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Polarization-based cooperative directional MAC protocol for ad hoc networks

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ABSTRACT

Numerous directional medium access control (DMAC) protocols have been developed to enhance the capacity of ad hoc networks using the underlying advanced physical layer techniques, such as beam-forming, multiuser detection (MUD), and multiple-input–multiple-output (MIMO). In this paper, we propose an innovative fully distributed DMAC protocol that cooperatively makes use of polarization diversity in low-mobility urban/suburban outdoor wireless ad hoc network environment. In the proposed cooperative polarization DMAC protocol (CPDMAC), each node directionally senses on both vertical and horizontal polarizations and dynamically adapts polarization that minimizes overall interference in the ad hoc network. Analysis is performed to establish relationship between vertically and horizontally polarized nodes in the network. Further, a theoretical lower bound is derived for probability of successful transmission to show capacity improvement as a function of cross polarization ratio (*CPR*). Simulation results confirm from 2% up to 400% improvement in average node throughput at data rate of 1.95 Mbps when compared to the traditional DMAC protocol. Moreover, our study clearly shows that the average throughput difference increases with increasing node density when compared to the traditional DMAC protocol.

1. Introduction

Performance enhancement in wireless ad hoc network poses unique challenges due to lack of central controller (distributed behavior), scarce channel resource, random interference characteristics, and dynamic topology [1] (see Chapters 1–6). The core medium access control (MAC) protocol in ad hoc network is primarily derived from the IEEE 802.11 distributed coordination function (DCF) protocol. The DCF heavily relies on physical and virtual carrier sensing, four-way handshaking and back-off mechanisms to minimize random channel contentions, reduce redundant signaling, and improve performance [2,3]. Over the last decade, researchers have made significant strides in performance improvement by modification of the core DCF protocol to harness advances in physical layer techniques. For example, techniques such as, beam-forming, multiple-input–multiple-output (MIMO), multiuser detection (MUD), multichannel configuration, and orthogonal frequency division multiplexing (OFDM) have been proposed with modifications to the DCF protocol for throughput improvement in wireless ad hoc networks [4–8].

It is well known that random contentions among omnidirectional nodes in distributed wireless ad hoc network significantly limit the throughput performance. In general, directional antennas can enhance network capacity (throughput) with narrow beam-width that reduces co-channel interference among contending nodes and increases effective spatial reuse [4,9–15]. However, directional beam-forming approach has also led to a set of problems; such as deafness, ready-to-send

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(RTS)/clear-to-send (CTS) collisions, hidden terminal due to unheard RTS/CTS, and destination discovery [12,13]. All the aforementioned problems lead to increased interference and bandwidth wastage. Studies have confirmed that if the destination location is known then for the traditional DMAC protocol about 80% of the failure rate is attributed to the deafness problem, whereas 15–20% is due to RTS/CTS collisions [12,13,16]. As such, recently there has been a considerable research focus on providing various solutions to deafness and destination discovery problems to improve network throughput performance [8,13,16–18]. Further, power control techniques proposed to mitigate RTS/CTS collisions and enhance spatial reuse are based on interference prediction assumption, temporal correlation, and heavy signaling which render such techniques as infeasible and too complex [24–26]. In essence, most of the solutions proposed for directional communication problems are based on many assumptions, entail heavy signaling and lack compatibility with each other (see Section 2).

Certain outdoor rescue and security applications require ad hoc networks to operate in dense (with contending nodes in close proximity of each other) and heavy load conditions, where throughput performance severely degrades due to limited spatial reuse and increased interference. For such applications, we propose a fully distributed asynchronous cooperative polarization-based DMAC protocol (termed CPDMAC) that minimizes interference without any additional signaling and easily integrates with the other DMAC protocols. In CPDMAC, a sender uses directional sensing to sense on both horizontal and vertical polarizations and chooses polarization channel that is free based on the receiver power threshold. This geographically interleaves (or isolates) similar polarizations, which in turn minimizes cumulative co-channel interference in a given sender–receiver direction. This increases the probability of successful transmission which leads to increased average throughput in the network. To the best of our knowledge polarization adaptation in a completely distributed and cooperative manner for asynchronous DMAC protocol has not been pursued so far. In addition, with respect to CPDMAC protocol, our contributions also include polarization based average interference analysis for directional ad hoc network, derivation of node relationship under polarization diversity that shows capacity improvement, derivation of lower bound for the probability of success and throughput analysis.

2. Literature review

In this section, we present a brief survey of some research work done to improve performance of wireless ad hoc network.

One such seminal contribution towards ad hoc performance improvement has been the development of the directional MAC (DMAC) protocol that makes use of directional beam-forming to reduce co-channel interference, and allows multiple concurrent sessions [4,9–15]. In [17], circular transmission of RTS and CTS control packets (termed as CRCM) in all directions (360° span) to notify all the nodes was proposed. However, it introduces excess control overhead that affects throughput performance. In [16], author proposed a directional MAC with deafness avoidance (DMAC/DA) as a modification to [17] by selectively transmitting wait-to-send (WTS) frames only to the potential deaf nodes. In another version, receiver-initiated directional MAC (RI-DMAC) was proposed where sender and receiver node polls the potential transmitter after the completion of every dialog. However, it was not clearly shown as to how a node can predict the potential transmitting nodes. Throughput and packet drop ratio performance was shown to improve significantly compared to [17]. In [8] authors proposed that CRCM cannot completely eradicate the deafness problem, as some nodes are busy when the RTS/CTS broadcast takes place. A combination of node cooperation and multiuser detection technique (MUD) to eliminate deaf nodes in the network was proposed. Throughput and energy consumption was shown to improve when compared to [17].

Another common approach proposed for interference avoidance in ad hoc networks is the multichannel technique. Although, most multichannel schemes are primarily designed for omni-directional MAC, however to some extent they can be adapted for the DMAC protocol. A few papers that propose omni-directional MAC protocol with two or more channels to minimize interference, are briefly discussed hereafter [19–23]. In [19] authors proposed a multichannel CSMA protocol. It assumes that a node can concurrently listen on all the channels (requires multiple transceivers). When a node wants to transmit, it first checks the last successfully used channel for idleness and then transmits on it. If that channel is not idle, a different idle channel is picked for transmission. In [20] authors proposed single-transceiver multiple channel MAC, but with temporal synchronization to avoid multiple channel hidden node problem. Dual busy tone multiple access (DBTMA) uses two channels. One channel is used for tone transmission, where as the other channel is used for data transmission to avoid hidden terminal problem [21]. In [22,23] authors proposed single control channel and multiple data channel protocol with two transceivers. A node concurrently listens on a control channel and on any one data channel that is negotiated dynamically.

Power control is also extensively explored as interference reduction technique in DMAC protocol. In [24], simple power control for DMAC was proposed which showed significant improvement in energy consumption and throughput performance. In [25] authors proposed a distributed power control scheme for DMAC based on temporal correlations and interference prediction that improved average throughput compared to DMAC by 48%. In [26], power controlled DMAC was proposed. In this scheme the RTS and CTS packets are sent with maximum power, but the data packets are transmitted with power control to minimize interference to other nodes. However, note that RTS/CTS packet transmitted at maximum power is likely to cause collision with ongoing data transmission due to power asymmetry. It is worth mentioning that for effective power control adaptation many proposed algorithms require complete interference information from the neighboring and the receiver nodes. In single channel