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Directional random access scheme for mobile ad hoc networking using beamforming antennas

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Abstract

It has been proposed to upgrade the performance of medium access control (MAC) schemes through the use of beamforming directional antennas, to achieve better power and bandwidth utilization. In this paper, we consider a shared wireless medium as employed in a mobile ad hoc wireless network. We present and analyze a random access MAC algorithm that is combined with the use of directional beamforming formed by each transmitting mobile entity. Mathematical equations are derived to characterize the throughput performance of such a directional-ALOHA (D-ALOHA) algorithm. We describe the interferences occurring at each receiving node by considering both distance based and SINR based interference models. The D-ALOHA protocol includes the establishment of a (in-band or out-of-band) control sub-channel that is used for the transmission of location update messages. The latter is used for allowing mobile nodes to track the location of their intended destination mobiles. We present a separation property result that allows us to express the network throughput performance as a product of two factors: (1) a stationary factor that represents the system throughput performance under a perfect receiver location update process, and (2) a mobility factor that embeds the user mobility and location update processes in expressing the level of throughput degradation caused due to location update errors. We employ our derived mathematical equations, as well as carry out simulation evaluations, to present an extensive set of performance results. The throughput performance of such a beamforming based MAC protocol is characterized in terms of the system's traffic loading conditions, the selected beamwidths of the antennas at the transmitting mobiles, the mobility levels of the nodal entities and the bandwidth capacity allocated to the control channel used for location update purposes. We show that the D-ALOHA protocol can provide a significant upgrade of network performance when the transmitting nodes adapt their beamwidth levels in accordance with our presented control scheme. The latter incorporates the involved tradeoff between the attained higher potential spatial reuse factors and the realized higher destination pointing process errors, and consequently uses nodal mobility levels and channel loading conditions as key parameters.

Keywords: MANET; Beamforming; Directional antenna; Random access; Location tracking

1. Introduction

In wireless communications, the fact that omnidirectional antennas spread out energy universally

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is one of the major causes of radio interferences and energy use inefficiencies. The use of directional antennas can reduce the occurrence rate of such interferences. It has been proposed to upgrade the performance of medium access control (MAC) layer schemes through the use of directional antennas, to achieve better power and bandwidth utilization [9,13]. However, the superior capabilities of smart antennas can be fully exploited only through the implementation of appropriately designed MAC schemes. The design of such an effective MAC protocol plays a prominent role in realizing the efficient utilization of the scarce physical assets of the wireless network, including bandwidth and energy resources. We present and analyze in this paper a random access MAC algorithm that is combined with the use of directional beamforming formed by each transmitting mobile entity as the basis for MAC schemes employed by entities that share multiple access radio channels through the use of properly configured directional antennas.

MAC schemes specialized for use with directional antennas have been well-studied in the context of extending the IEEE 802.11 CSMA/CA (Carrier Sensing Multiple Access with Collision Avoidance) MAC protocol in [1,2,10,17,18,14]. In [10], switched beam antennas are considered and a RTS–CTS-DATA-ACK exchange similar to that used in an IEEE 802.11 system is applied, but on a per-antenna basis. Signals are transmitted directionally according to predetermined physical location information and are received omni-directionally. In [14], steered beam directional antennas are considered and reception directionality is utilized. The paper presents "directional NAV" (DNAV) and a multi-hop RTS scheme to exploit the extended transmission range enabled by the use of directional antennas. A directional NAV scheme is also proposed in [17]. A transmission that is aimed in a direction of a received RTS or CTS is deferred. The work in [17] employs a scheme that caches Angle of Arrival (AoA) information to form antenna directionality. This scheme falls back to omni-directional mode only when the AoA profile is not available, and is identified as Directional Virtual Carrie Sensing (DVCS). In [2], it is proposed to utilize switched multi-beam antenna capability to locate the position of each link's end-node and establish communication pairs by sending RTS and CTS packets through the use of an omni-directional antenna. Power controlled directional MAC schemes have been studied in [1].

In [19], the employment of busy tones on separate channels in conjunction with the use of directional antennas is suggested to minimize transmission interference. Several studies have been performed to examine TDMA-based mechanisms using directional antenna. In [6], the study assumes the use of a multi-beam adaptive array (MBAA) capable system. A distributed algorithm is analyzed under which two-hop state information is gathered and used to schedule simultaneous transmissions, by multiple senders to multiple neighbors, on a slot-by-slot basis. In [16], a multi-layer system design that involves MAC and network layer mechanisms using directional antennas for ad hoc networking (UDAAN) is developed and evaluated based on an implemented testbed. In [26], a TDMA based scheduling scheme is presented for entities that employ directional antenna beams for both transmission and reception purposes.

It has been known [30] that the ratio of the propagation delay (and other channel acquisition factors) to the packet transmission time, identified as the acquisition factor, has to be sufficiently low for carrier sensing to become effective and for CSMA-type protocols to outperform (slotted and unslotted) random access MAC schemes ([12]). Therefore, for long range and/or high data rate wireless communication systems (for example, Wireless MANs), the medium access design choices come down to either Demand-Assigned based (TDMA, FDMA, or CDMA), or Random Access algorithms. The latter protocols are often used when operational simplicity is of critical design importance or when the medium is shared among a large number of bursty users, or when it is essential to have a highly survivable fully distributed MAC scheme. For the reasons mentioned above, random access protocols are universally employed for the realization of reservation multiple access communications channel systems. Thus, when Demand-Assigned MAC schemes are employed in wireless network systems (for example, cellular systems), random access schemes are used for regulating access across reservation/control sub-channels. Reviewing the literature, we note that the work in [5] investigates the use of directional antennas in slotted Aloha multihop packet radio networks. The studies presented in [3,4], involve the use of a basic ALOHA MAC protocol system with users employing omni-directional antennas, to transmit their messages to a central node that uses a radio receiver attached to an adaptive array antenna. In [15], an analysis is given of the 'single hop progress'