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

Seyed K. Fayaz [a,*], Fatima Zarinni [b], Samir Das [b]

[a] Carnegie Mellon University, United States
[b] Stony Brook University, United States

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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

* Corresponding author.
E-mail address: seyed@cmu.edu (S.K. Fayaz).

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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.