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Ez-Channel: A distributed MAC protocol for efficient channelization in wireless networks

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ABSTRACT

There is a significant interest in new wireless multiple access protocols that *adaptively* split a wide frequency channel into multiple sub-channels—perhaps of varying widths—and assign these sub-channels to competing transmissions. Existing protocols suffer from various limitations such as considerable protocol overhead, dependence on a centralized controller, and use of fixed-size channels. We introduce Ez-Channel, a novel MAC protocol that parsimoniously utilizes the OFDM sub-carriers to perform channelization and assignment of sub-channels to competing links. In addition to circumventing hidden and exposed terminal problems, Ez-Channel adapts channel assignments to the network topology. To eliminate the need for a centralized controller and to avoid an overwhelming amount of information exchange, the protocol uses a randomization technique enabling provably efficient localized decision making. Our extensive analytical and simulation studies show that Ez-Channel yields significant throughput improvements as compared to the state-of-the-art protocols.

1. Introduction

Splitting the channel resources in time and/or frequency domain has been widely considered in wireless networks to accommodate multiple competing transmissions. Straightforward analysis shows that splitting over frequency domain (i.e., use of multiple orthogonal channels and FDM) achieves a greater performance relative to splitting across time domain (TDM scheduling) under the maximum transmit power constraint (a typical practical constraint wireless networks operate under) [1]. Also, as the network speed increases (say, over 1 Gb/s), any form of scheduling-based approaches increasingly faces higher normalized overheads. This is because while the per-packet overheads involved in conflict-free scheduling are largely independent of channel bit rate, the useful time spent on the channel on a per-packet basis reduces with channel bit rate. This has been explained in [2] and is even experienced in relatively slower networks, e.g., 802.11n [3]. This problem is directly addressed by using concurrent packet transmissions on multiple orthogonal channels.

The advantage of using multiple channels is not restricted to high-speed networks alone. In networks where a large amount of spectrum, possibly non-contiguous, is used (e.g., white space networks [4]), appropriate wideband radio front ends may not always be cost or power efficient. Here, use of multiple smaller channels becomes a natural choice.

While traditionally multichannel systems have used a pre-defined and fixed channel split, recent work has focused on *channelization*' i.e., determining how to adaptively split the channel and then assign the individual sub-channels to competing transmissions [5]. Since the

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number of competing transmissions change dynamically in a typical network, such channelization approaches can show much superior performance relative to the use of fixed channels. Concurrently with the above development, the advent of the OFDM technology has given rise to the prospect of fast exchange of control information using OFDM sub-carriers. For example, the protocols proposed in [6,3,7] use OFDM sub-carriers to carry out frequency-domain contention, which is more efficient than time-domain contention, especially for high data rates.

While adaptive channelization has been investigated in literature, existing approaches only present limited potential. They use centralized decision-making [8], or target infrastructure networks only [9], or are suited specifically for standard-compliant 802.11-based networks [9], or use fixed-size channels [3], or simply describe a physical layer methodology to find free spaces in the spectrum and not a complete protocol suitable for packet-switched networks [10,11].

In this paper, we present *Ez-Channel*, a novel protocol that exploits the rich potentials of OFDM sub-carriers to parsimoniously exchange control information and perform adaptive channelization in a *completely distributed fashion*. Ez-Channel's strength is in its generalization—applicability across the infrastructure networks and in ad hoc/mesh network settings, either in stationary or mobile scenarios. Ez-Channel explicitly addresses synchronization issues in the case of infrastructure-less networks, which the existing distributed protocols in this domain side-step (e.g., [6,7]). Further, as opposed to some related work (e.g., [12,13]), Ez-Channel circumvents both hidden and exposed terminal problems.

In what follows, we first review the related work (Section 2). We present the Ez-Channel protocol (Section 3) followed by a synchronization mechanism that makes various protocol stages synchronous (Section 5). Ez-Channel's performance is evaluated analytically (Section 4) as well as via simulations against a suite of (i) multichannel/channelization protocols and (ii) protocols that perform frequency-domain contention (Section 6). We show that while Ez-Channel performs at par with the state-of-the-art in some of the simpler scenarios (e.g., all links interfere with one another), it provides a far superior performance in more complex interference scenarios that perhaps occur more frequently in real deployments.

2. Related work

The idea of considering the spectrum as a set of sub-channels has been investigated for a long time. Earlier work was focused on assigning a fixed set of sub-channels to network nodes and ensuring that the transmitter and the receiver of each link operate on the same sub-channel (e.g., SSCH [14], MMAC [15], DCA [16], and xRDT [17]). In contrast, Ez-Channel attains better spectrum usage by providing a dynamic channelization scheme.

Speaking about dynamic behavior, unlike centralized dynamic channelization techniques (e.g., [18,9,8]), Ez-Channel is a distributed protocol. Other distributed protocols, such as WiFi-NC [13] and B-smart [12], have drawbacks of their own. In WiFi-NC, the spectrum is split into a fixed set of sub-channels of equal widths, and a single radio is designed to operate on all the sub-channels simultaneously. However, since 802.11 DCF is used to gain access on each of the individual sub-channels, the well-known inefficiencies of 802.11 DCF (i.e., sub-optimal back-offs, fairness issues, exposed and hidden terminal problems) on each sub-channel limits WiFi-NC's throughput. On the other hand, Ez-Channel's contention mechanism avoids such problems. B-Smart [12] requires a separate control channel at all times and uses an 802.11 DCF-like technique for exchanging control information on the control channel. This can occasionally turn into a bottleneck. In contrast, Ez-Channel does not require a separate control channel. Other distributed protocols such as Jello [10] and Papyrus [11] find and use free spaces in the spectrum, but they are not designed for packet switched networks. Additionally, a node may sense and capture a free portion of the spectrum for as long as it desires, which hinders fairness.

We will also review recent protocols for high data rate WLANs since Ez-Channel is also meant to improve performance in such networks. WiFi-Nano [19] reduces the contention overheads in 802.11 DCF by reducing the slot size. However, the protocol still suffers from the well-known shortcomings of the 802.11 protocol, and it does not take advantage of splitting the channel among links. Recently, two related schemes have been introduced to significantly reduce the overhead of wireless MAC protocols: (1) frequency-domain contention [6,3,7]) and (2) sending acknowledgments via OFDM symbols [7]. Back2F [6] and REPICK [7], however, do not involve channelization. FICA [3] performs channelization, but uses fixed-size channels. In addition to using an enhanced scheme for frequency-domain contention and acknowledgment (based on the notion of clusters as introduced later), Ez-Channel, in contrast to the above works, offers a better utilization of the spectrum by performing adaptive channelization at the granularity of OFDM sub-carriers depending on the number of current active links in the neighborhood.

3. Ez-Channel protocol

The key idea of Ez-Channel is to dynamically split the available bandwidth into as many independent sub-channels of equal sizes as needed to ensure interference-free transmissions by otherwise interfering links. Interfering transmissions are allocated different sub-channels. Fig. 1 illustrates this. In each of the three sub-figures, an example network is shown on the left-hand side, and the right-hand side depicts the sub-channel(s) assigned to each link as yielded by Ez-Channel, each sub-channel shown in a distinct color. The enclosing rectangle in each example represents the channel that is split into the colored sections that indicate the sub-channels. Note that a transmitter causes interference at the receiver of another simultaneously active link if they are both in the same collision domain[1] and operate on the same frequency.

[1] We say that two links are located in the same collision domain if the transmitter of one link interferes with the reception of another when the links' frequencies overlap.

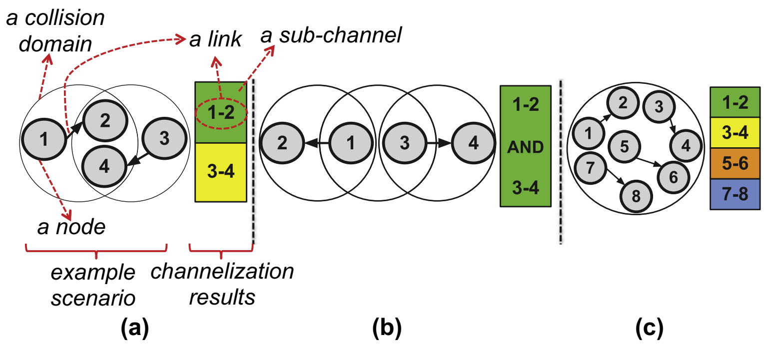


Fig. 1. Three example networks along with corresponding channelization results of Ez-Channel. (Symbols are introduced in sub-figure (a) in red.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Let us consider the three example channelizations resulted by Ez-Channel in the figure. As shown in Fig. 1a, receiver nodes 2 and 4 do not experience 'hidden terminal' problem, as links $1 \rightarrow 2$ and $3 \rightarrow 4$ use non-overlapping sub-channels (shown in green and yellow, respectively). In Fig. 1b, the 'exposed terminal' problem is prevented, as in Ez-Channel, channelization decisions are based on receivers' view of the network. As such, both links $1 \rightarrow 2$ and $3 \rightarrow 4$ use the entire channel (shown in green). Fig. 1c depicts a network with four links all of which are located within the same collision domain. In this case, the interfering links simultaneously operate on non-overlapping sub-channels—four sub-channels in this example (one per link). The mechanism through which these channelizations are achieved becomes clear in the next sub-section.

3.1. The protocol

In Ez-Channel, transmitters and receivers systematically exchange *tones* (i.e., short signals on OFDM channel sub-carriers) to learn how many links they may interfere with. This information is then used to split the channel into non-interfering sub-channels in a distributed fashion using only locally available information by each node. Distributed operation may on occasion fail to determine a perfect channel split.[2] This may cause interference and thus sub-optimal operation. Regardless, our evaluations will show later that the protocol performs very well on average and outperforms the competition.

Ez-Channel is executed synchronously in *rounds*—see Fig. 2. In each round, active nodes first split the channel among themselves such that links in the same collision domain use separate frequency ranges of the channel (stages 1–3). The links then use the corresponding sub-channels to transfer data (stage 4). Finally, the receivers acknowledge successful transmissions (stage 5). Note that the time periods in the figure are not to scale, and stages 1–3 and 5 (each of length T_{sub}) as well two SIFS periods (each of length T_{SIFS}) are very short compared with data transmission time in stage 4 (T_{data}). Except for the data transmission stage (stage 4), all other stages merely involve transmission of tones whose short transmission periods substantially reduce overheads.

Next we describe the details of Ez-Channel. Suppose the channel is composed of N_s sub-carriers (indexed 1 through N_s) that are logically divided into *clusters* of equal sizes, each composed of C contiguous sub-carriers. Clusters, as discussed shortly, provide a useful correspondence between the transmitter and the receiver of a link. Suppose there are n nodes in the network. Let i and j denote the indices of a typical transmitter and receiver, respectively; and let Id_j represent a unique identifier of node j, such as its MAC address. Also, let $\%$ denote the remainder operator modulo 10. Then $Cluster_j = C \times (Id_j \ \% \ \lfloor \frac{N_s}{C} \rfloor) + 1$ is the index of the first sub-carrier in node j's cluster.

Suppose, node i transmits to node j. Here are the five protocol stages:

Stage 1 (Contention): Node i transmits a tone on a randomly chosen sub-carrier that belongs to node j's cluster. Formally, the sub-carrier index chosen by node i is a random number $u_{i,j}$ computed as follows:

$$u_{i,j} = Cluster_j + Rand_{0,C-1} \qquad (1)$$

where $Rand_{0,C-1}$ is an integer chosen at random from the set $\{0, 1, \ldots, C-1\}$. Node j stores the indices of all sub-carriers it hears tones on as 1s in $S_{j,1}$, a binary, zero-initialized array of size N_s. (Subscript 1 in $S_{j,1}$ indicates stage 1 of the protocol.)

Stage 2 (Contention resolution and channelization on transmitter side): The goal of this stage is to determine the winners of the contention and split the channel among them. If $S_{j,1}$ includes at least one element with a value of 1 located in j's cluster (i.e., located between indices $Cluster_j = C \times (Id_j \ \% \ \lfloor \frac{N_s}{C} \rfloor) + 1$ and $Cluster_j = C \times (Id_j \ \% \ \lfloor \frac{N_s}{C} \rfloor) + C$ of $S_{j,1}$), this indicates a transmission attempt by (at least) one other node. In this case, node j selects a winner among the requests. The receiver arbitrates the requests based on a pre-defined rule. Without loss of generality, suppose the rule mandates that the request

[2] Optimal channel split and assignment is intractable even when implemented in a centralized fashion [12].

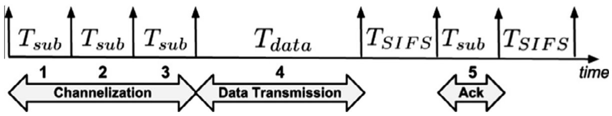


Fig. 2. Five stages of a round in Ez-Channel. (Times are not to scale.)

with the smallest index wins the contention.[3] Node j populates a zero-initialized array, $S_{j,2}$, based on $S_{j,1}$ as follows: in each cluster of $S_{j,1}$, if there is more than one element with a value of 1, only the first one is copied over into $S_{j,2}$; the other elements of $S_{j,2}$ are set to zero. Node j then transmits tones on sub-carriers that correspond to the elements of $S_{j,2}$ that have a value of 1.

Now consider node i. If it hears a tone in this stage, it sets the corresponding bit in its $S_{i,2}$ array (zero-initialized). Now, by scanning $S_{i,2}$, node i can determine if $u_{i,j}$ is the first non-zero element in node j's cluster in $S_{i,2}$. If so, node i concludes that its request to transmit to node j has been approved. Furthermore, node i can determine the total number of approved transmission requests in the neighborhood simply by counting the elements with a value of 1 in $S_{i,2}$. Collisions are indeed possible in Ez-Channel when there happen to be more than one winner, or when the same cluster is assigned to more than one receiver. (The impact of collisions will be analyzed later in Section 4.)

Finally, node i determines the sub-channel (i.e., a set of contiguous sub-carriers) that will be used for transmission to node j as follows. Once $S_{i,2}$ is populated, the winning transmitters can determine their sub-channels. Suppose node i is the winner among the nodes contending to transmit to node j, and element $u_{i,j}$ of $S_{i,2}$ is the r_i-th non-zero element among a total of R non-zero elements in $S_{i,2}$, then node i splits the channel into R sub-channels of almost equal sizes and assigns the r_ith sub-channel to itself. Formally, let $X = \lfloor \frac{N_s}{R} \rfloor$ and $Y = (N_s \ mod \ R)$; node i's sub-channel starts at sub-carrier $Start_i$ and ends at sub-carrier End_i, where:

$$Start_i = \begin{cases} r_i \times (X+1) - X & \text{if } r_i \leqslant Y \\ Y + X \times (r_i - 1) + 1 & \text{Otherwise} \end{cases} \quad (2)$$

$$End_i = \begin{cases} Start_i + X & \text{if } r_i \leqslant Y \\ Start_i + X - 1 & \text{Otherwise} \end{cases} \quad (3)$$

The goal of (2) and (3) is to ensure that the channel is split and assigned to the winners in a systematic way (i.e., without overlap between sub-channels and without leaving any part of the channel unassigned).

Stage 3 (Channelization on receiver side): In this stage, each receiver determines the sub-channel it has to listen to in Stage 4 (data transmission). To this end, each approved transmitter i sends a tone corresponding to each element of $S_{i,2}$ that has a value of 1. As the receivers hear the tones, they can determine the sub-channels they should be listening to during the following stage (data transmission) in the exact same way that the transmitters identified their sub-channels in stage 2.

Upon completion of stage 3, the channelization is complete, i.e., the transmitter and the receiver of each link will have identical sub-channels, which is dedicated to them.

Stage 4 (Data transmission): Node i sends data to node j over the sub-channel dedicated to this link. The feasibility of data transmission on a subset of sub-carriers has been demonstrated in previous studies (e.g., [10,3]).

Stage 5 (Acknowledgment): If the transmission from node i has been successful, node j sends an acknowledgment back using a tone on sub-carrier $u_{i,j}$.

The SIFS period between stages 4 and 5 ensures the receiver has enough time to determine whether data transmission has been successful before sending acknowledgment. The second SIFS (after stage 5 and before the next round) separates consecutive rounds.

Resolving Packet Collisions: Transmissions may collide under certain circumstances (see Sections 3.1, 3.3 and 4). To deal with collisions, the colliding transmitters need to randomly back-off. One such back-off mechanism is as follows: each transmitter i maintains an aggressiveness parameter, p_i, which is the probability that an active transmitter participates in the next round of the protocol, and is initialized to 1. If the transmitter fails in a transmission attempt, it halves p_i. Otherwise, it will update p_i to the new value of $min(2p_i, 1)$.

3.2. Practical considerations

Several aspects of a system implementation of Ez-Channel are worth discussing here. First, Ez-Channel requires that the same stage of the protocol be running by all active nodes at any given time (existing frequency-domain protocols have a similar requirement [6,7]). We elaborate on this in Section 5, where we design a synchronization method. Second, in order for concurrent transmissions over neighboring sub-channels not to interfere with each other, tones on different sub-channels must be maintained aligned in time. FICA [3] presents a distributed method to overcome symbol misalignment using the cyclic-prefix (CP) mechanism that can be directly adopted by Ez-Channel. Third, in Ez-Channel, every node needs to be equipped with transmit/receive antennas to simultaneously listen to and transmit tones on sub-carriers. This is shown to be feasible on commodity software radio platforms [6]. Another practical aspect is setting data transmission time T_{data}. If it is too long, the channel utilization will fall. If it is too short, the time overhead of the protocol will grow. We recommend using traffic patterns in recent history of the network to set this value.

[3] If node j has sent a transmission request in stage 1, it needs to do arbitration in this stage only if it has decided to proceed as a receiver. Otherwise, it will ignore all requests.

3.3. Imperfect channelization

A perfect channelization protocol must ensure no overlap between sub-channels of interfering links. This, however, requires information on the global topology of the network. It can be seen from the protocol description that Ez-Channel performs perfect channelization only if the interference between any two links is bidirectional[4]; otherwise, the resulting information asymmetry between the links may cause interference. This is highlighted in the following example.

Fig. 3 depicts an example network topology in which Ez-Channel will yield imperfect channelization. The middle link $(3 \rightarrow 4)$ will use one third of the channel, while the other two links $(1 \rightarrow 2$ and $5 \rightarrow 6)$ will each use one half of the channel. The fundamental problem is that links $1 \rightarrow 2$ and $5 \rightarrow 6$ are not aware of each other, but link $3 \rightarrow 4$ is aware of both of them. Even worse, if also $u_{1,2} < u_{3,4} < u_{5,6}$, link $3 \rightarrow 4$ will use the middle third of the channel which results in interference on all links.

Our simulations involving this specific situation (not presented here due to space limitations) reveal that this problem does not significantly reduce the performance of Ez-Channel. Nonetheless, the severity of the problem can be reduced by providing each node a wider view of the network such that all neighbors of the neighbors of any given node are aware of its existence, This can be achieved by repeating stages 1 and 2 of the protocol in order to propagate the transmission requests one hop further in the neighborhood. This, however, increases protocol overheads. For reasons of brevity, we do not analyze this issue further here. In the evaluations that will follow (Section 6), such situations do happen (randomly). But on average EZ-Channel still outperforms the competition.

3.4. Protocol features and use cases

Here, we summarize the advantages of Ez-Channel. First, it dynamically adapts to network topology changes, as channelization depends on current link interferences. Thus, the protocol is efficient with respect to spectrum usage in that no part of the channel may be wasted due to the use of pre-defined, fixed sub-channels. For instance, if the network in Fig. 1a transforms into the network in Fig. 1b, the nodes sub-channels will be adapted accordingly in the following round. Second, the protocol prevents hidden and exposed terminals (Fig. 1a and b). Third, each node only needs local information for channelization. However, access to global information will enhance the performance (see Section 3.3).

Ez-Channel can be used in both high-speed wireless networks and white space networks as they both gain from channelization. For using it in white space networks, some amount of help from the lower layer is necessary for two reasons. First, white space networks must implement primary avoidance (via spectrum sensing, or consulting a spectrum database). Second, white space spectrum can be fragmented

[4] A network whose nodes are all located within a single collision domain is an example of this case.

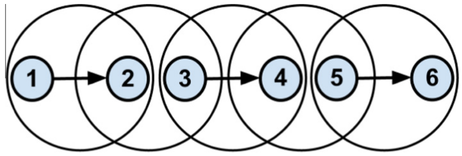


Fig. 3. An example topology to highlight imperfect channelization.

due to primary occupancy. This could make the available spectrum non-contiguous. The non-contiguous spectrum, however, can be mapped to a contiguous domain by a simple relabeling of sub-carrier indices so that the Ez-Channel's style of protocol operation is still applicable.

To make the use case of Ez-Channel in white space networks concrete, suppose the channel is composed of sub-carriers indexed 1 through N_s, as before. At a new stage inserted before stage 1 of the base protocol (Section 3.1), each node senses the channel and finds the set of free sub-carriers represented by $S = S_1 \cup \cdots \cup S_F$, where: *(i)* S_p is a set of contiguous and free sub-carriers, *(ii)* there is a gap of at least one occupied sub-carrier between the sub-carriers in S_p and those in S_q, and *(iii)* all sub-carrier indices in S_p are smaller than the corresponding values in S_q $(\forall p,\ q \in \{1, \ldots, F\}$ and $p < q)$. Let $N'_s = \sum_{p=1}^{F} |S_p|$ (Note that $N'_s \leqslant N_s$.). By relabeling the indices of sub-carriers in S consecutively from 1 to N'_s starting with S_1 and ending with S_F, Ez-Channel is directly applicable.

4. Analysis of Ez-Channel

This section presents the analytical formulations pertaining to the performance of Ez-Channel when all network nodes are located in a single collision domain—the performance in the general case is studied via simulations in Section 6. Since the total number of channel sub-carriers N_s is finite, there are two possible sources of failure in the protocol. A *sub-carrier collision* happens when multiple transmitters that are contending for transmitting to the same receiver win the contention. A *cluster collision*, on the other hand, refers to the event that the same cluster is assigned to multiple receivers.[5] In this section, first, we analyze these two types of collisions independently, and then calculate their combined effects using the notion of *aggregate collision probability*. We use the latter to determine the efficiency of the protocol. Finally, we show how to choose the best value for the cluster size.

4.1. Sub-carrier collision

A sub-carrier collision occurs when multiple transmitters that are trying to transmit to a given receiver win the contention. This can happen when all of them have chosen the same sub-carrier in stage 1 that also happens to be the sub-carrier with the smallest index among all

[5] One might think of a third type of collision if multiple tones are transmitted on the same sub-carrier during channelization. This is, however, not a problem since all that matters during channelization is the ability to determine whether at least one tone exists on the sub-carrier, which is shown to be feasible [3].

the chosen sub-carriers in the receiver's cluster. Suppose the set of active nodes in a given round of Ez-Channel is composed of n_r receivers, and moreover, n_t transmitters contend for transmitting to each receiver. In practice, n_t may reflect the average or maximum number of transmitters that simultaneously contend for any receiver if we are to analyze the protocol performance in an average or worst case sense, respectively.

Let us focus on receiver j, where $j \in \{1, \ldots, n_r\}$. A sub-carrier collision signifies that more than one of the n_t sub-carriers randomly chosen by the transmitters in stage 1 (all of which are within the receiver's cluster by construction) rank first. Let A denote such an event. If A_i represents the event that the ith element of the cluster is the first non-zero element of node j's cluster and is chosen by more than one contending transmitter, where $i \in \{1, 2, \ldots, C\}$, the probability of sub-carrier collision is:

$$P(A) = \sum_{i=1}^{C} P(A_i). \tag{4}$$

In order to calculate $P(A_i)$, suppose A_{i1} is the event that the ith element of the cluster is chosen by more than one contending transmitter, and A_{i2} is the event that it is ranked first among all non-zero elements of the cluster; then:

$$P(A_i) = P(A_{i1} \cap A_{i2}) = P(A_{i1}|A_{i2})P(A_{i2}). \tag{5}$$

It can be shown that:

$$P(A_{i1}|A_{i2}) = 1 - n_t \frac{1}{C-i+1}\left(1 - \frac{1}{C-i+1}\right)^{(n_t-1)} - \left(1 - \frac{1}{C-i+1}\right)^{n_t} \tag{6}$$

and

$$P(A_{i2}) = \left(1 - \left(1 - \frac{1}{C-i+1}\right)^{n_t}\right)\left(1 - \frac{i-1}{C}\right)^{n_t}. \tag{7}$$

4.2. Cluster collision

A cluster collision happens when a given cluster is assigned to more than one receiver, where one of their transmitters interfere with the other receiver. Let random variable X_c denote the number of receivers to which cluster c is allocated. We define indicator random variable X_{cj} as follows:

$$X_{cj} = \begin{cases} 1, & \text{if cluster } c \text{ is assigned to receiver } j, \\ 0, & \text{otherwise}, \end{cases} \tag{8}$$

where $c \in \{1, \ldots, N_{cluster}\}$ and $j \in \{1, \ldots, n_r\}$. $N_{cluster}$ here denotes the total number of clusters, i.e., $N_{cluster} = \lfloor \frac{N_s}{C} \rfloor$. Since $P(X_{cj}) = \frac{1}{N_{cluster}}$,

$$E[X_c] = \frac{n_r}{N_{cluster}}. \tag{9}$$

4.3. Aggregate collision probability

Having the sub-carrier and cluster collisions defined, the aggregate collision probability, shown by $P(B)$, reflects the combined effects of sub-carrier and cluster collisions. To combine the effects of these two types of collisions, parameter n_t in (6) and (7) must be replaced with $\lceil E[X_c] \rceil \times n_t$ because, effectively, at most $\lceil E[X_c] \rceil \times n_t$ transmitters contend within any given cluster. Therefore, the aggregate collision probability $P(B)$ is defined exactly as $P(A)$ was defined, with the difference that in calculating $P(A_{i1}|A_{i2})$ and $P(A_{i2})$, n_t must be substituted by $\left\lceil \frac{n_r}{N_{cluster}} \right\rceil \times n_t$. The collision probability is an important measure that helps determine the channel use efficiency of the protocol.

4.4. Channel use efficiency

What fraction of the time does the channel transmit data (without collision) using Ez-Channel? To answer this question, we need to account for the overhead associated with aggregate collision probability as well as the overhead of an Ez-Channel round (i.e., the entire duration of a round except for stage 4 – see Fig. 2). It is easy to verify that the expected number of successfully transmitting links (i.e., non-interfering transmitter–receiver pairs) in each round is $min(N_{cluster}, n_r) \times (1 - P(B))$. Furthermore, the overhead of the protocol in each round, i.e., which is the time taken by stages 1–3 and 5 and the two SIFS intervals, is equal to $4T_{sub} + 2T_{SIFS}$. Therefore, the efficiency of Ez-Channel in a single collision domain is given by:

$$E_{Ez-Channel} = \frac{min(N_{Cluster}, n_r) \times (1 - P(B)) \times T_{data}}{4T_{sub} + 2T_{SIFS} + min(N_{Cluster}, n_r) \times T_{data}} \tag{10}$$

To gain some intuition about $E_{Ez-Channel}$, we have also formulated the efficiency of REPICK [7], a recent frequency-domain contention protocol, taking into account collision probability in a similar manner to the analysis presented in this section. By plugging values for the parameters of (10) based on IEEE 802.11n and setting the cluster size to its optimal (see Section 4.5), we have observed that Ez-Channel outperforms REPICK by 35% on average. Low collision probabilities due to the notion of clusters, small protocol overhead in each round, and using multiple sub-channels are the key reasons behind the observed performance gap. As an example, the aggregate collision probability using Ez-Channel in a network with 128 nodes, where $N_s = 104$, is only 13%; the corresponding value in REPICK approaches 100%.

4.5. Setting the cluster size

As we have seen, in Ez-Channel, the receiver of a transmission is assigned a cluster, a set of contiguous sub-carriers used for contention purposes. A practical question is "What value of the cluster size C will maximize $E_{Ez-Channel}$?". We consider two cases that will be referred to as the *downlink setting* and the *uplink setting*. The downlink setting is characterized by $n_t = 1$ that implies exactly one transmitter contends for each receiver. In the uplink setting, on the other hand, $n_t > 1$.

We have numerically studied values of $E_{Ez-Channel}$ using an extensive set of real-world values of parameters n_t, n_r, N_s, T_{sub}, T_{SIFS}, and T_{data}, while varying C. We have found that the following heuristic for finding the optimal cluster size (i.e., that maximizes $E_{Ez-Channel}$) works quite well. *In the downlink setting, if number of receivers (i.e., n_r) is smaller than or equal to the total number of sub-carriers (i.e., N_s), $C^* = 1$; otherwise, $C^* = N_s$. In the uplink setting $C^* = N_s$.* For instance, in a wireless LAN that is not extremely dense (i.e., $n_r \leqslant N_s$), a given client that is the receiver of a link should be assigned a cluster size of 1; the corresponding value for an AP when it is a receiver is N_s. In practice, N_s is known *a priori* and n_r can be roughly estimated based on network usage history. (Note that an exact estimation of n_r is not required; we just need to know whether or not $n_r \leqslant N_s$.)

5. Stage synchronization

In Ez-Channel, similar to other frequency-domain MAC protocols (e.g., [6,7,3]), nodes that may interfere with each other require to execute the same stage of the protocol (e.g., contention, transmission) at the same time. We refer to this requirement as synchronization. Such synchronization is attainable by using either out-of-band or in-band solutions. Out-of-band solutions, such as equipping each node with a GPS, would incur no synchronization time overhead to such MAC protocols. When an out-of-band solution cannot be used, if all nodes are located within the same collision domain, the in-band synchronization method of the work in [6] is directly applicable to Ez-Channel. While the general case of multiple collision domains has been sidestepped by most of the frequency-domain protocols (e.g., [6,7]), our contribution in this section is to propose an in-band synchronization solution for this general case, which can be applied to Ez-Channel and other frequency-domain MAC protocols. Our synchronization method has two main components as described below.

5.1. Synchronizing nodes at the ACK stage

A certain sub-carrier of the channel, called ACK–SYN, is dedicated to denoting stage 5 of Ez-Channel. Each node sends a tone on ACK–SYN during stage 5 regardless of whether it has been active (transmitting/receiving) in the current round. Any new node joining the network may not start operating until it first hears a tone on ACK–SYN. In such an event, the node will set its current stage to stage 5 and gets synchronized with other nodes. While this simple solution is sufficient in many scenarios, next we discuss and resolve its shortcoming.

Suppose the network is composed of multiple isolated islands of nodes such that the nodes within an island are synchronized, but nodes across islands may not be synchronized. If an existing node moves to, or a new node arrives at a position at which it can hear nodes from two isolated and unsynchronized islands, it will bridge the two otherwise isolated groups of nodes. We call this situation the *connected islands problem* where this method will not suffice. The second component of the synchronization protocol tackles this issue.

5.2. Network-wide synchronization protocol

If the connected islands problem occurs, all nodes across all connected islands must stop their operations so that they can become synchronized together. We augment the ACK–SYN method with a halt mechanism. A predetermined sub-carrier denoted by STOP (different from ACK–SYN) is used to cause a domino effect that will stop all activities across the connected islands as follows.[6] If node u: *(i)* hears a tone on ACK–SYN, *(ii)* does not hear any tone on STOP, and *(iii)* its current stage is not stage 5, the connected islands problem has occurred. In such an event, node u will continuously send tones on STOP. Any node that receives this tone, must immediately stop its activities, and constantly send tones on STOP. Therefore, the STOP tones will reach any node for which there is a path to/from u. Node u keeps sending tones on STOP for a duration of t since initiating it. Parameter t, which has a predefined value, should be large enough to ensure that STOP tones can reach all nodes reachable from u within t. The next operations allow the nodes determine when they must stop sending tones on STOP and resume executing Ez-Channel rounds (while all nodes have become synchronized).

Let h denote a number that is larger than or equal to the diameter of the network in terms of number of hops and $h \leqslant N_s$. Starting at node u as the origin, each hop k is identified by a unique sub-carrier s_k. After a time period of t from the time node u initiated the STOP tones, it will transmit a *hop tone* on s_1 (i.e., the first of N_s sub-carriers) for a time period of T_{sub}. Any node that receives a hop tone on s_k, will transmit a hop tone on s_{k+1} (for a duration of T_{sub}). This hop relaying process will continue until the last hop. Note that during this process nodes are still constantly sending tones on STOP. The node that receives a hop tone on s_h will not relay any hop tone on s_{h+1}. All nodes are aware of the duration of the entire hop relaying process ($h \times T_{sub}$). Consider node w ($w \neq u$). By knowing its hop distance from u (i.e., the index of the sub-carrier it has first heard a hop tone on), once node w hears a hop tone, it knows the amount of time δ_w it has to wait before the entire hop relaying process ends. After an elapsed time of δ_w, node w will stop sending tones on STOP and start the T_{SIFS} period that follows stage 5 of Ez-Channel. Thus, all nodes located in the connected islands become synchronized.

In the rare case that multiple nodes initiate tones on STOP (i.e., more than two unsynchronized islands of nodes emerge at the same time) there may exist a node w that hears a hop tone on s_k originated from node x, and shortly after that, another hop tone on s_l originated from node y. In this case, w will calculate a new waiting time as follows. If the new waiting time is greater than or equal to what w calculated before, then w will ignore the more recent tone. Otherwise, w will update δ_w accordingly and will relay tones on s_{l+1}. Finally, if w hears two hop tones, s_k and s_l, at the same time, then w will ignore one of the tones based upon same calculations as above, and will update its δ_w in a similar manner.

Our proposed technique ensures synchronization within any given connected region of the network, which is sufficient—disconnected regions can be unsynchronized because they do not interfere with each other. Using

[6] Sub-carriers ACK–SYN and STOP are not used for any operations other than what they are reserved for.

simulations on two human mobility traces ([20,21]), we found that in average the synchronization mechanism adds at most a 7% time overhead to Ez-Channel. The observation here is that while our synchronization technique involves overhead while invoked, it is not triggered very often in real mobility scenarios.

6. Evaluations

In this section, we conduct extensive simulations in order to evaluate the performance of Ez-Channel with respect to network throughput and fairness. Ez-Channel's performance is compared with seven other protocols (all reviewed in Section 2): FICA [3], WiFi-NC [13], REPICK [7], plain 802.11 DCF, 802.11 DCF with packet aggregation as in 802.11n, B-Smart [12], and B-Smart+ (see below). In B-smart, a dedicated control channel is carved out from the given channel for exchanging the protocol information. In B-smart+, we ignore the bandwidth and collision overheads associated with the control channel. We do not consider Back2F [6] as a comparison point because its basic idea has been shown to be substantially outperformed by REPICK [7]. The simulations are carried out over a wide variety of network topologies and show that while Ez-Channel performs at par with the state-of-the-art in some of the simpler scenarios (e.g., all links interfere with one another), it provides a far superior performance in more complex interference scenarios in terms of both network throughput and fairness.

6.1. Simulation methodology

A custom-built, time-driven, discrete event simulator is developed for evaluations. A custom simulator has been deemed convenient as commonly used MAC layer simulators (such as ns2 or ns3, Opnet, and Qualnet) do not provide protocol models of any of the protocols tested other than the plain 802.11 DCF. Modeling a generic OFDM layer, as opposed to specific standards-based OFDM PHY layer, also typically require changes in the physical layer model. Thus, fundamentally, these simulation platforms provide little other than a simulation engine for our purpose. The engine also has its own quirks and interface constraints. The necessary details of the PHY and MAC layers in the custom simulator we have built are described below.

6.1.1. Physical layer models

The OFDM PHY is simulated and the SINR model is used to determine packet reception at receivers. The channel is 160 MHz as supported in 802.11ac. The nodes operate on the 5 GHz band. The transmit power of each node is 100 mW, the noise-level is -91 dBm for the 160 MHz channel, and the carrier-sense threshold is 5 dB. The free-space path loss model is used to model signal propagation. The modulation is QPSK and bit error rate (BER) at receiver is calculated based on the Q-function [1]. BER values determine the probability of correct reception of incoming packets. The PHY data rate in this setting is 256 Mbps.

Since FICA proposes new PHY and MAC schemes for high data rate WLANs, we closely follow the specifications of its PHY as presented in [3]. The rest of the protocols conform to the 802.11ac PHY specifications based on which the 160 MHz channel is composed of 512 sub-carriers. We observed a slight mismatch between the PHY data rates supported by FICA and the other protocols; however, the difference is negligible. The transmit power per active sub-carrier across all nodes is constant, so the transmission range of nodes is independent of the fraction of the channel they use.

6.1.2. MAC layer models

The important aspects of the MAC layer in the simulations are presented here. T_{SIFS} and T_{sub} (slot time) are 16 μs and 9 μs, respectively. These values are the same for both the FICA MAC and the other protocols, and are taken from the 802.11 standard.

The number of clusters in Ez-Channel is set based on the analysis in Section 4.5. T_{data} is set to be enough for sending eight 1500-Byte packets if the entire channel is used, so $T_{data} = 40$ time slots. We found this value to be appropriate via experiments. Based on the sub-channel width of each winning transmitter, the transmitter picks the number of back-to-back packets. For instance, if the transmitter is one of a total of four winning transmitters in the current round of Ez-Channel, it can send at most two 1500-Byte packets.

In order to make conditions favorable for the FICA MAC protocol, we have used FICA's *AIMD* back-off scheme that has been shown to be better than the FICA's *Rmax* back-off scheme [3]. We have examined the 802.11 DCF that operates on the entire wide channel, both with and without RTS/CTS. Both cases perform much worse than Ez-Channel. We only present the results for the case without RTS/CTS, as it is the default option at high data rates due to higher expected throughput [22]. For REPICK, besides following the details provided in [7], we also assume that nodes are always synchronized in terms of rounds without any synchronization overhead. For 802.11 DCF with packet aggregation, a maximum of 16 packets can be sent back-to-back. The control channel in B-Smart is 16 MHz, and nodes can only use discrete channel sizes of 16, 32, 64, and 128 MHz. We do not consider frequency-selective fading, as previous work [6] has shown that it does not hinder frequency-domain contention. These settings hold throughout the simulations unless otherwise noted. All results are averaged over 10 simulation runs.

6.2. Results for three sample scenarios

As the first step, we evaluate the protocols in the three sample scenarios of Fig. 1. Fig. 4a shows the network throughput for the hidden terminal case (Fig. 1a). It can be observed that Ez-Channel achieves a high channel utilization (about 82%). There are three reasons for this. First, the channelization process is based on the receivers' view of the network which results in preventing the hidden terminal problem. Second, the protocol overhead of Ez-Channel is small (roughly $4T_{sub} + 2T_{SIFS}$ in this case). Finally, the channel is divided into two non-overlapping sub-channels each being assigned to one of the links (Fig. 1a).

In this scenario, FICA also splits the wide channel between the two competing transmissions. However, in doing so, it occasionally causes collision on sub-channels, thus, wasting portions of the spectrum for the entire round. In FICA, collisions may occur on the fixed sub-channels when the two transmitters transmit on the same sub-carrier while contending for a given sub-channel. Moreover, FICA occasionally may have idle sub-channels during entire transmission rounds. This happens due to the very nature of FICA's contention process that can leave some sub-channels empty during contention (see [3]). Ez-Channel does not suffer from these issues and achieves a higher channel utilization.

In WiFi-NC with k sub-channels, the 160 MHz channel is divided into k sub-channels of equal sizes. Concurrent transmissions on sub-channels independently execute the 802.11 DCF. As the results show, while WiFi-NC surely provides better throughput than single-channel 802.11 DCF, it still performs significantly worse than Ez-Channel. WiFi-NC suffers from collisions as well as the channel remaining idle due to time-domain back-offs. While not shown here, we observed similar results for WiFi-NC with 16 sub-channels.

For similar reasons as the case of WiFi-NC, 802.11 DCF with packet aggregation achieves a significantly lower network throughput compared with Ez-Channel. Note that, this is despite the large number of aggregated packets (16 1500-Byte packets). If fewer number of packets were aggregated by 802.11 DCF, then even lower throughput would be resulted by this scheme. For comparison purposes, we also show the throughput of 802.11 DCF, where each transmitter sends only one packet every time it gains access to the channel.

While REPICK also adopts a frequency-domain contention scheme, which shortens the contention and acknowledgment periods (each becoming equal to T_{sub}), it performs poorly in this scenario. In fact, it performs close to the plain 802.11 DCF, and Ez-Channel yields a 2.8 times improvement over REPICK. In REPICK, the transmitter contends for the first packet in a sequence of packets. Therefore, the hidden terminal problems cannot always be avoided. The hidden terminal occurs in B-Smart, as it uses 802.11 DCF over its control channel. Finally, B-Smart+, while naturally performs better than B-Smart, faces degraded performance because of using sub-channels of predetermined sizes.

Fig. 4b shows the network throughput for the exposed terminal examples of Fig. 1b. Ez-Channel performs well in this scenario too and achieves a network throughput of around 400 Mbps. This is another example of where Ez-Channel's *adaptive* channelization proves helpful in enhancing network throughput. Note that in the prior case (i.e., hidden terminal), Ez-Channel was able to split the channel into two sub-channels, which was the ideal choice for that scenario. Here, Ez-Channel identifies, in a distributed fashion, that both transmissions should be provided with the entire channel as their sub-channels (Fig. 1b). It can be seen that WiFi-NC and 802.11 with packet aggregation attain much lower throughput values than Ez-Channel because at most one of the two transmitters can transmit at a given time on the same portion of the channel despite the fact that it would harmless if both links were simultaneously active. Note that REPICK's reverse contention mechanism can sometimes cause only one of the senders to transmit at a time which reduces the network throughput. As expected, 802.11 provides the poorest performance in this scenario. Conversely, FICA performs well. However, if the two senders get unsynchronized then FICA's performance could be degraded to half of its current value.

Fig. 4c demonstrates the network throughput for the single collision domain scenario of Fig. 1c. Similar to the previous examples, Ez-Channel performs well in this scenario too. Ez-Channel splits the entire channel into four sub-channels and assigns a separate sub-channel to each link. Even though 802.11 with packet aggregation and WiFi-NC perform close to Ez-Channel, it should be noted that only 4 links are contending in the network. As we will see shortly, the performance of these protocols deteriorate in networks with a larger number of nodes due to collision and back-off overheads.

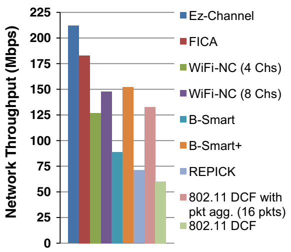
It is clear from the right-hand side of Fig. 1 that Ez-Channel leads to fair utilization of the channel, as the contending nodes gain equal shares of the channel in these three examples. As we will see in Section 6.3, this property of the protocol holds up well in more complex scenarios too.

6.3. Results for random scenarios

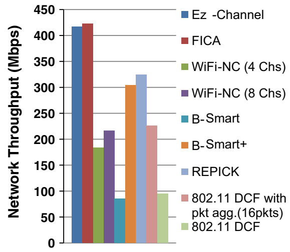
We also evaluate the protocols in random network topologies where we consider both networks with a single and multiple collision domain(s). The following formula is used for evaluating the level of proportional fairness P in the network [23]: $P = \log_2\left(\prod_{l=1}^{L} r_l\right)$, where L is the number of links, and r_l is the total throughput observed for both downlink and uplink flows of link l. A larger value of P indicates a better level of fairness for a given number of links. Note that B-Smart+ is excluded from the fairness evaluations, as its channelization decisions are assumed to be given by an oracle.

In the single collision domain setting, three APs are randomly placed in the network. The number of randomly located clients varies between 2 and 128. Fig. 5a shows the network throughput values. Ez-Channel performs at par with FICA, and both of them perform better than the other protocols. Fig. 5b shows that the high network throughput of Ez-Channel is not an artifact of reduced fairness.

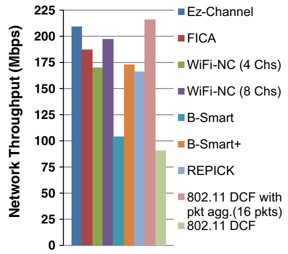
For multiple collision domains, 20 APs are randomly placed within a 250 × 250 m area, and the number of clients in the network is varied from 2 to 128. Fig. 6 demonstrates the network throughput and proportional fairness. Ez-Channel significantly outperforms all other protocols with respect to both metrics. It is interesting that FICA's throughput reduces significantly in multiple collision domains with a larger number of nodes in the network. This is because nodes may encounter constant collisions, unnecessary retransmissions, and starvation in FICA [24]. The comparison points other than FICA face the limitations that are mentioned Section 6.2, namely, collisions, back-off



(a) Results for scenario of Figure 1-a.

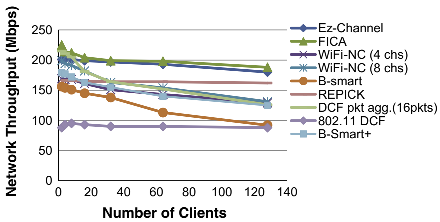


(b) Results for scenario of Figure 1-b.

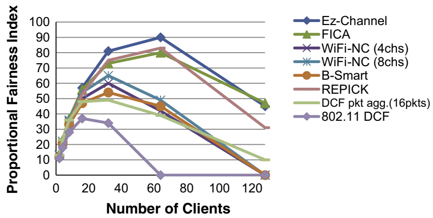


(c) Results for scenario of Figure 1-c.

Fig. 4. Network throughput for sample scenarios of Fig. 1.

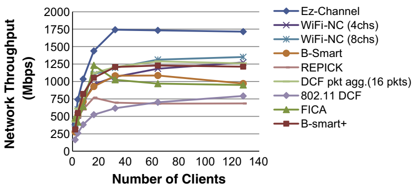


(a) Network throughput in random single collision domain networks.

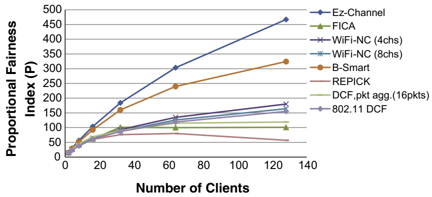


(b) Fairness in random single collision domain networks.

Fig. 5. Evaluations in single collision domain.



(a) Network throughput in multiple collision domains.



(b) Evaluations in multiple collision domains.

Fig. 6. Evaluations in multiple collision domains.

time, the hidden and exposed terminals, and fixed subchannels. It is noteworthy that Ez-Channel successfully handles a large number of nodes because of the low probability of collisions and effective channelization.

7. Conclusions

We introduce Ez-Channel, a MAC protocol for channelization in wireless networks. It is distributed and adaptive to changes in the network. Ez-Channel uses OFDM subcarriers to parsimoniously exchange the information needed by network nodes to make channelization decisions locally. It circumvents both hidden and exposed terminal problems. Mathematical analysis as well as simulation studies show that Ez-Channel outperforms the state-of-the-art MAC protocols in realistic settings of high-speed networks. Moreover, the in-band (stage) synchronization mechanism for infrastructure-less networks that we propose is independently applicable to existing frequency-domain MAC protocols.

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