A Cross-Layer Cooperative Schema for Collision Resolution in Data Networks

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Abstract: Cooperative cross-layer techniques are proposed in the collision resolution areas of data networks. A multichannel extension of cooperative medium access protocol - a cross-layer cooperative protocol for collision resolution in data networks is presented. At the physical layer, the proposed approach is based on orthogonal frequency division multiplexing. At the medium access control layer, various schemes of orthogonal frequency division multiplexing subchannel allocation for wireless traffic with diverse quality of service requirements are proposed and studied. The total bandwidth is divided into non-interfering subchannels and each packet occupies one subchannel for its transmission. First, two schemes are proposed for rate-limited traffic. Users transmit packets on all subchannels. Collisions on a subchannel are resolved via cooperative transmissions, involving either the subchannel on which they occurred only, or all subchannels in a shared fashion. Second, for the case of bursty traffic, a random subchannel selection scheme is proposed to adaptively control the number of transmitted packets for each active user. Third, to accommodate heterogeneous traffic with diverse quality of service requirements, a fixed subchannel selection scheme is presented, where packets with the same traffic type are allocated to the same cluster of subchannels. The simulation work is performed in MATLAB software.

Keywords: Collision Resolution; cross-layer approach; orthogonal frequency division multiplexing

1. Introduction

Wireless communication is not only one of the most vibrant research areas in the communication field, but it is also one of the biggest engineering successes of the last twenty years. Cooperation and cross-layer design are two emerging techniques for improving the performance of wireless networks.

1.1 Cooperation in data networks

It is well known that multiple-input multiple-output (MIMO) systems can significantly improve the performance of data networks, e.g., increase data rate, reduce interference, and improve link reliability. However, due to the cost, size or hardware limitations, multiple antennas are not available at network nodes in many scenarios. For such scenarios, user cooperation can create a virtual MIMO system and thus enable a single-antenna user to enjoy the benefits of MIMO systems.

Transmissions via cooperation can be typically modeled as a traditional relay channel. Figure 1 illustrates a simple relay channel model, in which there are one source, one destination and one relay in the network. The source first transmits its message to the destination; the relay overhears the message due to the broadcast nature of the wireless channel. Then, the relay forwards the message to the destination in either a "decode-and-forward" (DF) or, an "amplify-and-forward" (AF) fashion.

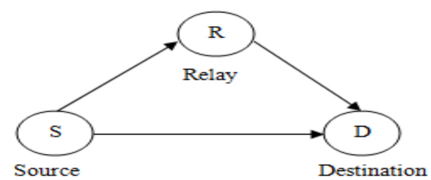


Figure 1: Cooperative Relaying

1.2 Cross-Layer design in data networks

Traditionally, protocol design in wired and wireless networks was primarily based on layered approaches that facilitated standardization and implementation. For example, the physical (PHY) layer is responsible for the reliable and efficient delivery of information bits, while the medium access control (MAC) layer is responsible for resource management among multiple users in the network. In layered protocols, each isolated layer in the protocol stack is designed and operated independently, with predefined interfaces between layers that are static and independent of network constraints and applications.

2. Literature Review

2.1 General Survey

Future wireless networks are complex extensions of cellular networks. They will need to accommodate multimedia services such as video, teleconferencing, internet access, and voice communications. Multimedia sources have diverse bandwidth requirements and are bursty in nature, thus fixed bandwidth allocation schemes are inefficient for them. Simple medium access schemes for bursty sources include random access methods. An example of such system is the slotted ALOHA [5], which allow users to transmit in an uncoordinated fashion every time they have a packet to transmit.

Collision resolution (CR) has been investigated from both the MAC and physical layer perspectives. According to [7], in a K-fold collision, the packets involved in the collision are not discarded but rather stored in memory and later combined with retransmissions initiated during the slots following the collision slot. Moreover, to avoid extra control overhead, the NDMA scheme requires that all collided users retransmit in each of the time slots following the collision, which may drain the battery power of users involved in high order collisions.

Recently a new cooperative media access control (MAC) protocol of random access wireless network was proposed in [5]. Due to that scheme, when there is a collision, the destination node (base station) does not discard the collided packets but rather saves them in a buffer. In the slots following the collision, a set of nodes designated as relays, form an alliance and forward the signal that they received during the collision slot. Based on these transmissions, the base station formulates a multiple-input multiple-output (MIMO) problem, the solution of which yields the collided packets. The method of [5], referred to here as ALLIANCES, maintains the benefits of ALOHA systems in the sense that all nodes share access to media resources efficiently and with minimal scheduling overhead, and enables efficient use of network power.

2.2 *Cooperative Medium Access Protocol*

The cooperative medium access protocol scheme described in the context of cellular networks or wireless LAN, where a set of nodes, denoted by, $\mathcal{R} = \{1, 2\ldots J\}$ communicates with the Access Point (AP). Thus all the transmission initiated by a source node $i \in \mathcal{R}$ are directed to a single destination $d \notin \mathcal{R}$ which is the base station or the access point.

Consider a small-scale slotted multi-access system with J users, where each node can hear from a base station or access point (BS/AP) on a control channel. Link delay and online processing (packet decoding) time are ignored and all transmitters are assumed synchronized. Each user operates in a half-duplex mode. Every user and the BS/AP are equipped with only one antenna. All transmitted packets have the same length and each packet requires one time unit/slot for transmission.

The system model is as shown in figure 2.

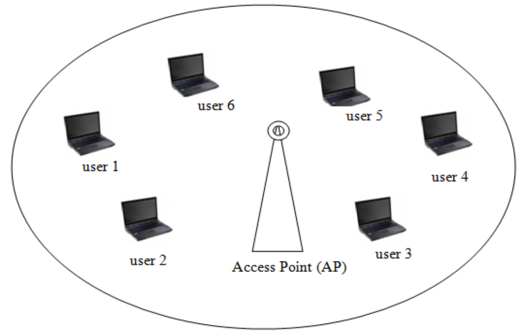


Figure 2: System Model

Let us consider a network with J nodes. Suppose that K packets have collided in the n-th slot. All nodes not involved in the collision enter a waiting mode and remain there until the collision is resolved. The collision resolution period is defined as a cooperative transmission epoch (CTE), beginning with the n-th slot. The AP will send a control bit to all nodes indicating the beginning of CTE and will continue sending this bit until the CTE is over.

Let the packet transmitted by the i-th node in slot n consist of N symbols, i.e.

$$x_i(n) \triangleq [x_{i,0}(n), \ldots\ldots, x_{i,N-1}(n)] \quad (1)$$

Let $S(n) = \{i_1, \ldots\ldots, i_k\}$ be the set of sources and $\mathcal{R}(n) = \{r_1, \ldots\ldots, r_{\hat{k}-1}\}$ be the set of nodes that will serve as relays, and 'd' denotes the destination node. During the n-th slot, the signal heard by the AP and also the source node is:

$$y_r(n) = \sum_{i \in S(n)} a_{ir}(n) x_i(n) + w_r(n) \quad (2)$$

where, $r \in d \cup \mathcal{R}(n), r \notin S(n), a_{ir}(n)$ denotes the channel coefficient between the i-th node and the receiving node r; and $w_r(n)$ represents the noise.

Once the collision is detected, the AP sends a control bit, for example '1' to all the nodes indicating the beginning of a cooperative transmission epoch (CTE). The CTE consists of $\hat{k} - 1$ slots with $\hat{k} \geq K$ The BS keeps sending the same control bit in the beginning of each CTE slot. During slot, $n + 1$, $1 \leq K \leq \hat{k} - 1$ one node is selected as a relay. The selection is based on the predetermined order, for example, each node computes the $r = mod\ (n + k, J) + 1$ and the node which ID equals to 'r' knows that it has to serve as a relay.

Due to the half duplex assumption, if the chosen node happened to be a source node during the collision slot, it will simply retransmit its own packet. Thus, only one relay is active during each of the slots of the CTE. Nodes that are neither involved in the collision nor act as relays remain silent until the CTE is over. When the

CTE is over the BS sends a '0' to all nodes, informing them of the end of the CTE.

The received signal at the BS is:

$$z_d(n+K) = \begin{cases} a_{rd}(n+k)x_r(n) + w_d(n+k), \\ r \in \mathcal{R}(n) \cap S(n) \\ a_{ir}(n+k)c(n+k)y_r(n) + w_d(n+k), \\ r \in \mathcal{R}(n), r \notin S(n) \end{cases} \quad (3)$$

where,

$z_d(n+k)$ is a $1 \times N$ vector

$w_d(n+k)$ denotes the noise vector at the access point

$c(n+k)$ is the scaling constant

An example of this procedure for a collision of two users is as shown in the figure below:

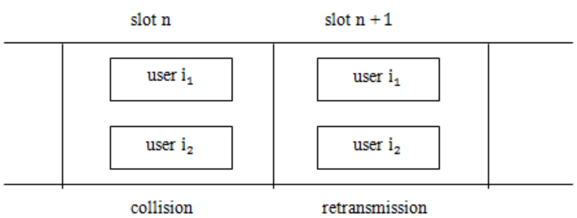


Figure 3: Packet Collision and Retransmission

Let us define matrices X, whose rows are the signals sent by source nodes i.e. $x_{i_1}(n), \ldots\ldots, x_{i_k}(n)$ and Z, whose rows are the signals heard by the destination node during slots $n,\ n+1, \ldots\ldots,\ n+\hat{k}-1$ i.e. $z_d(n),\ z_d(n+1),\ z_d\big(n+\hat{k}-1\big)$

with $z_d(n) = y_d(n)$. Without loss of generality, let us further assume that among the $\hat{k}-1$ nodes, the first l nodes are non-source relays nodes, while the next η nodes are the source relays, where $l + \eta + 1 = \hat{k}$

The received signal at the destination can be written in matrix form as:

$$\mathbf{Z} = \mathbf{H}\,\mathbf{X} + \mathbf{W} \quad (4)$$

where, the matrix **H** and **W** contains channel coefficients and noise respectively. Once, if the **H** i.e. the $\hat{k} \times K$ matrix is estimated, the transmitted packet can be obtained via maximum likelihood decoder.

The channel estimation and active user detection is done through the orthogonal ID sequences, s_i (i is the user index) that are attached to each packet as in [7]. The ID sequences are also used as pilots for channel estimation. At the BS, the correlation of the received signal and the ID sequences s_i, is performed.

Due to the orthogonality of the s_i , it holds:

$$z_s(n)\, s_i^H = \begin{cases} 0 & user\ i\ is\ absent \\ 1 & user\ i\ is\ present \end{cases} \quad (5)$$

The collision order K, can be detected by comparing $|u_i(n)|$ to a pre-defined threshold. The CTE extends over $\hat{k}-1$ slots with $\hat{k} \times K$. If the channel conditions between relay and destination during a certain CTE slot is so bad that it impossible for the BS to collect information, the BS will increase by one. The BS will continue updating until enough information is gathered for resolving the packets.

After detection of the collided user set $i_1, \ldots\ldots, i_k$, the channel matrix H can be obtained based on $u_{i_k}(n+m)$ with $0 \leq m \leq \hat{k}-1$. Once the receiver collects independent mixtures of the original transmitted packets, the collision can be resolved via a maximum likelihood (ML) or a linear equalizer (e.g. zero-forming (ZF) and minimum mean square error (MMSE) equalizer.

3. Methodology

In this section, Multichannel Cooperative MAC protocol - a multichannel extension of cooperative MAC protocol that further improves throughput in case of high traffic load is explained and studied.

3.1 Multichannel Cooperative Protocol

The cooperative protocol assumed a flat fading channel. However, in reality the channel is usually frequency selective. Although frequency selective fading is difficult to deal with, if compensated for successfully, it can be viewed as a source of multipath/frequency diversity.

Consider a similar scenario as in [5], except that the channel has L taps. The physical layer is based on orthogonal frequency division multiplexing (OFDM) system with F carriers. The carriers are grouped into groups of F/M to form M subchannels $C_m, = 0, \ldots\ldots, M-1$ .Without loss of generality, assume that F/M is an integer. Also, we assume that the subchannels are non-interfering with each other.

A user cannot hear and transmit on the same subchannel at the same time. Each packet has a fixed length, contains b bits, and occupies one subchannel for its transmission. If B blocks of OFDM symbols, say QPSK symbols, are transmitted in one slot, then each packet contains $b = 2BF/M$ bits.

3.1.1 Transmission on all subchannels

Each user transmits on all subchannels simultaneously. Therefore, if a collision occurs, the collision order is the same on all subchannels. Let us term the process of resolving packets that collided over C_m as CTE_m. Two different schemes for resolving collisions will be considered and compared.

Scheme A - Collisions on each subchannel are resolved independently

A collision on subchannel C_m is resolved by involving C_m only. For a K-fold collision on C_m, the subchannel C_m will be reserved for the next $K-1$ slot, and the collision will be resolved along the lines of [5]. For simplicity, we take $\hat{k} = K$. From the MAC layer point of view, K slots are needed to resolve the M collisions of order K, and thus the delay is exactly the same as in ALLIANCES and NDMA. Therefore, the analysis of [7] applies in this case.

Scheme B - Subchannels are used in a shared fashion to resolve collision on a particular subchannel.

In this scheme, advantage of the available subchannels is taken to reduce the average processing time, i.e., the time that a packet spends on the channel. Let the collision order on each subchannel in slot n be K. During CTE_m, a set of nodes designated as relays use a set of subchannels indicated to them by the BS to retransmit what they heard during the collision slot on C_m. If the relay node is a source node that transmitted over C_m, it will not retransmit its original packet to the subchannel as indicated by the base station rather it will retransmit to the another subchannel. Following a collision slot, the BS will first allocate all available and necessary subchannels for CTE_0, then allocates subchannels for CTE_1, until CTE_{M-1}. Let T_m denote the processing time on the channel (in slots) for each packet that collided on C_m or equivalently, the duration of CTE_m plus one.

The average processing time is:

$$T_m = \frac{1}{M}\sum_{m=0}^{M-1} \tau \qquad (4)$$

Example 3.1: Let us consider a system with only two subchannels. In slot n, three packets collide over each of C_0 and C_1 respectively. In the (n + 1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot n + 2, it allocates two subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. At the end of the (n + 1)th slot, the collision that occurred over C_0 has been resolved. The collision that occurred over C_1 is resolved at the end of (n + 2)th slot. So the processing time for packets over C_0 is 2 slots, while the processing time for packets over C_1 is 3 slots. Therefore, the average processing time is (3 × 2 + 3 × 3)/6 = 2.5 slots. Note that the average processing time of Scheme A is 3 slots. We can now see that CTE_0 and CTE_1 are resolved by using both C_0 and C_1. The required control and also details on relay selection are given in Section 3.1.2, where the more general case of unequal collision orders on the various subchannels is considered.

3.1.2 Random Subchannel Selection

One way to reduce the collision order is to implement traffic control by taking advantage of the available multiple subchannels. Let us assume that each active node is allowed to transmit over no more than p ($1 \leq p \leq M$) randomly selected subchannels in each slot. Again, each packet occupies one subchannel for its transmission. We assume that the subchannels are selected sequentially, i.e., once a channel is selected it is taken off the list of available subchannels. This approach prevents collisions of packets of the same user.

The maximum number of transmitted packets for each active user, p, can be selected by taking into account the throughput or traffic load, so that the use of bandwidth is maximized while the collision orders are kept properly small. An adaptive approach was followed for selecting p. Based on the average system throughput during the previous time interval, the BS will take one of the following three actions: increase p by 1, decrease p by 1, or keep p unchanged. Then, the BS will broadcast its decision via the error-free control channel to all users using one bit at the end of a slot (0 sent: decrease p by 1; 1 sent: increase p by 1; nothing sent: keep p the same as in previous slot). During the startup period, the value of p can be predetermined by the BS, for example $p = \left[\frac{M}{2}\right]$.

Resolving collisions: the "highest-to-lowest" scheme - Following a collision slot, the BS will decide how to allocate subchannels to resolve collisions according to some predefined strategy. In the following, a simple strategy was proposed that achieve the least average processing time.

Let $K(n)$ denote the number of packets that were transmitted in the n-th slot, and $K_m(n)$ denotes the number of packets that were transmitted over subchannel C_m in the n-th slot. It holds that $K(n) = \sum_{m=0}^{M-1} K_m(n)$. The average processing time is:

$$T_m = \frac{1}{K(n)}\sum_{i=0}^{M-1} K_m(n)\, \tau_m(n) \qquad (5)$$

where, $\tau_m(n)$ denotes the processing time (in slots) for each packet that collided over C_m, or equivalently, the duration of CTE_m plus one.

The optimum scheme would be that the BS performs an exhaustive search to evaluate all possibilities and then chooses the collision resolution order with the least average processing time. However, the computational complexity of such approach would be $M!$, which may be very high when M is large. In the following, a sub optimal scheme is proposed.

From equation (5) collisions of higher order carry more weight in the calculation of the average processing time. We allocate all available and necessary subchannels to resolve collisions over one subchannel at a time, starting from the highest order collision and moving towards the lowest order collision. If the number of available subchannels is larger than the collision order, the collision can be resolved in only one additional slot. Otherwise, more slots will be required. Depending on the availability of sub-channels, collision resolution on several subchannels can be carried out in parallel (i.e., in the same slot).

Example 3.2: Let us consider a system with only two subchannels. In slot n, three packets collide over C_0, and two packets collide over C_1. In the (n +1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot n + 2, it allocates one subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. At the end of the (n + 1)th slot, the collision that occurred over C_0 has been resolved. The collision that occurred over C_1 is resolved at the end of (n + 2)th slot. So the processing time for three packets over C_0 is 2 slots, while the processing time for two packets over C_1 is 3 slots. Therefore, the average processing time is (3 × 2 + 2 × 3)/5 = 2.4 slots. This experiment indicated that the average processing time improved by a small amount.

Control Overhead and Relay Selection: To indicate the state of each subchannel, in the beginning of every slot, the BS will broadcasts an α-bit control message over every subchannel to all nodes. The α-bit message ($\alpha = \log_2(M+1)$) conveys to the nodes one of the following M + 1 possible states of that subchannel: State0: subchannel reserved for $CTE_0, \ldots\ldots$, State M–1: subchannel reserved for CTE_{M-1}; State 0: subchannel reserved for new packets.

For relay node selection, a simple scheme is proposed that establishes a predetermined order. A counter, w is maintained by each user, generated by some predetermined function of the slot number. Looking at the control channels, nodes know the states of all subchannels. All states, except State M, imply that a relay is needed. Counting the total number of such states yields the number of needed relays in a given slot. Suppose that the number of needed relays during slot n is χ. Those relays will be determined based on the outcome of $r = \text{mod}\ (w + m, J) + 1$ (J: the number of network users), for $m = 1, \ldots, \chi$, that is computed by all nodes. Then node whose ID equals r knows that it has to serve as a relay. The subchannels over which the relays retransmit can also be determined based on some predefined rule, e.g., mod $(w + m, M)$. Such scheme prevents the relays from overlapping in frequency, thus facilitating packet recovery at the BS.

Example 3.2: Consider a two-subchannel system with J = 6 users. During slot $n = 0$, $K_0 = 3$ packets collide over C_0, and $K_1 = 2$ packets collide over C_1. The counter is defined as $w = 2n + 5$. Two relays are required to resolve the collision over C_0. This is indicated to all nodes in the next slot via 4 control bits. During slot n = 1, the nodes $r_1 = \text{mod}\ (w+1, J) + 1$ = mod (8, 6) + 1 = 3 and $r_2 = \text{mod}\ (9,6) + 1 = 4$ are selected as relays. These nodes will respectively transmit on subchannels, $C_{\text{mod}(8,2)} = C_0$, and $C_{\text{mod}(9,2)} = C_1$. During slot $n = 2$, one more subchannel is needed to resolve the collision on C_1. This is shown to all users in the control bits that are sent to them in slot n = 2. The node with ID equal to 5 is selected as relay.

More complex cases, where more collisions occur on more subchannels, can be handled in an analogous manner. According to this approach, within the same CTE, a relay will not be reused until all relays have been used.

3.1.3 Fixed Subchannel Selection

To accommodate such heterogeneous traffic, a fixed subchannel selection scheme is proposed, in which packets with the same traffic type are assigned to the same subchannel. Suppose that there are Q types of traffic, each of which may have different BER and delay requirements, and different modulation types. The M ($M \geq Q$) subchannels are divided into Q clusters, so that the subchannels of each cluster are used exclusively for transmissions of one traffic type. The number of subchannels assigned in each cluster can be either predetermined based on the long-term statistical percentage of each traffic type, or adaptively determined by the BS based on the amount of real-time traffic that each cluster needs to accommodate. In the latter case, additional control bits are needed. New packets are transmitted over the preassigned clusters only. In this way, collisions occur only among packets of the same traffic type.

Collision Resolution over subchannels: Propose a subchannel allocation scheme for resolving collisions to best satisfy the delay requirements of all traffic types. The Q clusters are sorted according to the delay requirements of the traffic that they are assigned to. A subchannel with tighter delay requirement has higher priority.

Suppose that a collision occurs over subchannel C_m whose delay requirement is D_m. The BS first checks whether the delay requirement can be satisfied by using C_m only. If so, only C_m is used during CTE_m. Otherwise, in addition to C_m, subchannels with equal and more relaxed delay requirement are also allocated to CTE_m. Such strategy renders available subchannels with high priority open for transmission of new packets during the CTE of subchannels with low priority. When multiple collisions occur over multiple subchannels in the same slot, the BS uses the above strategy to allocate subchannels, starting from the collision subchannel with highest priority (i.e. tightest delay requirement) and moving towards the collision subchannel with the lowest priority, until all collision subchannels have been accommodated. Control overhead and relay selection can be implemented in a similar fashion as in Section 3.1.2

For illustration purposes, let us consider a system with two subchannels and two traffic types. Traffic Type I is allocated to C_0 and type II is allocated to C_1, while their corresponding delay requirements are 3 and 6 slots. Let us consider the following example:

Example 3.4: During slot *n*, 3 packets of type I collide over C_0 and 4 packets of type II collide over C_1. The waiting time in the queue for collided packets is zero. We first accommodate traffic I since it has higher priority. Using C_0 the delays is 3 slots, thus the delay requirement of traffic type I can be satisfied and only C_0 is allocated for CTE_0. Also, C_1 is allocated for CTE_0. Note that during the last 2 slots CTE_1, C_0 is not used, but is rather left open for new packets.

Remark: Although in the above only the relay requirement is considered, other QoS requirements like BER could also be taken into account in subchannel allocations. As it will be seen that improving BER might induce longer packet delays. Thus, BER and delay are not independent, and the above subchannel allocation scheme would need to be extended to a joint BER-delay design.

3.2 Mathematical Formulation

Let us consider that the physical layer is an *F*-carrier OFDM system, where the carriers are divided into groups of *N* carriers each, i.e., $C_0, \ldots\ldots, C_{M-1}$ with $N = F/M$.

Let $h_{ij}(m;n); m = 0, \ldots\ldots, L-1$ denote the *L* channel taps between nodes *i* and *j* during slot *n*. We will assume that *L* is the length of the longest among all internodes channels.

The *F*-point discrete Fourier Transform (DFT) of $h_{ij}(m;n)$ is:

$$H_{ij}(k;n) = \sum_{m=0}^{L-1} h_{ij}(m; ne^{-j\frac{2\pi k_m}{F}})$$

$$k = 0, \ldots\ldots, F-1 \tag{6}$$

OFDM with sufficiently long Cyclic Prefix (CP) can convert a frequency selective channel into multiple flat fading channels. The effect of the channel over the *k*-th carrier is just a multiplication by the carrier gain, $H_{ij}(k;n)$

A packet consists of *B* OFDM symbols. Let $x_i^m(n)$ is a $B \times N$ matrix denoting the packet sent by user *i* over subchannel *m*, in slot *n*. Each row of that matrix contains an OFDM symbol before modulation. In the absence of collision and after demodulation, the received packet at the BS equals:

$$\mathbf{y}_d^m(n) = \mathbf{x}_i^m(n) + \mathbf{w}_d^m(n) \tag{7}$$

$\mathbf{H}_{id}^m(n) = [\mathbf{H}_{id}(mN;n), \ldots\ldots, H_{id}(m+1)N-1;n]$ $(N \times N)$ $B \times N$ matrix denoting noise at the BS over C_m. Now, suppose that a collision of order C_m occurs on subchannel C_m in slot *n*. Let us focus on CTE_m. Suppose that node *r* is selected as the *j*-th relay $j = 1, \ldots\ldots, \hat{k}_m - 1)$ during slots $(n+k)(\hat{k}_m \geq k_m)$. Note that *k* may be different than *j*, since according to [4], multiple relays can be used in the same slot. The value of *k* is determined by the availability of subchannels and the subchannel allocation scheme. If *r* was a source node during the collision slot, it will simply retransmit its packet at a subchannel that is selected according to some rule (not necessarily on C_m). Otherwise, it will transmit over C_l, the signal that it received during slot *n over* C_m. Since relays use different subchannels or slots, their transmissions do not overlap. Therefore, each relay transmission provides the BS with a linear equation that contains the initially collided packets.

Without loss of generality, let us assume that among the $\hat{k}_m - 1$ nodes, the first η nodes are source relays, and the next *l* nodes are non-source relays. It holds $\eta + l + 1 = k_m$.

Let us form a matrix, Z, $(B \times k_m N)$, whose first block column is the packet received at the BS during the collision slot, and subsequent blocks are packets from relay transmissions received at the BS during CTE_m .

It holds:

$$Z = \mathbf{X}^m \, H + W \tag{8}$$

where, $\mathbf{X}^m$ is a $(B \times k_m N)$ matrix based on the packets of users that collided over C_m.

H is a $(k_m N \times k_m N)$ channel matrix.

W is a $(B \times k_m N)$ matrix formed based on the noise at the BS during the collision slot, and each subsequent retransmission.

3.2.1 Collision Detection

For collision detection we need to include a user ID in the packet of each user, with ID's being orthogonal between different users. To maintain orthogonality of IDs despite the channel, we propose to distribute the ID symbols as follows:

All will be on the same carrier, and will be distributed one in each OFDM block. For example, for some j, the columns $j, j+N, \ldots\ldots, j+K_m$ of matrix $\mathbf{X}^m$ will contain the orthogonal IDs of users, $i_1, i_2, \ldots\ldots, i_{K_m}$ respectively. After extracting the j-th column of Z and performing cross-correlation with the known user IDs, we can determine whether a user is present in the collision by comparing the cross-correlation result to a threshold [5].

3.2.2 Channel Estimation

For channel estimation we need to include a number of pilot symbols in each packet of each user. At least one OFDM symbol full of pilots is needed.

Let S be the row selection matrix that selects rows of Z containing pilots. Then,

$$\mathbf{SZ} = (\mathbf{SX}^{\mathrm{m}})\mathbf{H} + \mathbf{SW} \qquad (9)$$

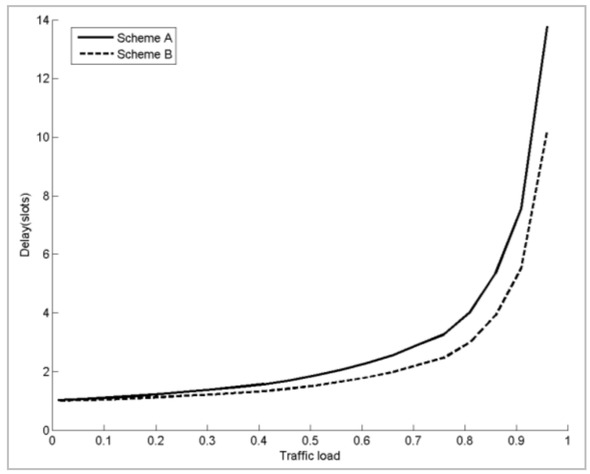
where, $\mathbf{SX}^m$ contains pilots only. We can obtain a least square solution of H as $(\mathbf{SX}^m)^H \mathbf{SX^m}]^{-1}(\mathbf{SX}^m)^H \mathbf{SZ}$. Once the channel matrix $\mathbf{H}$ is estimated, the transmitted bits over C_m can be obtained via a ML or ZF equalizer as in [5].

4. Simulations

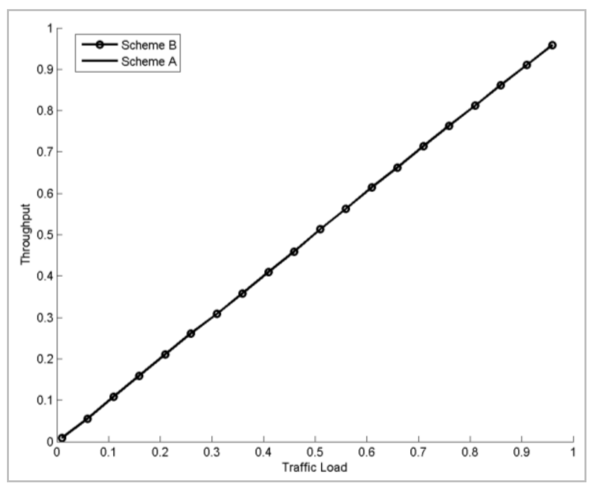
The proposed schemes are programmed and simulated in MATLAB software. Consider a network with total users, J = 32, and each user is equipped with a buffer of infinite size. The users' ID sequences are selected based on the rows of a J-th order Hadamard matrix. The IDs are used to estimate the number of users involved in a collision. The frequency selective channel has L = 3 taps. Each tap is chosen independently from the sum-of-sinusoids simulation model for Rayleigh fading channels of [6]. The number of OFDM carriers is 64, and only 48 carriers are used to transmit data packets. The OFDM symbol duration is 4 μs and the guard interval is 800 ns. Each packet contains 1000 OFDM blocks, and its duration is 4.8 ms. QPSK modulation is used. The channel matrix is estimated using pilots with 32 OFDM symbols as described in section 3.2. The SNR is 20 dB. Packets received at the BS with BER higher than Pe = 0.02 are considered lost or corrupted.

4.1 Performance of Scheme A and Scheme B

The throughput is defined as the average number of packets that are successfully transmitted in one time slot, normalized by the number of subchannels M. Each user is fed with a Poisson source with rate λ large packets per slot, so the total traffic load of the system is λJ. The total simulation time is 2000 slots, and performs 20 Monte-Carlo experiments.



(a) Delay



(b) Throughput

Figure 4: Delay and Throughput of Schemes A and B

In Figure 4 (a), the delay performance of Scheme B, as compared with A is shown. Both schemes exhibit the same throughput as it can be seen in Figure 4 (b), where a ML equalizer is used.

4.2 Random Subchannel Selection Scheme

Consider a scenario where some users in the network generate bursty traffic. During the total simulation time over 500 slots, K users generate packets with Poisson rate, $\lambda = 0.3$ in the first 100 slots, while no incoming packets are generated in the remaining 400 slots. 20 Monte-Carlo experiments are performed.

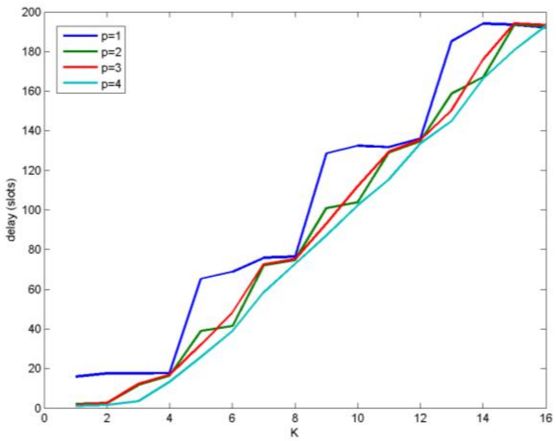


Figure 5: Average delay for the random subchannel selection scheme

The staircase-like behavior in Figure 5 shows the delay versus the number of active users K. A ZF equalizer is used for signal recovery. As expected, under low traffic load (small K), the throughput does not vary significantly between different p's. Under high traffic load (large K), a smaller p can result in higher throughput. Figure 6, shows the number of operations versus K, when a ML equalizer is used for signal recovery. The computational complexity of a ML equalizer is exponentially distributed increasing with the collision order. One can see that the computational complexity of the ML equalizer can be greatly reduced by using a small p.

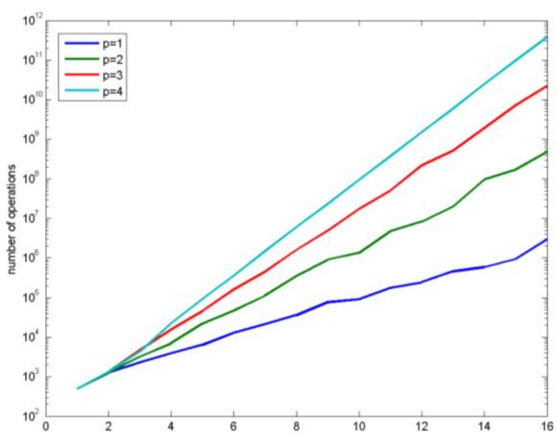


Figure 6: Computational Complexity for the random subchannel selection scheme

4.3 Fixed Subchannel Selection Scheme

Consider the three types of traffic: type I real-time traffic, type II delay sensitive non-real-time traffic, and type III delay tolerable non-real-time traffic. It is known that type I has the tightest delay (highest priority) and the most relaxed BER requirement. Type II has priority over type III. The number of subchannels is fixed to $M = 4$. Each user can support all types of traffic. Based on their percentage, type I is assigned 2 subchannels for its transmission, and type II & III are assigned 1 subchannel, respectively. To show the interplay of different traffic types, assume each active user sends up to two packets of type I and one packet of type II and III for new transmissions.

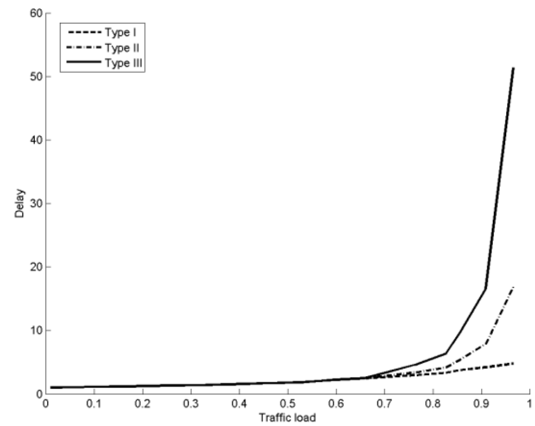


Figure 7: Average delay of different traffic types (fixed subchannel selection)

The delay performance is shown in the Figure 7. At low traffic, all traffic types only use their own subchannels and their delays are same. Under high traffic ($\lambda J > 0.7$), type I has the highest priority, and may use subchannels allocated to type III traffic as well as its own subchannels for collision resolution. Type II still uses its own subchannel. Thus, the delay for type I become shorter while the delay for type III is longer as compared to type II.

4. Conclusions

In this paper, a multichannel extension of cooperative protocol - a cross-layer cooperative protocol for collision resolution in data networks was presented. Two schemes (Schemes A and B) was studied, and showed that Scheme B can achieve shorter delay than Scheme A. For the case of multimedia traffic, two different approaches to subchannel selection were proposed. In the first approach the subchannels were selected randomly by each active user with equal probability, which may be suitable for the scenario of heavy traffic, without strict delay requirements. The second approach is geared towards heterogeneous traffic with diverse QoS requirements. At the physical layer, the proposed approaches are based on OFDMA.

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