Performance of a Cluster-Based MAC Protocol in Multiuser MIMO Wireless LANs

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***Abstract*—The IEEE 802.11n specifies MIMO techniques to enhance data rate in WLANs. However, using carrier sense multiple access with collision avoidance (CSMA/CA), it can support only point-to-point links. On the other hand, it is known that multiuser MIMO techniques significantly increase the spectral efficiency of a network. There are already some enhanced MIMO signal processing techniques available which enable concurrent multiuser transmissions by utilising multiuser interference cancellation techniques. Multiuser interference can also be cancelled in a distributed manner. To enhance IEEE 802.11n systems such that multiple users can transmit simultaneously, we propose a novel *cluster-based* CSMA/CA (CB-CSMA/CA) protocol. According to this protocol, nodes in a network are grouped in clusters such that the nodes which belong to the same cluster can transmit or receive simultaneously. In this paper, we explain the basics of the protocol and investigate throughput performance of the CB-CSMA/CA. We apply the CB-CSMA/CA to a multiuser zero-forcing relaying network, where several amplify-and-forward relays assist the communication between multiple source and destination pairs and perform distributed channel orthogonalisation. This cooperative network can be considered as a future application for next generation WLANs. As it is shown, the CB-CSMA/CA provides a significant throughput gain over point-to-point systems.**

***Index Terms*—Cooperative networks; Cluster-based CSMA/CA protocol; Multiuser zero-forcing relaying; Throughput; Amplify-and-forward relays.**

I. Introduction

In recent years, advanced signal processing techniques have improved the spectral efficiency significantly by realising the spatial multiplexing gain in a distributed manner. A distributed spatial multiplexing gain can be achieved by cancelling multiuser interference using multiple-antennas at the transmitter/receiver side or using the cooperative nodes. It is expected that upcoming WLANs will benefit from such multiuser MIMO transmissions. However, the existing IEEE 802.11n supports only MIMO point-to-point links. A new multiuser MIMO physical layer (PHY), which enables distributed spatial multiplexing gain, could be based on the IEEE 802.11n PHY. However, to support such multiuser MIMO transmission a new medium access control (MAC) is needed.

The fundamental channel access method of the IEEE 802.11n MAC is the distributed coordination function (DCF) which is based on carrier sense multiple access with collision avoidance (CSMA/CA) [1]. DCF has been originally designed for point-to-point links and prevents distributed spatial multiplexing by the collision avoidance mechanism. This problem has already been considered in different publications [2][3][4]. To solve it, we propose a cluster-based CSMA/CA (CB-CSMA/CA) scheme which facilitates concurrent multiuser transmissions. We explain the advantages compared to the other schemes in the next section.

In this paper, we present this new protocol and the required modifications of the IEEE 802.11 MAC. Furthermore, we investigate the throughput and delay by taking into account both PHY and MAC layers. The proposed MAC protocol can be applied to different types of networks. A typical application is an infrastructure network where all communications are carried over a multiple-antenna access point (AP). Another application is multiuser zero-forcing relaying (MUZFR) in ad hoc mode. In this paper we focus on the latter as an advanced and more challenging application. As it is explained in the following sections, the amplify-and-forward (AF) relays in a MUZFR network perform distributed channel orthogonalisation so that several source-destination (SD) pairs can communicate simultaneously.

II. Distributed Multiuser Scenarios

We focus on indoor scenarios and consider multiuser MIMO networks. We aim to utilise distributed spatial multiplexing. We distinguish between two different types of distributed multiuser networks: In the first type, there is a multiple antenna node which performs the multiuser interference mitigation. In the second type, each node may have only a single antenna and the interference mitigation is handled by cooperation among nodes.

Infrastructure network with a multiple-antenna AP: A typical example of the first type is an IEEE 802.11n infrastructure network with a multiple-antenna AP where all communications are carried over the AP. Assuming N_a antennas at the AP, N_a single-antenna stations (STAs) can communicate with the AP simultaneously. The AP can mitigate interference and decode multiple streams in the uplink (for example by performing successive interference cancellation), or separate them in the downlink (for example by utilising transmit beamforming).

Multiuser Zero-Forcing Relaying: As an example of the second type we consider a multiuser zero-forcing relaying network [5]. In this case, multiple SD pairs communicate concurrently over N_r AF relays. During the first time slot (uplink), multiple sources transmit to all relays concurrently

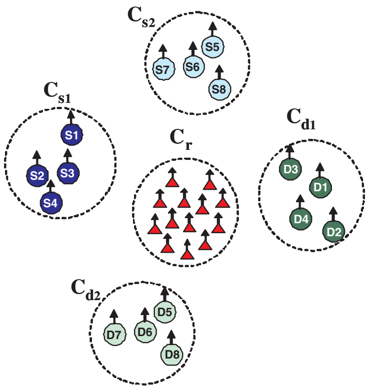


Fig. 1. A MUZFR network with 13 AF relays, 8 sources and 8 destinations. Each source- and destination-cluster consists of 4 STAs.

through the same physical channel. Each relay scales and rotates the received signal and forwards it in the second time slot (downlink) to the destinations. The AF relay amplification factors are determined in a way that interference from all interfering sources at destinations is cancelled and each destination receives only the packets from its communication peer. In this way, a distributed spatial multiplexing gain is achieved. In a MUZFR network, all relays have to be synchronous in time, frequency and phase and need to know the channel state information (CSI) of all other relays for both uplink and downlink.

Let N_{r} be the number of single-antenna AF relays. In [5] it is shown that by appropriate allocation of the gain factors at the AF relays, multiuser interference can be cancelled out. In order to let N SD pairs transmit concurrently we need at least:

$$N_{\mathrm{r}} = N(N-1)+1 \tag{1}$$

relays to perform interference cancellation [5]. In this way, multiuser interference can be cancelled out in a distributed manner without exchanging received information at the relays. If AF relays have multiple antennas, the number of required relays becomes smaller than that in (1) [6].

III. CB-CSMA/CA Protocol

To enhance the spectral efficiency in both considered types of networks, multiple STAs should be able to transmit simultaneously. However, this is not possible by using standard CSMA/CA protocols. In order to do so, we classify the nodes in a network into multiple clusters. The nodes belonging to the same cluster access the channel at the same time. Similarly, they may receive data simultaneously. Hence, from the MAC layer point of view, the clusters replace the individual nodes. Since multiple transmissions from a single cluster can be resolved, a collision happens only if more than one cluster transmits in the same time slot. Consequently, the spectral efficiency for the given system improves and at the same time the probability of collision in the network is substantially reduced.

We consider three types of clusters: source-, destination- and relay-clusters. In a system with totally N_{c} clusters, we denote the v^{th} cluster by C_v, where $v \in \{1, 2, \ldots, N_{\mathrm{c}}\}$. A cluster, which generates the data packets, is called the source-cluster and denoted by C_{s_v}. The size of the source-cluster is limited by the maximum number of concurrent streams which can be efficiently decoded. This leads to a cluster size of at most N_{a} STAs in the considered IEEE 802.11n infrastructure network or a cluster size of at most $N_{\mathrm{nc}} = \lfloor \frac{1+\sqrt{4N_r-3}}{2} \rfloor$ STAs in the considered MUZFR network, cf. (1). A cluster which is receiving data is a destination-cluster and denoted by C_{d_v}. A relay-cluster, denoted by C_{r_v}, is a cluster of relays which receives and forwards data to other clusters without having their own data.

The proposed CB-CSMA/CA protocol can be applied to different types of multiuser MIMO networks. In the following we focus on the MUZFR scenario. Figure 1 depicts a MUZFR scenario where the relay cluster consists of 13 AF single-antenna relays. In this case each source- and destination-cluster can at most have 4 STAs.

A. General Modifications of DCF

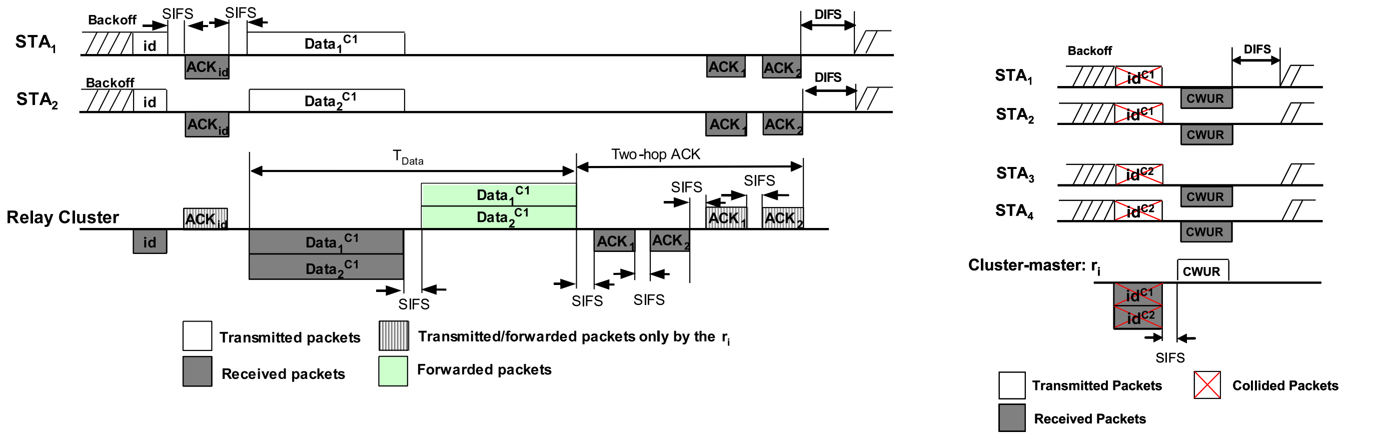
Assuming the CSMA/CA access method is used, to let multiple STAs transmit at the same time, in addition to form clusters we need to consider two major modifications to the current backoff procedure: (i) having the same initial backoff duration for all cluster members and (ii) updating this value at the same time. The first requirement can be achieved for example by having the same random generator seed for all STAs that belong to one cluster, so that the same pseudo random numbers are generated. Considering the second requirement, the STAs within a cluster should be *event-synchronous* such that they can have the same backoff value. This is necessary since according to the IEEE 802.11, the backoff window (CW) size doubles after any unsuccessful transmission up to a maximum value. Thus, after a transmission, STAs in a cluster should all know whether they need to increase the backoff interval or not.

For two-hop relay links our CB-CSMA/CA adopts an approach which is similar to [7]: relay clusters forward the received data packets after a short interframe space (SIFS), without participating in another contention procedure prior to the second-hop transmission. In this way, delay is reduced and the uplink and downlink utilisation is balanced.

B. Ad Hoc Specific Modifications

We consider the distributed spatial multiplexing gain in an ad hoc network where there is not any AP to assist the communications between each source and its destination. As it is explained in this section, in addition to the above general modifications, for the CB-CSMA/CA the following modifications of the standard ad hoc transmissions are required:

- Each cluster has a cluster-master.
- Each source-cluster sends an *identification message* prior to data transmission.
- Upon reception of the identification message, if a collision has occurred a contention window update request



(a) successful transmission

(b) collision of STA_1 and STA_2 in C_1 with STA_3 and STA_4 in C_2

Fig. 2. CB-CSMA/CA access mechanism in the MUZFR scenario.

(CWUR) packet is broadcasted to all clusters so that the involved clusters are notified and update their backoff value prior to the next transmission attempt.

Here we explain all these changes for the considered MUZFR scenario. In the MUZFR network there is not any AP to assist the communications. Instead, there are some idle nodes which can act as AF relays as explained in Sec. II. Since in the ad hoc mode, there is not any central node, decisions about updating the contention window should also be handled in a distributed manner. However, a totally distributed exchange of packets implies lots of overhead. Therefore, in ad hoc scenarios, we assume that each cluster has a cluster-master.

It is assumed that one of the relays, say r_i, knows the number of available AF relays and it pre-defines the clusters. It allocates all relays to a single relay cluster C_r and acts as the cluster-master of C_r.

We assume that the AF relays are simple nodes that are equipped with a single antenna and that they do not generate their own data packets. Consequently, they do not need to participate in the contention procedure. The AF relays only scale and forward the data packets to other STAs, without decoding them. However, as it is explained in the following, we assume that they are able to decode the identification message and they are all synchronised to the timing synchronization function [8].

C. Transmission Procedure

According to the CB-CSMA/CA, the source-cluster which has won the contention, acquires the channel. First, the source-cluster sends an identification message. The identification message is a common packet transmitted by all members of the source-cluster such that all STAs in the basic service set can decode this packet. It includes information about the rate and length of the actual transmission as well as MAC addresses of the source- and destination-cluster. Consequently, the relays know which gain factors to apply, see Section IV-C.

The identification message is a short packet transmitted at the lowest data rate. Therefore, it is assumed that it is error-free. However, as different clusters send different identification messages, the identification messages collide if more than one cluster transmits in a time slot. Accordingly, upon reception of an identification message the cluster-master of the relay-cluster (r_i) can post-detect the collision as explained in the following.

Assuming an error-free identification message, if r_i cannot decode the identification message it assumes that a collision has occurred. However, as the identification message is collided, r_i cannot obtain the information about involved clusters. Hence, it broadcasts a short packet, called CWUR packet, to all clusters. Upon reception of CWUR all source-clusters enter the next backoff process but only the source-clusters which have been involved in the pending transmission increase their CW unless it has already reached the maximum value. In the latter case they keep the maximum CW for the upcoming transmission.

If the cluster-master r_i can decode the identification message it acknowledges the reception by multicasting an acknowledgement packet ($\mathrm{ACK_{id}}$) to all members of the source-cluster. Then the source-cluster sends the data packet to all AF relays. The relays scale the received packets with the respective gain factors and forward them to the destination cluster. The destinations which successfully decode the packets, transmit the acknowledgement (ACK) packets one after the other, for example, in a pre-determined order.

In the case of channel errors (which are transmission errors caused by the channel), the sources which do not receive the ACK retransmit their data packet in the next transmission attempt. Since AF relays do not decode the data and hence cannot detect channel errors, the channel error can first be detected after the second-hop transmission.

Figure 2 shows the CB-CSMA/CA channel access mechanism in the MUZFR network for the successful and the collided transmissions, respectively. It is assumed that STA_1

TABLE I
ANALYSIS PARAMETERS

Parameters	Values	Definition
SIFS	16 μs	SIFS time
DIFS	34 μs	DIFS time
δ	1 μs	Propagation delay
$CW_{\min}$	15	Minimum CW
$CW_{\max}$	1023	Maximum CW
σ	9 μs	Slot time
T_{s}	4 μs	OFDM symbol duration
L	1024 Byte	Payload size
N_{tot}	64	Number of subcarriers per OFDM symbol
N_{sub}	52	Number of data subcarriers per OFDM symbol
BW	20 MHz	Total Bandwidth
Data rate	19.5 Mb/s	Data rate
Basic rate	6.5 Mb/s	Data rate of ACK, RTS, CTS, ACK_{id} and CWUR packets
Data $\mathrm{MAC_H}$+ FCS	40 Byte	Data MAC Header and frame check sequence (FCS) field length
ACK $\mathrm{MAC_H}$+FCS	14 Byte	ACK and CTS MAC Header and FCS field length
RTS $\mathrm{MAC_H}$+FCS	20 Byte	RTS MAC Header and FCS field length
$T_{\mathrm{PLCP_P}} + T_{\mathrm{PLCP_{SIG}}}$	20 μs	PLCP Preamble and SIGNAL duration

and STA_2 belong to cluster C_{s1} while STA_3 and STA_4 are members of cluster C_{s2}. The DCF interframe space and the identification message are denoted by DIFS and id, respectively. Both DIFS and SIFS values are defined by the IEEE 802.11n [1].

As it is shown in Figure 2, the ACK packets are transmitted by the destinations and forwarded by r_i sequentially with a SIFS period in between. In this way, the ACK duration depends on the number of concurrent streams per cluster. To avoid collisions at the beginning of the next transmission attempt, the length field in the identification message should be extended such that it includes the data and all ACK packets durations. We assume that the maximum cluster size and therefore the ACK duration and ACK timeout are fixed.

D. Advantages of CB-CSMA/CA

The CB-CSMA/CA scheme has some distinct advantages compared to existing proposals: it requires neither sequential contention per node for the data transmission as it is needed in [9] and [4], nor a control channel as in [3] or [10]. In contrast to [2] where there is a multipacket transmission only if accidentally more than one STA transmits in a time slot, the CB-CSMA/CA is designed such that each transmission attempt contains as many data packets as the number of active members at the source-cluster. Besides, by grouping nodes into clusters the collision probability of the CB-CSMA/CA depends on the number of contending clusters rather than total number of contending stations. As it is shown in Section IV, the CB-CSMA/CA collision probability is considerably reduced compared to the standard IEEE 802.11 MAC. Furthermore, as it has been explained, the CB-CSMA/CA is able to post-detect collisions with high probability. Furthermore, the CB-CSMA/CA can be applied to networks with different signal processing methods.

IV. PERFORMANCE ANALYSIS

In this paper we focus on the MUZFR scenario, where all stations and relays are equipped with single antenna. We analyse the PHY and MAC layer performance by simulating the outage probability, and calculating the MAC throughput and head-of-line (HoL) delay, respectively.

A. Analysis Parameters

We assume that all nodes are in a basic service set and can hear each other. Furthermore, it is assumed that there are totally N_{sd} SD pairs and 13 AF relays. Hence at each transmission attempt four sources can transmit simultaneously, cf. (1). Accordingly, the SD pairs are grouped into clusters of size four, $N_{\mathrm{nc}} = 4$. For the PHY layer simulations we consider an OFDM system with a total bandwidth of 20 MHz where each node uses all subcarriers [1]. The ETSI non-line-of-sight indoor channel model A with root-mean-square delay spread of 50 ns is used [11]. For clarity of exposition, we neglect the path loss and assume that all STAs have the same distance from the AP/relays and on average they have the same channel conditions. Furthermore, it is assumed that the signals transmitted from different antennas are uncorrelated. All parameters which are used for the performance analysis are given in Table I.

B. Reference System

We consider an equivalent ad hoc scenario operating based on the IEEE 802.11 standard as the reference system. In this setup SD pairs communicate directly with each other one after the other according to the DCF basic access mechanism. Additionally we consider transmissions based on the request-to-send (RTS) and clear-to-send (CTS) access method, where each STA sends an RTS packet prior to the data transmission. In this case, the destination which is ready to receive the packet replies with a CTS packet. We assume that single hop links in both the MUZFR network and the reference system have the same distance.

C. Physical Layer Performance

By definition an outage occurs if the instantaneous rate R drops below the target outage rate R_{out}. Thus, the outage probability of a link is defined as [12]:

$$P_{\text{out}} = \Pr(R < R_{\text{out}}). \tag{2}$$

In order to calculate the data rate in a MUZFR network we go through the following steps. Let $\mathbf{h}_{\text{SR}}^i$ be the vector of channel coefficients from the ith source to all relays, and $\mathbf{h}_{\text{RD}}^j$ the vector of channel coefficients from all relays to the jth destination at a certain subcarrier. The equivalent channel matrix $\mathbf{H}_{\text{SD}}$ for this subcarrier is the concatenation of the source-relay channel matrix $\mathbf{H}_{\text{SR}} \in \mathbb{C}^{N_{\text{r}} \times N_{\text{nc}}}$, the relay gain factors, and the relay-destination channel matrix $H_{\text{RD}} \in \mathbb{C}^{N_{\text{nc}} \times N_{\text{r}}}$. The elements of the equivalent channel matrix at this subcarrier can be written as [5]:

$$\mathbf{H}_{\text{SD}}[i, j] = \mathbf{g}^T \cdot (\mathbf{h}_{\text{RD}}^j \odot \mathbf{h}_{\text{SR}}^i), \tag{3}$$

$\forall i, j \in \{1, ..., N_{\text{nc}}\}$ and i $\neq$ j. $\mathbf{g} \in \mathbb{C}^{N_{\text{r}}}$, is the relay gain vector. The operators $(\cdot)^T$ and $\odot$ indicate matrix transpose and Hadamard (element-wise) product, respectively. If the relay gain vector $\mathbf{g}$ is chosen in a way that $\mathbf{g}^T \cdot \mathbf{H}_{\text{SD}} = 0$, the interference between different source-destination links is nulled. Any vector $\mathbf{g}$ that lies in the nullspace of $\mathbf{H}_I$ fulfils the above equality. The relay gain factors depend on the source and destination channels. The CSI can be estimated locally at each relay or destination and disseminated to all relays in an initialisation phase. The relay gain factors have to be updated occasionally depending on how fast the channels are changing.

Assuming Gaussian codebooks, the instantaneous rate of the ith SD link at the lth subcarrier is obtained from:

$$R_i^l = \log_2(1 + \text{SNR}_i), \tag{4}$$

where the instantaneous SNR at the subcarrier lth and for the ith SD link is given by:

$$\text{SNR}_i = \frac{P \left| \mathbf{H}_{\text{SD}}[i, i] \right|^2}{\sigma_n^2 (1 + (\mathbf{g} \odot \mathbf{h}_{\text{RD}}^i)^H (\mathbf{g} \odot \mathbf{h}_{\text{RD}}^i))}, \tag{5}$$

where P and σ_n^2 are the transmit power and the noise variance per subcarrier, respectively. Finally the instantaneous two-hop data rate of the ith SD link over the whole bandwidth can be obtained from:

$$R_i^{\text{2hops}} = \frac{0.8}{2} \cdot \frac{1}{64} \sum_{l=1}^{52} R_i^l \ \ [\text{b/s/Hz}], \tag{6}$$

where, the factor $\frac{1}{2}$ is introduced since for transmitting a packet from a source to a destination two time slots of equal lengths are used and the factor 0.8 is accounted for the spectral efficiency loss introduced by the guard interval [1].

Equation (6) provides an upper bound for the PHY data rate. Although for practical modulations the achievable rate is below this capacity value, in this work this upper bound is used for comparison-based results. In this way our analysis is valid for any sophisticated coding which may be applied in future systems.

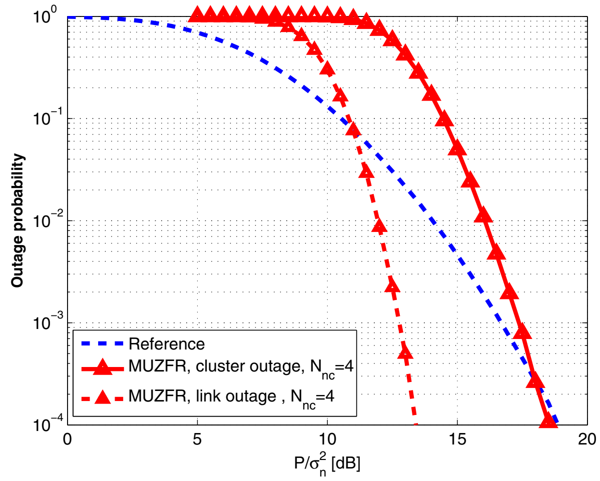


Fig. 3. Outage probability vs. P/σ_n^2 for MUZFR and the reference system. In the MUZFR network each source- and destination-cluster has 4 STAs.

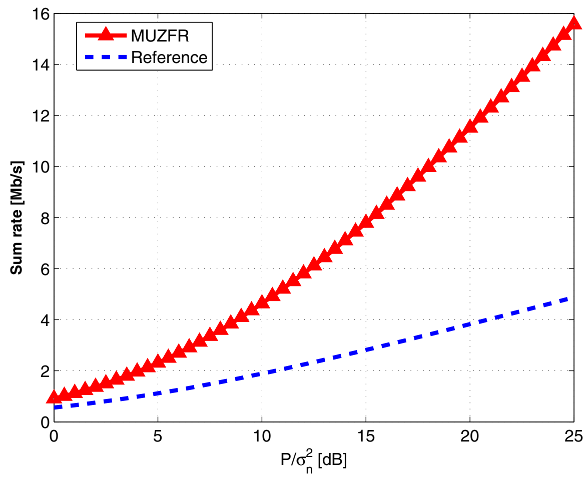


Fig. 4. Sum rate for MUZFR and the reference system.

We assume that a cluster is in outage whenever any of the concurrent transmissions is in outage[1].The outage probability results for both MUZFR and the reference with $R_{\text{out}} = 26$ Mb/s are plotted in Figure 3. For the MUZFR both the cluster outage probability and the individual outage probability (here called link outage probability) are depicted. As it can be seen, in the high SNR regime where multiuser interference can be cancelled out with high probability, the MUZFR outperforms the reference system. In the reference scenario at each transmission attempt there is a single-input single-output (SISO) link. As the outage probability curves do not show the spatial multiplexing gain, we also plot the sum rate. As it is depicted in Figure 4 the MUZFR achieves much higher PHY sum rate than the reference system. This is

[1]This definition results in an upper bound of the probability of outage, since in an outage event some links may be in outage while the others not and hence some packets can still be successfully transmitted.

due to the fact that the MUZFR enables a distributed spatial multiplexing while the reference system supports at most one STA at each time instant.

D. MAC Layer Performance

We consider a symmetric case, in which the number of sources and destinations is the same. We assume a bidirectional communication between each source and its respective destination. Hence, a source- and its destination-cluster interchange their functions at different time slots. Therefore, there are totally $2N_{\text{sd}}$ active STAs or equivalently in the CB-CSMA/CA case $N_{\text{c}} = 2\lceil N_{sd}/N_{\text{nc}}\rceil$ clusters.

1) Throughput: The following throughput analysis is based on the Markov chain model introduced in [13] and the extensions in [14] to incorporate packet errors. It is assumed that all STAs are in saturation, i.e., they allways have a non-empty buffer, and there is no bound on the maximum number of retransmissions. However, assuming perfect event-synchronisation, the main difference to [13] is that in the CB-CSMA/CA applications, clusters replace individual STAs. Consequently, the total number of the contending units should be set to the total number of the clusters. Assuming constant number of contending STAs (here clusters) then similar to [13], the probability that a cluster transmits in a randomly chosen time slot, is given by

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}, \tag{7}$$

where W and m can be calculated from the minimum and maximum contention window sizes, denoted by $CW_{\min}$ and $CW_{\max}$ respectively, as follows: $W = CW_{\min} + 1$ and $CW_{\max} = 2^m W - 1$. Both $CW_{\min}$ and $CW_{\max}$ are defined by the standard [1] and

$$p = \begin{cases} 1-(1-P_{\text{col}})(1-P_{\text{e}}) & , \text{ in the reference system} \\ P_{\text{col}} & , \text{ in the MUZFR network} \end{cases}$$

where P_{col} is the conditional collision probability which is the probability of collision for a packet being transmitted on the channel and P_e is the packet error probability. Since collisions can be post-detected in the MUZFR network, the CW size is only updated after collisions and hence $p = P_{\text{col}}$. As calculated in [13], in a network with n contending nodes (here clusters), each transmitted packet collides if at least one of the other nodes (here clusters) transmits in the same time slot:

$$P_{\text{col}} = 1 - (1-\tau)^{n-1}. \tag{8}$$

Note that n is equal to number of source- and destination-clusters, i.e., N_{c} in the MUZFR scenario while it is equal to the number of contending STAs, $2N_{\text{sd}}$, in the reference setup. By solving the equations (7)-(8) transmission and collision probabilities are obtained.

Figure 5 shows the conditional collision probability for the CB-CSMA/CA with different cluster sizes and that of the standard DCF. In both systems P_e is set to zero. As it is seen the CB-CSMA/CA reduces the collision probability significantly. For a certain number of active STAs, larger

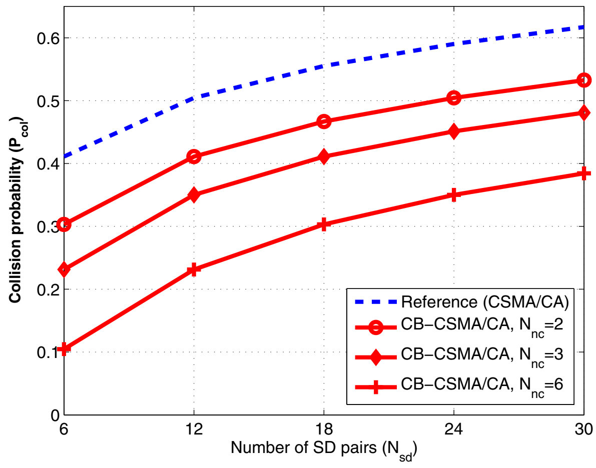


Fig. 5. Conditional probability of collision vs. number of SD pairs.

source-cluster size results in a lower collision probability. However, in the MUZFR scenario larger source-cluster size implies increasing the number of relays further, which might not be feasible in a small wireless network.

Throughput is defined by the average payload bits which are transmitted successfully in a time slot divided by the duration of the time slot. After calculating τ we can easily calculate the throughput. For the reference system we can follow all steps as explained in [13] and the extensions to include P_e in [14]. However for the MUZFR we need to calculate the average time the channel is sensed busy due to successful transmission (T_s), collision (T_c), and packet error (T_e) as in the following, cf. Figure 2:

$$\begin{aligned} T_s &= T_{\text{id}} + \delta + SIFS + ACK_{\text{id}} + \delta + SIFS + 2T_{\text{Data}} \\ &\quad + 2\delta + \text{SIFS} + N_{nc} \cdot (2\text{SIFS} + 2T_{\text{ACK}} + 2\delta) + \text{DIFS}, \\ T_c &= T_{\text{id}} + \delta + SIFS + T_{\text{CWUR}} + \text{DIFS}, \\ T_e &= T_{\text{id}} + \delta + SIFS + ACK_{\text{id}} + \delta + SIFS + 2T_{\text{Data}} \\ &\quad + 2\delta + \text{SIFS} + T_{\text{ACK}_{\text{timeout}}} + \text{DIFS}, \end{aligned}$$

where $T_{\text{ACK}_{\text{timeout}}} = N_{\text{nc}} \cdot (2\text{SIFS} + 2T_{\text{ACK}} + 2\delta)$, T_{Data} and T_{ACK} are the duration of the data and the ACK. T_{CWUR} is the duration of the CWUR packet which is supposed to be equal to T_{ACK}. The ACK, CWUR, RTS, and CTS packets are transmitted at the lowest PHY rate.

In both the reference and the MUZFR scenarios the durations of the data and the ACK packets can be obtained as follows:

$$\begin{aligned} T_{\text{Data}} &= T_{\text{PLCP}_{\text{P}}} + T_{\text{PLCP}_{\text{SIG}}} \\ &\quad + \left\lceil \frac{40 + (16+6)/8 + L}{BpS(m)} \right\rceil \cdot T_{\text{s}} \end{aligned} \tag{9}$$

$$\begin{aligned} T_{ACK} &= T_{\text{PLCP}_{\text{P}}} + T_{\text{PLCP}_{\text{SIG}}} \\ &\quad + \left\lceil \frac{14 + (16+6)/8}{BpS(m')} \right\rceil \cdot T_{\text{s}}, \end{aligned} \tag{10}$$

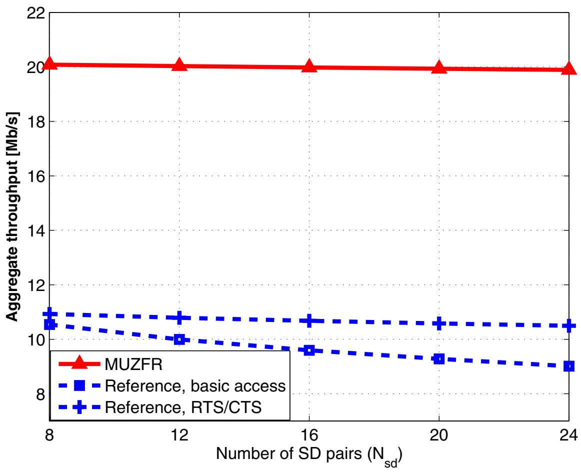


Fig. 6. Aggregate throughput vs. number of SD pairs.

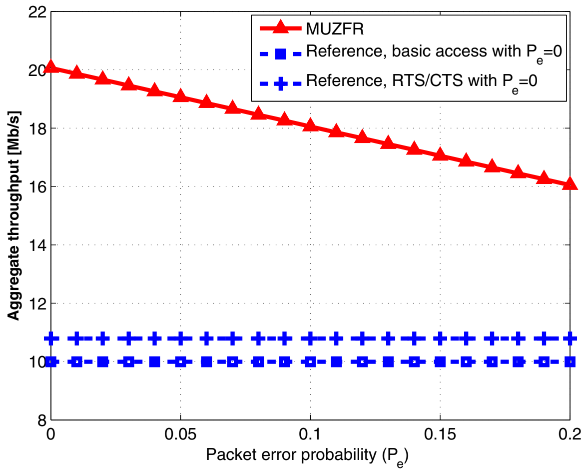


Fig. 7. Aggregate throughput for $N_{\text{sd}} = 12$ vs. packet error probability of MUZFR.

where T_{PLCP_P} and $T_{\text{PLCP}_\text{SIG}}$ are the PHY layer convergence protocol preamble and SIGNAL duration, respectively. T_s is the duration of one OFDM symbol and $BpS(m)$ is the number of bytes per OFDM symbol for a given modulation. It is assumed that the identification message has a format similar to that of the RTS packet but instead of the MAC addresses of the STAs, it includes the MAC addresses of the source- and the destination-cluster. It also includes a preamble as defined by the legacy preamble[2]. The ACK_id has the same duration as that of the ACK. In MUZFR setup at each transmission attempt there are totally $\tilde{L} = N_{\text{nc}}L$ data bytes transmitted while in the reference system there are only $\tilde{L} = L$ bytes.

Using the parameters in Table I, the throughput of both scenarios for $P_e = 0$ are plotted in Figure 6. We choose the same link data rate for both scenarios. This is a reasonable choice since in high SNR regime both scenarios have similar outage performance. As it can be seen in Figure 6 the CB-CSMA/CA scenario significantly outperforms the reference scenario.

To compare the performance of both systems in the medium SNR regime, we choose P_e of the reference system to be zero again but this time allow different P_e values for the MUZFR case. The results for $N_{\text{sd}} = 12$ are shown in Figure 7. Throughput of the reference system does not change with the P_e values on the x-axis since P_e of the reference system is set to zero. We observe that even when the MUZFR experiences a packet error probability of 0.2 its throughput is about 49% above that of the reference system with RTS/CTS access mechanism and no packet error.

2) Delay: In this paper we consider the packet delay introduced by the MAC protocol, i.e., HoL delay. The HoL is defined by the time interval between a moment a packet reaches the head of the queue until it is successfully received by its destination. As investigated in [15] for a network with

[2]The legacy preamble includes short and long training sequences and a signal field [1] and is 20 μs long.

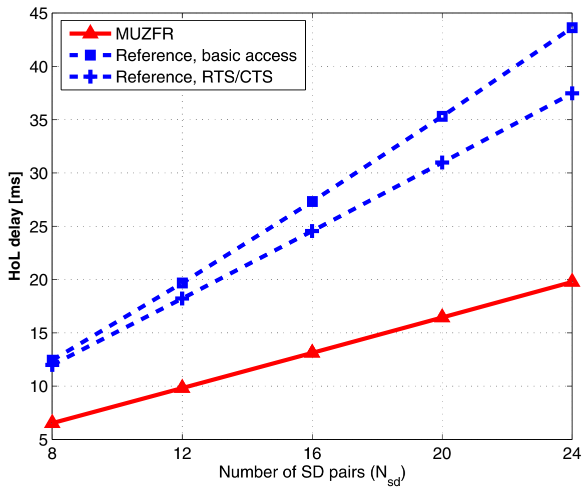


Fig. 8. HoL Delay vs. number of SD pairs.

n contending nodes, the packet delay D can be calculated via Little's Result as:

$$D = \frac{n}{S/\tilde{L}}, \tag{11}$$

where S is the aggregate throughput. Since in the MUZFR setup relays do not compete for the channel and forward the packets after a SIFS we can directly apply (11) to this scenario too. The HoL delay values for $P_e = 0$ are depicted in Figure 8. The CB-CSMA/CA application enjoys around 45-47% smaller delay values compared to the reference system based on the RTS/CTS access mechanism.

V. Summary

In this paper we proposed a novel cluster-based CSMA/CA scheme which enables multiuser streams and reduces the collision probability in a network.

The CB-CSMA/CA showed a promising throughput and delay improvement compared to a reference system based on the IEEE 802.11. The proposed protocol can support applications with high data rate requirements as well as the ones with low delay constraints in a variety of networks. It is a promising approach for a variety of network configurations with single-hop and two-hop communication links over decode-and-forward or amplify-and-forward relays.

In this paper we focused on the DCF which is a prevalent access method in indoor WLAN scenarios. However, the cluster-based MAC scheme can be supported easily in the centralised mode. To do so, in the infrastructure mode, the hybrid coordinator instead of polling a certain node at each time instant, should poll one cluster after the other and the polling frame should be a multicast packet destined to all nodes belonging to a source-cluster.

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