we choose the solution with the highest expected sum throughput.

The result of the calculation, i.e. the selected candidate $S2$ as well as the bit rate and power adjustment for $S1$ and $S2$, is distributed in a Schedule packet, which is a broadcast packet. To avoid singaling errors, the Schedule packet is transmitted at the lowest rate. Thereafter, the selected candidate as well as the originator of the RTS packet are transmitting their data packets with parameters (bit rate + power) given in the schedule packet.

Note, because all data is available we do not need to assume that the channel is symmetric like we did in SPCwMDBasic. This enables very accurate predictions in the SIC simulator. Finally, the computational overhead of the proposed algorithm is high, which can be reduced by the use of look-up tables. The required computational time can be reduced even further by parallelizing. Since there are no dependencies in the loops the algorithm is trivial to parallelize in hardware.

Algorithm 2 SIC simulator is executed by the common receiver (R) to determine the rates as well as the transmission powers of both users (S1 and S2) participating in the SPC. This algorithm is used by SPCwMDPlus.

procedure PLUSSICSIMU ▷ S1 = originator of the RTS packet; S2 is the buddy node with the strongest signal; R is the common receiver
 (S_{S1-R}, N_{S1-R}) ▷ signal/noise measured by RTS
 (S_{S2-R}, N_{S2-R}) ▷ signal/noise measured by Join
 $thr_{best} \leftarrow \emptyset$
 for $r_1, r_2 \in \text{Rates} \times p_1, p_2 \in (0, \text{p}_{\text{max}})$ **do**
  ▷ Permutations of rates and power of S1 and S2
  if $S_{S1-R} + p_1 - p_{max} > S_{S2-R} + p_2 - p_{max}$ **then**
   ▷ S1 is the primary user.
   $S_{UL} \leftarrow S_{S1-R} + p_1 - p_{max}$
   $S_{LL} \leftarrow S_{S2-R} + p_2 - p_{max}$
   $N_{UL} \leftarrow S_{LL} + N_{S1-R}, N_{LL} \leftarrow N_{S2-R}$
   $R_{UL} \leftarrow r_1, R_{LL} \leftarrow r_2$
  else ▷ S2 is the primary user.
   $S_{UL} \leftarrow S_{S2-R} + p_2 - p_{max}$
   $S_{LL} \leftarrow S_{S1-R} + p_1 - p_{max}$
   $N_{UL} \leftarrow S_{LL} + N_{S2-R}, N_{LL} \leftarrow N_{S1-R}$
   $R_{UL} \leftarrow r_2, R_{LL} \leftarrow r_1$
  end if
  $PDR_{UL} \leftarrow \text{pdr}(S_{UL}, N_{UL}, R_{UL})$
  $PDR_{LL} \leftarrow \text{pdr}(S_{LL}, N_{LL}, R_{LL})$
  $thr \leftarrow PDR_{UL} \cdot \frac{\text{b}(R_{UL})}{\text{TXOP}} + PDR_{UL} \cdot PDR_{LL} \cdot \frac{\text{b}(R_{LL})}{\text{TXOP}}$
  if $thr > thr_{best}$ **then**
   $thr_{best} \leftarrow thr, R1_{best} \leftarrow r_1, R2_{best} \leftarrow r_2$
   $p1_{best} \leftarrow p_1, p2_{best} \leftarrow p_2$
  end if
 end for
return $(thr_{best}, R1_{best}, R2_{best}, p1_{best}, p2_{best})$
end procedure

C. Protocol Details

To support UL-SPC and MUD the proposed protocols requires the exchange of signaling information. Especially in multi-rate environments the signaling overhead per data packet becomes high[7]. We therefore implemented an approach, which is similar to the one proposed by the OAR protocol [25]. After gaining access to the medium a station may transmit not only one packet but multiple packets as long as it does not exceed a predefined time duration (TXOP). Fig. 7 illustrates this concept. In contrast to OAR not every packet is acknowledged individually. Instead at the end of the TXOP a block acknowledgment is transmitted. The data packets are separated by a short interframe space (SIFS).

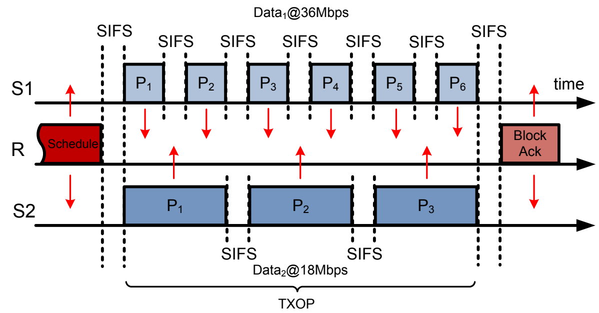

Figure 7. Illustration of TXOP in SPCwMD.

Consider the example depicted in Fig. 7. Here two nodes ($S1$ and $S2$) are simultaneously transmitting packets to a common receiver (R). Nodes $S1$ and $S2$ are sending packets at a rate of 36 and 18 Mbps respectively. In SPCwMD the duration of a TXOP is defined as the time duration to send a packet with 1500 Bytes at the lowest possible rate (here 6 Mbps). 1500 Bytes was chosen as it is commonly the maximum packet size in IP based networks. Therefore node $S1$ and $S2$ can send up to 6 and 3 packets of maximum size respectively.

The packet format is depicted in Fig. 8. The RTS packet is similar to the one in 802.11 RTS/CTS except that it contains information about the buffered data packets destined to the chosen destination. This is necessary for an accurate calculation of the expected throughput during the TXOP phase. The CTS+Invite packet contains an array of the candidates addresses. Furthermore, for the basic version of SPCwMD we need additional information like the signal and noise level of the link from the initiator of the RTS to its destination. It also contains information about the buffered data packets from the initiator of the RTS. In the basic version the Join packet contains the candidates as well as the address of the best candidate and throughput so far observed whereas in the plus version the packet is used to inform the common receiver about the buffered data packets at the candidates. Finally, the Ack packet contains a bitmap of the acknowledged data packets.

D. Comparison

This section will highlight the different advantages and disadvanteges of the two versions of SPCwMD. The advantages of SPCwMDBasic is the smaller protocol overhead as

[7]Imagine a situation where the data packets are sent at 54 Mbps and the control packets with 6 Mbps.

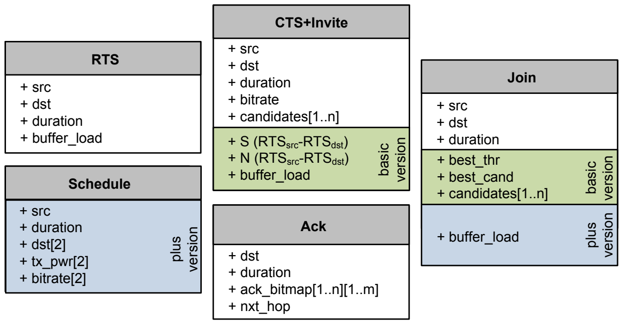

Figure 8. Packet format in SPCwMD.

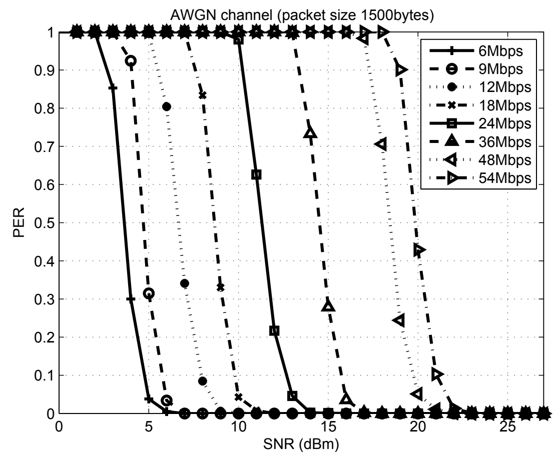

Figure 9. Packet error rate (PER) vs. SNR in an AWGN channel for large packets (1500 Bytes).

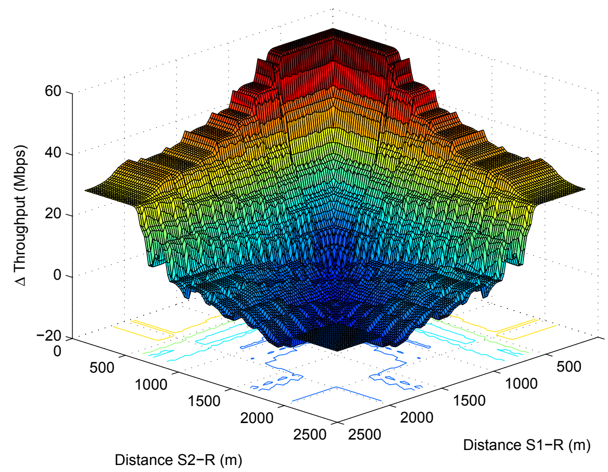

Figure 10. Throughput gain of SPCwMDPlus over 802.11 with OAR.

well as better fairness when compared to SPCwMDPlus. A higher degree of fairness is easier to guarantee since the data packet of the originator of the RTS packet is always sent with maximum transmission power and the highest possible rate assuming orthogonal medium access. However, SPCwMDBasic has many disadvantages. First, it requires physical channel symmetry (reciprocity), i.e. the SNIR of the channel from B to C is the same as from C to B. Thus SPCwMDBasic would suffer from environments with physical channel asymmetry[8]. Furthermore, with SPCwMDBasic it is not possible to achieve the full degree of freedom in the superposition coding. This is due to the fact that the bit rate and the power control of one of the two participating nodes cannot be adjusted. Only the transmission power as well as the rate of an invited candidate is adaptable, but not the one of the originator of the RTS packet, which always sends its data packet with the maximum possible transmission power whereas the rate adjustment assumes orthogonal medium access. Finally, there is a constraint on the selected candidates. Due to the distributed agreement among the candidates a direct connectivity between candidates is required, i.e. the candidates are forming a clique.

Most of the problems of SPCwMDBasic are solved by SPCwMDPlus. First, it does not depend on environments with link symmetry since the Join packets are used for channel estimation. Furthermore, it is possible to adapt the power and bit rate of both involved transmissions. Finally, no direct connectivity between candidates is required, i.e. the number of possible candidate sets is higher. However, SPCwMDPlus has also some drawbacks. The most important is the slightly higher protocol overhead due to the additional schedule packet, which requires a channel with larger coherence time. Also, SPCwMDPlus is more computation intensive. However, the expensive computations are performed only on gateway nodes.

IV. Results

In this section we present analytical as well as simulation results. Here we assumed an 802.11g physical layer (OFDM). The SNR vs. packet error rate (PER) relationship for an AWGN channel is depicted in Fig. 9[9].

A. *Analytical*

In the following we assume a simple large-scale path loss model with a path loss exponent of $\beta = 3.5$ and neither shadowing nor fading; so there is no gain from MUD. The scenario consists of 2 mesh nodes sending packets towards a gateway node. The distance between the two mesh nodes and the gateway were varied. We furthermore ignored the signaling overhead (RTS, CTS+Invite, Join, Schedule and Ack) for this analysis.

At first we compare SPCwMDPlus with 802.11 with OAR[10]. In Fig. 10 the gain in throughput of SPCwMDPlus over 802.11 with OAR is depicted. In most situations SPCwMDPlus is able to clearly outperform 802.11 with OAR by up to 54 Mbps. On the average the gain from SPCwMDPlus was about 13 Mbps. However, there are also situations where SPCwMDPlus performs worse. These are situations where the distance from both nodes towards the gateway node was nearly the same.

[8] From the MIT Roofnet study we know that most links are asymmetric [2]
[9] We used the OFDM simulator provided by Heiskala et al. [12]

[10] According to OAR the highest bit rate is selected with a maximum bit error rate of 10^{-5}

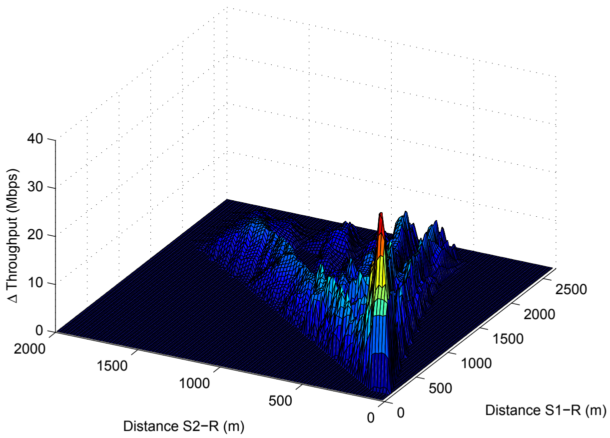

Figure 11. Throughput gain of SPCwMDPlus over SPCwMDBasic.

Simulation Parameter	Value
Fading model	Shadowing
Path loss exponent β	3.5
Shadowing standard deviation σ	12 dB
Shadowing coherence time T_{shad}	10 ms
Physical layer	802.11g OFDM
Bit rates	$6, 9, 12, 18, 24, 36,$ $48, 54$ Mbit$/s$
TXOP duration	1500 Bytes @ 6 Mbit/s $\approx$ 2 ms
Radio Sensitivity	-96dBm
UDP flow duration / payload size	10 sec / 1460 Bytes
UDP flow rate	saturated
No. flows	9
Seeds	30
Nodes	10

Table I
SIMULATION PARAMETERS

Finally we compare the performance of SPCwMDBasic and SPCwMDPlus. Fig. 11 shows the gain in throughput of SPCwMDPlus over SPCwMDBasic. We identify situations where SPCwMDPlus outperforms SPCwMDBasic by more than 35 Mbps. The average throughout gain was around 1 Mbps when using SPCwMDPlus instead of SPCwMDBasic. It should be noted, that the results are not symmetric due to the fact that in case of SPCwMDBasic node $S1$ was not aware of SPC.

B. *Simulations*

JiST/SWANS is used in our simulation study [4]. We extended the simulator to support different bit-rates proposed by the 802.11g specification. In the following we will evaluate two scenarios. An environment with clear LOS and a highly obstructed environment with NLOS. In the LOS environment we will see the benefit of SPC whereas in the NLOS environment we can observe the additional gain from MUD. Here because of a higher SIR the sum rate (UL+LL) increases.

1) Simulation Parameter: In the evaluation section we assume that a SIC receiver is used, which tolerates a maximum delay spread of 0.8 μs. Furthermore we distinguished between two scenarios - one environment with clear LOS and a highly obstructed environment with NLOS. The former is modeled with a deterministic large-scale path loss model whereas the later considers shadowing. In both scenarios we will place the gateway node in the center of a circular field whereas the remaining nodes are distributed randomly. A packet flow is set-up from each node to the gateway node. The remaining simulation parameter are depicted in Table I.

2) Protocols: We will compare the two versions of SPCwMD with 802.11 RTS/CTS using the OAR [25] rate selection algorithm with the distinction that the data packets within a TXOP are acknowledged by a single block Ack instead of multiple Ack packets. In the following we will refer to this as 802.11 OAR+. To keep the scope of the simulations focused, we have not set up a multihop path. Therefore every node is considered as a possible candidate by SPCwMD (instead of overhearing Acks as described before). Finally, UDP was used as the transport protocol.

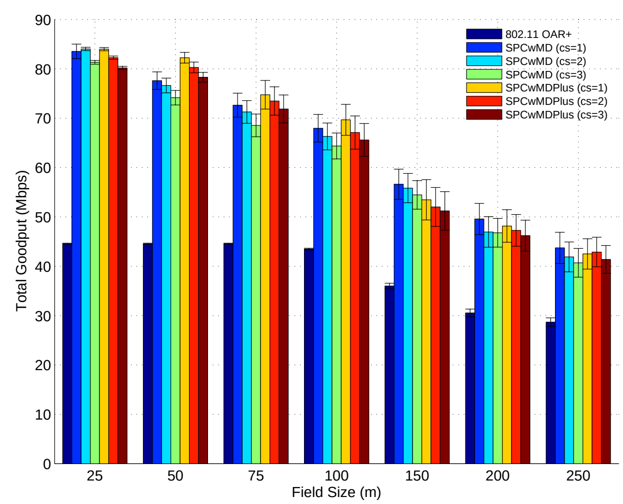

Figure 12. Average throughput ($\pm$ standard error of the mean) for LOS scenario.

3) Throughput: At first we compare the protocols in an environment with clear LOS (Fig. 12). Here the channel is deterministic. For a small field size the performance of SPCwMD (1 candidate) is around 88% higher than of 802.11 OAR+. For greater field sizes the advantages decreases to 53%. The reason is that for a larger field size the possibility to find a candidate, which is close to the gateway decreases. In case the of SPCwMDBasic as well as SPCwMDPlus using more candidates does not help. With a deterministic radio channel it is optimal to select the best candidate. The performance degrades when multiple candidates are selected because of the higher protocol overhead. Finally, we can see that SPCwMDBasic and SPCwMDPlus are offering nearly the same results. That means the advantage of SPCwMDPlus to be able to adjust the power as well as bit rate of both participating nodes is small. Note that SPCwMDPlus has the highest signaling overhead.

Now we consider a highly obstructed environment (NLOS, Fig. 13). In this scenario the channel can no longer be regarded as deterministic, effects like Shadowing occur. Here SPCwMDPlus with 2 candidates offers the highest throughput for all field sizes. It outperforms 802.11 OAR+ by 84% and

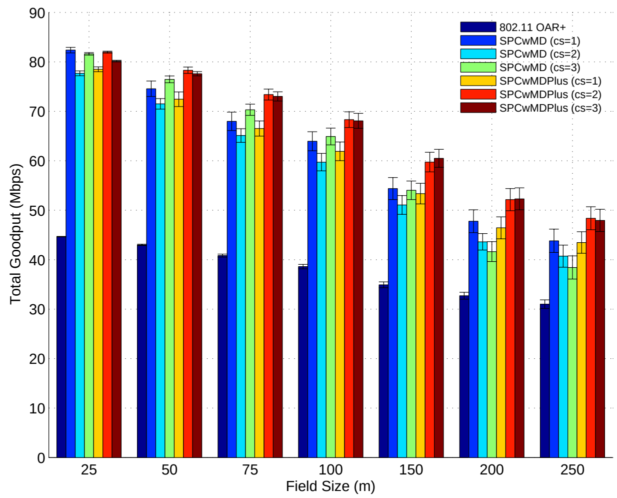

Figure 13. Average throughput (± standard error of the mean) for NLOS scenario.

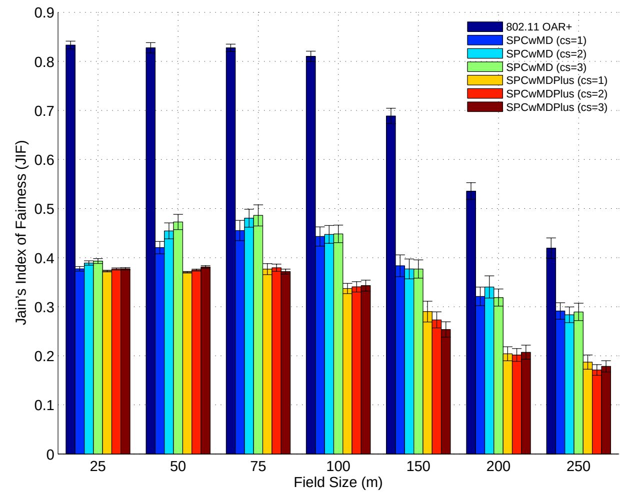

Figure 14. Jains Index of Fairness (JIF) for LOS scenario (± standard error of the mean).

56% for small and large field sizes, respectively. Having more than 1 candidate makes sense: SPCwMDPlus with 2 candidates outperforms the version with only 1 candidate by 5-13% due to the MUD gain. The reason is that the candidate selection is using only long-term channel estimation (averaging). However, short-term variations can be considered when selecting multiple candidates. This is achieved by utilizing the Join packets as probes for the current state of the channel. Despite the higher protocol overhead SPCwMDPlus outperforms SPCwMD by up to 10% depending on the field size.

4) Fairness: Both versions of SPCwMD are as fair as 802.11 OAR+ in terms of UL medium access. This is due to the similar contention-based access. Therefore, like in 802.11 OAR+ stations that are close to the destination can transmit during the same time more bits. In addition with SPCwMD stations that are close to the receiver are more often selected for joining in superposition coding. In order to provide a fairness measure for the different approaches, the Jains Index of Fairness (JIF) is computed with the average user terminals (UTs) throughput R_k calculated for a varying number of nodes and field densities [9]:

$$\text{fairness} = \frac{(\sum_{k=1}^{K} \bar{R_k})^2}{K \cdot \sum_{k=1}^{K} \bar{R}_k^2} \tag{1}$$

, where K is the number of flows.

The results are depicted in Fig. 14. The following observation can be made. SPCwMDBasic has a higher fairness index than SPCwMDPlus. The reason is that in SPCwMDPlus the bit rate as well as power of the initiator of the transmission (originator of the RTS) can be adjusted. This leads to the situation that nodes, which are far from the gateway will send with a lower bit rate and possible lower power compared to the orthogonal medium access.

V. Outlook

With both proposed protocols one cannot fully benefit from MUD. The reason is that the initiator of the RTS packet, $S1$, always participates in the subsequent data transmission. Only the invited candidate, $S2$, benefits from MUD. However, with UL-SPC it is possible to benefit twice from MUD. Imagine an UL-SPC protocol were you are able to select the best two candidates, i.e. the signal strength of both candidates is well above their average. Here the MUD gain would be twofold. On the one hand the sum rate (UL+LL) increases, because of a higher SIR. On the other hand one of the participating users, the secondary user, can reduce its transmission power and therefore reducing interference to neighboring transmissions.

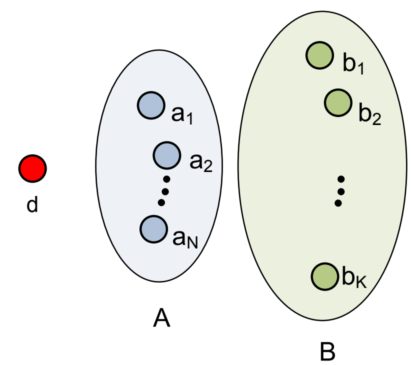

Figure 15. Network where each node from group A (B) has the same average SNR towards the gateway node d.

Consider the network depicted in Fig. 15. Here each node from group A (B) has the same average SNR towards d: $\forall i, j : \bar{\gamma}_{a_i,d} = \bar{\gamma}_{a_j,d}, 1 \leq i, j \leq N$ and $\forall i, j : \bar{\gamma}_{b_i,d} = \bar{\gamma}_{b_j,d}, 1 \leq i, j \leq K$. Now, assume w.l.o.g. that node a_1 and b_1 have the highest instantaneous SNR in their groups: $\forall i : \gamma_{a_1,d} > \gamma_{a_i,d}, 2 \leq i \leq N$ and $\forall i : \gamma_{b_1,d} > \gamma_{b_i,d}, 2 \leq i \leq K$. Now, we want to calculate the average gain from MUD.

At first we consider SPCwMDPlus. Because of its contention-based access each node has the same probability ($p_{\text{mac}} = \frac{1}{N+K}$) to get access to the medium. So the expected instantaneous SNR of $S1$ towards d equals its average SNR ($\gamma_{S1,d} = \bar{\gamma}_{S1,d}$), i.e. their is no MUD gain.

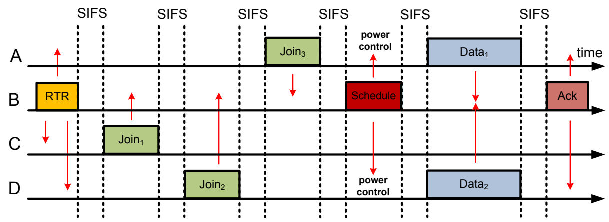

Figure 16. Illustration of a polling-based MAC supporting SPCwMD.

In contrast, $S2$ is the best node from its group, i.e. it has the highest SNR. We assume that for a large number of nodes the instantaneous SNR will be δ dB above the average SNR ($\gamma_{S2,d} = \bar{\gamma}_{S2,d} + \delta\text{dB}$). Now we can calculate the expected gain from MUD for SPCwMDPlus as follows $G = \lim_{N,K\to\infty} \frac{2\delta+\delta\cdot(N-1)+2\delta+\delta\cdot(K-1)}{N+K} = \lim_{N,K\to\infty} \frac{\delta\cdot(2+N+K)}{N+K} = \delta$.

Now, we consider a protocol that is able to select the best user from each group, i.e. $\gamma_{S1,d} = \bar{\gamma}_{S1,d} + \delta\text{dB}$ and $\gamma_{S2,d} = \bar{\gamma}_{S2,d} + \delta\text{dB}$. Here the expected gain from MUD is $G' = 2\delta$. We see that the latter approach offers a twofold increase in MUD gain[11].

This raises the question how such a protocol could look like. A possible solution is a polling-based approach (Fig. 16). Instead of letting the sender content to the medium the receiver offers its willingness to receive packets. Therefore it multicasts a ready-to-receive (RTR) packets to its neighbors. The selected candidates will reply with a Join packet. The rest of the operation is similar to SPCwMDPlus. Currently, we are working on such an approach.

VI. Conclusions

In this paper we propose a solution to the problem of network congestion around gateway nodes in wireless mesh networks. Our solution applies the use of uplink superposition coding for data transmissions towards gateway nodes. Additionally, in a fading environment MUD can be exploited to further improve the performance. We suggest two contention-based MAC protocols, which are suitable for ad-hoc networks without any centralized infrastructure. With the help of simulations we were able to show that our protocols outperform 802.11 based on the OAR rate selection algorithm by up to 88%. In a fading environment an additional gain of 5-13% from multi-user diversity was observed. Finally, the proposed protocols are fair.

References

[1] Overview of deployed wireless community networks.
[2] Aguayo, D., Bicket, J., Biswas, S., Judd, G., and Morris, R. Link-level measurements from an 802.11b mesh network. *SIGCOMM Comput. Commun. Rev. 34*, 4 (2004), 121–132.
[3] Alimi, R., Li, L., Ramjee, R., Viswanathan, H., and Yang, Y. R. ipack: in-network packet mixing for high throughput wireless mesh networks. In *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE* (2008), pp. 66–70.
[4] Barr, R., Haas, Z. J., and van Renesse, R. JiST: an efficient approach to simulation using virtual machines. *Software: Practice and Experience 35*, 6 (2005), 539–576.
[5] Bicket, J., Aguayo, D., Biswas, S., and Morris, R. Architecture and evaluation of an unplanned 802.11b mesh network. 31–42.
[6] Biswas, S., and Morris, R. Opportunistic routing in multi-hop wireless networks. *in Proc. 2nd Workshop on Hot Topics in Networks (HotNets-II), Cambridge, MA* (2003).
[7] Biswas, S., and Morris, R. Exor: Opportunistic muliti-hop routing for wireless networks. *SIGCOMM* (2005).
[8] Bortnikov, E., Cidon, I., and Keidar, I. Scalable realt-time gateway assignment in mobile mesh networks.
[9] Calvo, D. B. *Fairness analysis of wireless beamforming schedulers*. PhD thesis, Technical University of Catalonia, Spain, 2004.
[10] Cover, T. Broadcast channels. *IEEE Transactions on Information Theory 18* (1972).
[11] Das, S. M., Pucha, H., and Hu, Y. C. Mitigating the gateway bottleneck via transparent cooperative caching in wireless mesh networks. Tech. rep., Purdue University, 2006.
[12] Heiskala, J., and Terry, J. *A Theoretical and Practical Guide*. SAMS publishing, 2002.
[13] Johnson, D. B., and Maltz, D. A. Dynamic source routing in ad hoc wireless networks. In *Mobile Computing*, Imielinski and Korth, Eds., vol. 353. Kluwer Academic Publishers, 1996.
[14] Katti, S., Gollakota, S., and Katabi, D. Embracing wireless interference: analog network coding. 397–408.
[15] Knopp, R., and Humblet, P. A. Information capacity and power control in single-cell multiuser communications. *IEEE International Conference on Communications (ICC)* (1995), 331–335.
[16] Kramer, G., Gastpar, M., and Gupta, P. Cooperative strategies and capacity theorems for relay networks. *Information Theory, IEEE Transactions on 51*, 9 (2005), 3037–3063.
[17] Kurth, M., Hermann, U., Zubow, A., and Redlich, J.-P. Network coding for bit error recovery in ieee 802.11 mesh networks. *IEEE International Conference on Communications* (2009).
[18] Kurth, M., Zubow, A., and Redlich, J. P. Cooperative opportunistic routing using transmit diversity in wireless mesh networks. *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE* (2008), 1310–1318.
[19] Laneman, J., Tse, D., and Wornell, G. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory 50* (2004), 30623080.
[20] Laroia, R., Li, J., and M., S. Controlled superposition coding in multi-user communication systems. *U.S. Patent No. WO 2004/075470 A2* (2004).
[21] Larsson, P. Selection diversity forwarding in a multihop packet radio network with fading channel and capture. *MC2R 5* (2001), 47–54.
[22] Larsson, P., and Johansson, N. Multiuser diversity forwarding in multihop packet radio networks. *WCNC 2005* (2005).
[23] Li, L., Alimi, R., Ramhjee, R., Shi, J., Sun, Y., Viswanathan, H., and Yang, Y. R. Superposition coding for wireless mesh networks. *In Proc. ACM/IEEE MobiCom* (2007).
[24] Miu, A. K., Balakrishnan, H., and Koksal, C. E. Improving loss resilience with multi-radio diversity in wireless networks.
[25] Sadeghi, B., Kanodia, V., Sabharwal, A., and Knightly, E. Opportunistic media access for multirate ad hoc networks. *ACM MOBICOM* (2002).
[26] Tse, D., and Viswanath, P. *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.
[27] Valenti, M., and Correal, N. Exploiting macrodiversity in dense multihop networks and relay channels, 2003.
[28] Zhang, S., Liew, S. C., and Lam, P. P. Hot topic: physical-layer network coding. 358–365.

[11] We restricted ourself to the SPC case with 2 users. In general SPC is possible with n users. Here the MUD gain is n-fold.