Beamforming for Heterogeneously Equipped Nodes in Wireless Ad Hoc Networks

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Abstract—It has long been known that adaptive beamforming has the potential to enhance the performance of wireless ad hoc networks significantly. However, due to the decentralized nature of such infrastructure-less networks, it is not straightforward to fully realize the potential performance gains of beamforming in a realistic manner. To this end we devise a fully distributed cross-layer concept, comprising physical and MAC layer functionalities. Our proposed Channel Information Exchange (CIE)-MAC protocol enables to benefit from beamforming capabilities, such as interference management by means of nulling, thus increasing the spatial reuse. Moreover, it can handle heterogeneous scenarios with nodes which are equipped with different numbers of antennas, including the extreme case of single antenna nodes. The novel CIE-MAC protocol succeeds to avoid common drawbacks of existing protocols, like deafness and hidden terminal problems, and it is designed to operate in realistic fading environments. Simulation results, including a spatio-temporal correlated channel fading model as well as channel estimation errors, illustrate the CIE-MAC capabilities.

I. INTRODUCTION

During the last years, beamforming was adapted to the field of wireless ad hoc networks [1]. While this technique promises large gains in spatial reuse by multiple interference suppression and a strong coverage extension by transmit and receive beamforming gains, new challenges arise for the MAC protocol design in order to overcome certain shortcomings that beamforming especially in ad hoc networks occupies.

Three major problems related to directional control signaling are listed in [2], namely underutilization, deafness, and the hidden terminal problem. Underutilization is related to the coverage extension that is a strong advantage of directional transmission. While a node achieves a certain antenna gain \( G_0 \) in case it transmits or receives omnidirectionally, this gain can be increased to \( G_B \) \( (G_B \geq G_0) \), if the node directs the antenna array to its associated communication partners. The resulting overall directional communication gain of \( G_B \times G_B \) increases thereby the communication range compared to the overall omnidirectional gain of \( G_0 \times G_0 \), leading to a coverage extension. If however, e.g. during the control signaling, one node or both nodes do not direct their antenna array into the direction of the communication partner, the coverage extension is diminished, leading to the so-called underutilization.

Deafness describes the problem that a node that is beamformed towards a communication partner is not able to reply to a control signaling message send from another node placed in a different direction than the communication partner. This can result in misinterpretations on higher layers of the latter node, since on these layers the unsuccessful control signaling is counted as congestion or link failure. Moreover, the beamformed node will also not follow ongoing control signaling that announces the start of a new transmission. If it starts a new transmission on its own after its previous one was finished, it is highly probable to interfere the transmission which it did not hear the control signaling of.

This is the hidden terminal problem due to beamforming. The hidden terminal problem due to asymmetry in gain is caused by the differences in gain \( G_B \) and \( G_0 \) of beamformed data transmission and omnidirectional control signal transmission: Even if a node is out of omnidirectional communication range of two nodes communicating and can thus not overhear the control signaling, it might still cause interference during data transmission.

In [2] it is argued that the problem of asymmetry in gain might not appear very frequently, since the interfering node must be out of omnidirectional communication range to both, transmitter as well as receiver during the beforehand control signaling phase, and then the interference might not be that large, if the receiver changes its gain from \( G_0 \) to \( G_B \).

The authors describe the problems implicitly assuming that all nodes are equally equipped, i.e., all nodes have the same number of antennas. However, if the nodes have different numbers of antennas, also the beamforming gain \( G_B \) that is a function of the number of antennas, individually changes, and thus the communication range. This poses new challenges to the design decisions of a new MAC protocol, especially when different beamforming vectors are applied for transmission and reception as well as for control signaling and data transmission. Moreover, since different equipment on the receiver side results in different interference capabilities, a weaker receiver must be able to object to an announced transmission in order to protect its own ongoing one.

In a fading environment, an additional challenge has to be taken into account, namely the channel state information. The protocols presented in [2] and [3] assume that there is a certain pre-knowledge of Direction of Departure (DoD), Direction of Arrival (DoA), or channels, that can be gained.
by higher layers. Thus, these protocols are restricted to quasi-static channels.

In this paper, we especially address the challenges arising, if nodes with different numbers of antennas exist, including the extreme case of single antenna nodes. This does not only influence the physical layer capabilities, but also poses challenges to the MAC layer design. We develop our new protocol, called Channel Information Exchange (CIE)-MAC protocol for a time-varying environment, i.e., no a priori knowledge of DoDs, DoAs, or channels is required.

We base our new protocol design on two existing protocols, namely BeamMAC [3] and NULLHOC [4]. The former one solves the deafness problem and the underutilization, and, as a major advantage, it allows weak receivers to object to announced transmissions. However, it is only applicable in quasi-static channels. The NULLHOC protocol can be performed in fading, however it suffers from underutilization and, as a major drawback, it does not allow weaker receivers to protect their transmissions.

Taking the advantages of both protocols and avoiding their respective disadvantages, we develop a new MAC protocol that avoids the described hidden terminal problems, takes all specific challenges into consideration that arise for heterogeneously equipped nodes, and is applicable in fading.

The structure of the paper is as follows. In Sec. II and Sec. III, we shortly summarize the protocols that serve as a basis for our newly presented CIE-MAC protocol. The latter one is presented in Sec. IV. In Sec. V, simulation results are presented and Sec. VI draws the conclusions.

II. THE BEAMMAC PROTOCOL

Originally, the BeamMAC protocol was developed as an asynchronous protocol [3]. However, later on the authors adapted BeamMAC to a time slotted frame structure that they developed for another protocol [5]. Besides some contention resolution signals that are left out here for simplicity, the BeamMAC frame structure is depicted in Fig. 1.

![Fig. 1. General frame structure of the BeamMAC protocol.](image)

behind BeamMAC is that all transmissions, control signaling as well as data signaling, are directional. Data transmission takes thereby only place during the DATA phase, while during the announcement ANN, objection OBJ, and acknowledgement ACK phases, only control signaling is exchanged.

Notice that the data packet to be transmitted is split into up to N blocks. Each frame contains one block as data payload, resulting in N consecutive blocks for one data packet. A transmitter announces the transmission of a data packet only once for N consecutive blocks. Thus, in the next frame, a new transmitter can start a transmission. This allows for up to N parallel transmissions.

A node willing to transmit sends an announcement ANN in the respective slot. Since from higher layer information it already knows the direction to its associated receiver, it beamforms the ANN signal into the appropriate direction. Neighboring devices that are receivers in ongoing transmissions and overhear the message can estimate the amount of additional interference the newly announced transmission will cause to their own ongoing transmissions. In case the new transmission would corrupt their ongoing data receptions, they send an OBJ. Only if a transmitter that announced a transmission cannot sense any OBJ in the respective slot, it is allowed to transmit its data packet with the beamforming pattern already applied during ANN. Otherwise it has to abstain from transmitting. After a successful transmission, the receiver sends an acknowledgement.

Advantages and Drawbacks: The major advantage of the BeamMAC protocol lies in the ANN-OBJ principle. By allowing receivers to object to an announced transmission, difficult estimations of the amount of additional interference that a new transmission will cause performed by the transmitter of this new transmission are dispensable. Moreover, heterogeneously equipped nodes are able to control the interference to an amount which they individually can tolerate.

By the specific frame structure, the deafness problem is solved, since control and data messages are transmitted in a time division manner. This frame structure also solves the hidden node problem caused by beamforming, since all nodes can follow the control signaling exchange, even if they are in ongoing data transmissions.

Another advantage is the directional transmission of all kinds of signals, leading to the maximum coverage extension, thus avoiding any underutilization. This however is only possible since an a priori knowledge of the DoD to its associated receiver is known by a transmitter. This assumption is valid for quasi static channels; however, it makes the protocol unapplicable in fading environments.

III. THE NULLHOC PROTOCOL

In the following, we shortly summarize the NULLHOC protocol [4]. The NULLHOC protocol is asynchronous. Its basic idea is that all nodes that plan to start transmitting must spatially null all receivers involved in ongoing transmissions in their vicinity while nodes that plan to take part as a receiver in a new transmission must spatially null all transmitters of ongoing data transmissions. The former avoids that a new transmission destroys already existing ones, while the latter assures that the receiver of the new transmission can receive interference free.

The control signaling exchange comprises – similar to 802.11 – Request To Send (RTS) and Clear To Send (CTS) messages. However, in NULLHOC, a third control signal, namely Data Send (DS) is exchanged. A successful transmission is acknowledged by the receiver with the help of an ACK message. Data as well as acknowledgement messages are transmitted directionally. RTS, CTS, and DS are transmitted omnidirectionally. Before the control signal content is transmitted, there is a phase for channel estimation included into each of the these signals. Here, the nodes transmit with
all antennas, while for the actual control information exchange they only transmit with one antenna. By the channel estimation phase it is possible for all nodes that overhear the control messages to estimate the channel to the node transmitting the message. The control information mainly contains the transmission weights that will be applied during the upcoming transmission.

The computation of weight $w_k$ of node $k$ proceeds as follows:

1. Compute effective channel vector $h_{k,i}$ for each node $i$ of the $K$ nodes involved in ongoing transmissions that have to be nulled $h_{k,i}^T = w_i^T H_{i,k}$. Here $w_i$ is the weight that node $i$ uses during its transmission and $H_{i,k} = \text{the channel between this node } i \text{ and node } k$. This information was gained by overhearing preceding control signaling.

2. Calculate the effective channel $h_{k,d}^T$ to the desired partner $d$ that will use the weight $w_d$ during the planned transmission $h_{k,d}^T = w_d^T H_{d,k}$.

3. All effective channels (effective channel of own partner $d$ and effective channels of $K$ nodes to be nulled) are stacked to build an effective channel matrix $H_{\text{eff},k} = [h_{k,d}, h_{k,1}, ..., h_{k,i}, ..., h_{k,K}]$.

4. The desired weight $w_k$ is the minimum norm solution to the equation

\[ H_{\text{eff},k} w_k = c, \text{ with } c = [1 \ 0 \ ... \ 0]^T. \tag{1} \]

Transmit weights are subsequently normalized to unit norm.

The RTS contains the weight a transmitter will use for the reception of the ACK. The receiver includes the weight it will apply during data reception and ACK transmission into the CTS. Notice that the weight $w_d^T$ to calculate the effective channel to the associated partner (step 2) is not known yet by the receiver. Thus, for this weight it assumes a vector of ones, normalized to unit power. The transmitter successively adapts its transmit weight, informing its receiver and all surrounding nodes with the help of the DS signal. The weight included is thereby the weight applied by the transmitter for the data transmission.

**Advantages and Drawbacks:** The major advantage of the NULLHOC protocol is its applicability in fading, since all information required to calculate the beamforming weights can be gained by overhearing the control messages. By spatially nulling the nodes of ongoing transmissions, the spatial reuse can be significantly increased.

Since the control signals are transmitted omnidirectionally, no coverage extension can be achieved, leading to the so called underutilization. The authors also realize that data and control packet collisions can take place. Thus, the protocol might suffer from deafness as well as from the hidden terminal problem due to beamforming. The latter problem might degrade the performance significantly, since the authors assume no possibility for a receiver to object to a transmission announced by such a node (only transmit contention). Problems related to the asymmetry in gain will not occur, since the weight applied during data transmission is calculated such that it spatially nulls ongoing transmissions. In Tab. I the drawbacks are summarized for the BeamMAC as well as the NULLHOC protocol.

**IV. THE CIE-MAC PROTOCOL**

In the following, we describe our proposed Channel Information Exchange (CIE)-MAC protocol. This protocol applies advantageous strategies of both beforehand summarized protocols, thereby avoiding their disadvantages listed in Tab. I. The only disadvantage remaining for CIE-MAC is the underutilization, which is due to the design decision to transmit and receive control signaling omnidirectionally. The reason for this decision is to avoid the problem of directed neighbor discovery, which requires either a huge amount of control signaling overhead, or suffers from channel changes in fading (mobile) environments.

**A. Requirements and Assumptions**

Regarding the protocol design, there are certain requirements that have to be met. Besides the known challenges for beamforming in ad hoc networks, we identified the following requirements for CIE-MAC: applicability in fading, support of heterogeneously equipped nodes, and a receiver objection possibility. In order to meet the above mentioned requirements, we make the following assumptions: time slotted frame structure, frame level synchrony, and that the coherence time of the fading channel lasts at least $N$ consecutive blocks (explained later).

**B. Frame Structure**

The newly developed frame structure of the CIE-MAC protocol is depicted in Fig. 2. The control signaling part consists of minislots, an announcement message (ANN), an allowance message (ALL), a data send message (DS), and, after the data transmission, an acknowledgement message (ACK). The data signal contains the data payload (DATA).

Similar to BeamMAC, the data packet to be transmitted is split into up to $N$ blocks, allowing for up to $N$ parallel transmissions. The channel is assumed to stay nearly constant during the course of $N$ blocks. All control signaling is performed omnidirectionally, i.e., opposite to NULLHOC, also

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**TABLE I**

**DRAWBACKS OF THE BEAMMAC AND THE NULLHOC PROTOCOL.**

<table>
<thead>
<tr>
<th>Drawback</th>
<th>BeamMAC</th>
<th>NULLHOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>quasi-static channel assumption</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>only transmit contention</td>
<td></td>
<td></td>
</tr>
<tr>
<td>deafness</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>hidden terminal problem by beamforming</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>a priori knowledge of DoDs and DoAs required</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>underutilization</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Frame structure of the new frame synchronous CIE-MAC protocol.
the ACK message is transmitted omnidirectionally. Since the transmissions start one after the other and last for $N$ blocks each, the probability that two ACK collide is quite low.

C. Protocol Description

Similar to the NULLHOC protocol, the ANN, ALL, and DS messages are split into two phases each. The first phase is used for channel estimation purposes. Here, the nodes transmit with all antennas. The second phase of each control signal is used for the control information exchange and performed with one antenna. Here, the weights to calculate the effective channels are exchanged. The procedure is as follows

1) Each node willing to transmit randomly chooses one minislot. If a node overhears a signal in one of the preceding slots, it backs off (lost contention resolution).

2) A successful node starts transmitting an ANN on its own. It includes a weight into this message. Opposite to NULLHOC this weight is not meant to be applied during the reception of an ACK message, but to allow the associated receiver to better adapt its weight for the data transmission. The weight included into the ANN is calculated based on all effective channels of potential receivers that have to be nulled by the transmitter. Since the channel is assumed to be constant over the course of $N$ blocks, the information about the effective channels to the other receivers is still valid and not outdated. Because the transmitter has no knowledge about the channel to its own receiver, it assumes the effective channel to this receiver to be simply a vector of ones, normalized to unit power. The weight the transmitter includes into the ANN message is then the minimum norm solution as described in Eqn. 1.

3) All nodes overhearing the ANN message calculate the interference caused by the announced transmission. If the interference is larger than the amount they can tolerate and they are receivers in ongoing data transmissions, they transmit an ALL with an error ID included (receiver objection). If the addressed receiver decodes the ANN, it transmits an ALL with the transmitters ID and includes a weight into the message. This weight is calculated based on all effective channels to transmitters in the vicinity of the receiver that have to be nulled. Additionally, the receiver includes the effective channel to its transmitter ($w_d$) into the calculation. Notice that opposite to NULLHOC, the receiver already knows $w_d$ by the preceding ANN message. The weight is the minimum norm solution to Eqn. 1.

If other receivers than the addressed one transmit an ALL message, the ALL messages are highly probable to collide, and then the transmitter cannot decode the ALL. In this case, it backs off, and does not start a data transmission, since it was objected by a receiver. If only the addressed receiver transmits an ALL, the transmitter can decode the message, and goes on transmitting the DS message.

4) The transmitter adapts its weight based on the effective channel information to its receiver gained by the ALL message. It includes this adapted weight into the DS message. The DS is required to inform neighbors that a transmission will really be started and to update their information on the weight applied.

After the control signaling part, the data transmission starts with the predefined weights and lasts $N$ consecutive blocks. If all blocks are received error free, the receiver acknowledges the transmission by sending an ACK message.

D. Advantages

The CIE-MAC protocol is fully applicable in fading, since it does not assume any a priori knowledge of channels, DoDs or DoAs. By transmitting the control signals omnidirectionally, it overcomes the neighbor discovery problem for nodes outside the omnidirectional range. By the time slotted structure, also the hidden terminal problem due to beamforming and the deafness problem is solved. By allowing receivers to object to announced transmissions, also the heterogeneous capabilities on the receiver side are taken into account. The latter one is required, if due to missed control signaling messages or channel estimation errors the nulling does not perform satisfactorily.

V. Simulation Results

In the following, we present simulation results for the CIE-MAC protocol. All simulations are performed with an event-based simulator programmed in C++. We apply the spatially correlated Rayleigh fading channel model A from the 802.11n standard [6] with the correlation matrices generated as described in [7]. We assume the channel to stay constant over $T_{BLOCK}$. In order to achieve also a temporal correlation between the blocks, we apply a method described in [8].

We focus on the statistics for the ALL messages, especially on those ALL messages that are corrupted since multiple ALL are sent within the same frame. We distinguish two different cases of ALL corruptions: (1) a receiver intends to object a transmission that would cause too much interference to it and (2) ALL collisions without a receiver willingly objecting. While the former represents the receiver objection required, if heterogeneously equipped nodes exist, the latter represents an undesired, principle problem that is caused by the fading properties of the channel and appears for all kinds of MAC protocol designs. This is depicted in Fig. 3. In this specific scenario, TX 1 and TX 2 cannot communicate. Thus, both start ANN messages, and the ALL reply of the receivers collide at TX 2. For static channels, this is very improbable, since the distance between TX 1 and TX 2 must be quite large, and TX1 must still reach RX 1. Thus, the distance between RX 1 and TX 2 in general will be large. For fading channels however, there exists in general no static range where it is assured that nodes receive their mutual packages. I.e., even if two nodes are close, they might not overhear their mutual control messages.

We simulate a 500 m $\times$ 500 m scenario with 50 nodes randomly distributed. For investigating the ALL collisions, we assume two node constellations (NC)s. NC-1 assumes all
nodes equipped with 4 antennas, while NC-2 assumes 15 nodes with 1 antenna and 35 nodes with 4 antennas. We subdivide the ALL collisions into the ones with a receiver objecting (OBJ) and without (NOBJ). We compare the collisions for three different cases: (a) no channel estimation error exists, (b) a gaussian distributed channel estimation error with a power of 5 % of the channel power is added to the channel, and (c) an estimation error of 10 % of the channel power is added. The simulation results in % are depicted in Tab. II. While without channel estimation errors, the most part of colliding ALL for NC-1 with 66.1 % is due to fading influences as explained by Fig. 3, for NC-2 the majority of collisions with 60.2 % is already caused by receiver objections. For 5 % channel estimation error both NCs have most of the collisions due to receiver objections (65.6 % for NC-1 and 72.4 % for NC-2). For 10 % estimation error, this effect is with 68.7 % (NC-1) respective 75.9 % (NC-2) further increased. This clearly indicates how important a receiver objection is in fading, since even if a protocol assumes to transmit interference free, due to channel estimation errors this is not guaranteed. This problem gets even more severe, if heterogeneously equipped receivers exist that have varying interference tolerance levels, represented by the increased amount of collisions due to receiver objections for NC-2.

The associated throughput performance without channel estimation errors is plotted in Fig. 4. Besides NC-1 and NC-2 we simulate a constellation NC-3 where all nodes are equipped with a single antenna only. This serves as a worst case constellation. As a reference, we plot the results that would be achieved by 802.11 for an Additive White Gaussian Noise (AWGN) channel.

As expected, NC-1 performs best, achieving good gains compared to NC-2 that still performs satisfactorily. Even with all nodes equipped with a single antenna, some kind of spatial reuse compared to 802.11 is possible, since for CIE-MAC, nodes that can sense but not decode each other estimate the additional interference and are probable to transmit simultaneously, while for 802.11 nodes within mutual sensing range have to abstain from transmitting. Also, the interference is measured by CIE-MAC on the receiver side, while 802.11 is strictly transmitter oriented.

### VI. Conclusions

In this paper, we develop a new protocol called Channel Information Exchange (CIE)-MAC protocol. The protocol is designed based on two previously presented MAC protocol designs, namely BeamMAC [3] and NULLHOC [4]. By appropriately combining the advantages of both protocols without integrating their disadvantages, the CIE-MAC protocol can overcome common problems known for directional transmission in wireless ad hoc networks. The new protocol is applicable in fading and especially addresses the challenges, if heterogeneously equipped nodes (i.e., nodes with a varying number of antennas) exist. If receivers offer different number of antennas, they also face individual interference tolerance levels. This is taken into account by a specific receiver objection capability of the protocol. By simulation with a spatio-temporal correlated Rayleigh channel model it is shown that there exist indeed a requirement that receivers can object to announced transmissions. This is on the one hand motivated by specific fading influences explained in the paper, but also due to channel estimation errors and due to different interference tolerance levels of heterogeneously equipped nodes.

### REFERENCES


