Computer Communications 72 (2015) 116–129

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

An intelligent hybrid spread spectrum MAC for interference management in mobile ad hoc networks

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ARTICLE INFO

Article history:
Received 8 August 2014
Revised 26 December 2014
Accepted 27 April 2015
Available online 28 May 2015

Keywords:
Medium access control
Ad hoc networks
Transmission capacity
Frequency hopping
Direct sequence spread spectrum

ABSTRACT

This paper presents and analyses a fully distributive intelligent hybrid spread spectrum MAC for ad hoc networks. The IHSS MAC scheme has been developed with the aim to mitigate far field interference with the use of a robust DSSS physical layer, while managing near field interference with the use of intelligent slow frequency hopping. The IHSS design ensures a minimum required SINR threshold at active receivers, under low outage probability constraints. IHSS does not inhibit any nodes in space neither thins them out in time. A lower bound on transmission capacity for the case where the size of the frequency hopping zone is variable is derived in this paper. The mathematical model is validated through simulation. The simulation is based on a hopping sequence selection methodology that randomizes the available hopping sequences within a frequency hopping zone around each active receiver. The implementation utilises the RTS/CTS concept of the CSMA MAC, with a slight modification. The performance criterion used for analysis is transmission capacity normalized by the required bandwidth. It is observed that implementation of a suitable sized frequency hopping zone using the proposed IHSS MAC, shows superior performance over ALOHA and guard zone based MACs.

1. Introduction

Absence of a central controlling authority and infrastructure is a characteristic feature of ad hoc networks. Consequently, control and management functions are distributed amongst nodes throughout the network. The research on wireless ad hoc networks is fuelled by the fact that these networks represent the most general type of wireless networks. Almost all other types of networks, including cellular, sensor, vehicular, relay, etc. can be treated as sub types of MANETs. While the idea of forming networks 'on the fly' is attractive, it also poses some formidable challenges to design optimization and analysis.

Requirements of data rate and round the clock connectivity are increasing every day. Complex and dynamic networks, such as vehicular ad hoc networks (VANETs), require increased data rates, improved connectivity and efficient interference mitigation under dense node conditions.

Addressing the challenges of connectivity and resource availability requires efficient routing and medium access control (MAC) [1,2]. Efficient MAC mitigates interference and improves resource availability.

Compared to cellular networks, interference in a complex and dynamic ad hoc network cannot be managed in a centralized manner. If interference management is not performed efficiently in a distributed network, the signal to interference plus noise (SINR) falls below the required threshold. This results in an increase in outages. Medium access control (MAC) design is an important factor for managing interference efficiently.

An efficient MAC must be designed in a way such that:

1. Its implementation is simple in a distributed network.
2. Probability of outages is upper bounded by a small number through effective interference management.
3. The scarce resources (time, space and spectrum) are utilised efficiently.

Most MAC schemes achieve the first two design considerations through inhibiting or suppressing some of the active nodes in time, space, frequency or codes. A few surveys [3,4] provide insights into the MAC schemes for ad hoc networks. Examples include ALOHA [5,6] spread spectrum CDMA [7], TDMA/FDMA [8], directional MAC [9], etc.

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http://dx.doi.org/10.1016/j.comcom.2015.04.006
0140-3664/

Spatial reuse of frequency channels is one methodology for addressing the third MAC design consideration. In narrowband systems, reused frequency channels must be assigned to spatially separated locations to mitigate the interference caused by co-located (in both space and spectrum) frequency channels. However wideband spread spectrum physical layers provide interference averaging. This inherently increases the spatial reuse. Though the reused frequency channels cannot be exactly co-located (for reasonable spreading gains of the spread spectrum physical layer), the spatial separation between them can be much lesser. Achieving a high spatial reuse while ensuring that interference is managed efficiently is a challenging goal. Transmission capacity is a concept that determines utilisation of space at a certain time while upper bounding the outage probability. Spatial or temporal thinning might be required which limits the transmission capacity of the network [10].

Transmission capacity is defined as the intensity of simultaneous and successful transmissions [11–13]. The usefulness of the concept of transmission capacity lies in its tractability, easy computation and relationship with throughput [11]. In an average sense, if all nodes transmit at the same data rate, transmission capacity can be used directly to compute the network throughput. It is well known that medium access control (MAC) plays a key role in optimizing the transmission capacity of ad hoc networks [11,12].

If we look at the existing MAC approaches, the simplest one, ALOHA, and slotted ALOHA, do not guarantee a low outage probability. On the other hand, direct sequence spread spectrum (DSSS)shows suboptimal performance as spreading gain increases, in terms of normalized transmission capacity [14]. Approaches like CSMA and other guard zones based schemes are inhibitive in nature. They limit the transmissions in the near vicinity of active nodes for safeguarding the nodes' transmissions, and thus limiting the number of simultaneous transmissions. [15–17]. This will be discussed in detail in Section 2.

A novel medium access control (MAC) approach utilising a cross layer hybrid spread spectrum system, called intelligent hybrid spread spectrum (IHSS) was presented in [18]. The proposed IHSS approach for medium access control aims at improving the transmission capacity of ad hoc networks above the existing schemes. The strength of the proposed scheme lies in the fact that no node has to abstain from transmission at any given instance of time, while also fulfilling an outage probability constraint. By using a hybrid of DSSS and slow frequency hopping (SFH), the requirements of improved transmission capacity, outage probability and simplicity of implementation can be met simultaneously by the proposed IHSS MAC. This scheme is a cross-layer design. As opposed to the proposed MAC design that utilises a DSSS PHY layer and a FH-CDMA MAC layer, all the existing hybrid spread spectrum schemes are physical layer modulation techniques aimed at improving the bite error rate (BER) performance of the network [19,20].

The rest of the paper is structured as follows: Section 2 presents a review of commonly used MAC schemes. Section 3 outlines the proposed IHSS MAC scheme. Section 4 provides a theoretical analysis of the proposed IHSS MAC and compares its performance with existing MAC approaches. Section 5 presents insights into implementation. Section 6 shows simulation results and proves the validity of the theoretical model. It also explains the effect of mobility on the performance of the IHSS MAC. Section 7 concludes the paper and points out the future research goals.

2. Existing MAC approaches

An efficient MAC scheme ensures that every node could transmit whenever it requires sending some data. At the same time, a large proportion of transmission efforts should be successful, especially for delay sensitive and energy efficient networks. A failed effort, also known as an outage, causes an increase in contention rate, and leads to drop in overall network throughput. It also causes wastage of power and time used for transmission.

A successful transmission is ensured by eliminating all interferers falling inside the contention domain of the receiver. This elimination guarantees that the signal to interference plus noise ratio (SINR) at the receiver is above a minimum required threshold. The elimination of interferers creates empty spheres (exclusion zones), that do not contain any interferers, around each receiver. The size of the spheres is inversely proportional to the number of simultaneous transmissions in any given area (also known as transmission capacity). An efficient MAC scheme tries to improve the transmission capacity by reducing the size of the spheres and packing them closely and tightly [21].

With the inception of ad hoc network concept, ALOHA and its variants were considered attractive options, due to their ease of implementation in a distributed network. Nelson conducted the first study of ALOHA's performance in a multi-hop network by considering a finite number of nodes within two hops [22]. By using the concept of spatial reuse, Ghez et al. defined the ALOHA based model for an infinite network [23].

In simple ALOHA, any node which has data to send, can transmit without any restriction. If a collision occurs, the colliding nodes wait a random amount of time and retransmit the destroyed packets. The work of Baccelli et al. [5] investigates the ALOHA MAC design for ad hoc networks with randomly distributed nodes. Their work captures the spatial distribution that is enforced through the use of p-persistent ALOHA MAC. In p-persistent schemes, when a node has a data to send, it accesses the channel with a certain medium access probability (MAP) p. Such an approach is ideal from an implementation perspective in ad hoc networks. It does not require any coordination in a distributed topology.

Baccelli et al. also proved that the medium access probability p determines the size of a random exclusion zone around each node. The mean radius of the exclusion zone is proportional to $\frac{1}{\sqrt{p}}$. They showed that by fine tuning the MAP for maximizing the intensity of successful transmissions, the outage probability goes as high as 0.63.

Weber et al. found the transmission capacity of uniformly distributed random nodes for an ALOHA-like MAC [12] using the probability distribution function of aggregate interference at a typical receiver [24]. They also showed that the capacity is primarily limited by the nearest interfering node.

The idea to use spread spectrum techniques for ad hoc networks has also been proposed by the researchers. In [10], the authors have pointed out the desirability of using spread spectrum techniques at the physical layer of ad hoc networks. Spread spectrum techniques inherently provide better security and protection against interference.

The two spread spectrum techniques commonly considered suitable for ad hoc networks are frequency hopped spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). By dividing the bandwidth into M sub-channels, FHSS results into thinning of interferers on a certain band. On the other hand, in DSSS, the spreading and despreading of the signal reduces the SINR requirement by M [10]. In [14] the authors find the achievable transmission capacity using ALOHA in networks with spread spectrum physical layer.

Carrier sense multiple access (CSMA) [23] is a very popular MAC protocol for wireless ad hoc networks. Concept of medium sensing and random back-off minimizes the probability of simultaneous transmission of any two nodes within each other's contention domain.

To avoid the hidden node problem in CSMA [25], the IEEE 802.11 [26] standard uses RTS/CTS (request to send) packet exchange in CSMA/collision avoidance (CA). This has the effect of creating guard zones around both transmitters and receivers in the same time slot. Guard zone is defined as an area around an active node, where all interfering transmissions are inhibited [15–17]. Contrary to the approach used in CSMA, only the receiver is required to be protected