Computer Communications 56 (2015) 89–97

Contents lists available at ScienceDirect

Computer Communications

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

Guard zone-based scheduling in ad hoc networks

Aamir Hasan [a], Ahsan Ali [b,*]

[a] Institute of Avionics and Aeronautics, Air University, Islamabad, Pakistan
[b] Center for Advance Studies in Engineering (CASE), Islamabad, Pakistan

ARTICLE INFO

Article history:
Received 3 July 2013
Received in revised form 1 April 2014
Accepted 21 November 2014
Available online 27 November 2014

Keywords:
Ad hoc networks
Capacity
Stochastic geometry

ABSTRACT

Scheduling algorithms in ad hoc networks allow nodes to share the wireless channel so that concurrent transmissions can be decoded successfully. On one hand, scheduling needs to be efficient to maximize spatial reuse and minimize retransmissions due to collisions. But on the other hand, the scheduling algorithm needs to be easily implementable in a distributed fashion with little, if any, coordination with other nodes in the network.

In this paper we propose and evaluate a simple scheduling technique that suppresses transmissions by nodes around the desired receiver. Using stochastic geometry, we derive a near-optimal *guard zone* which can be easily realized in a distributed manner, and exhibits about a 2–40 fold increase in capacity compared to ALOHA; the capacity increase depending primarily on the required outage probability and node density. The capacity loss is about 15–25% compared to a well-known near-optimal centralized scheme. In contrast to centralized scheduling (which is highly impractical), our scheme lends itself to distributed implementation and also protects active links. Our derivations cleanly capture how the optimal guard zone size varies with different network parameters like path loss, outage, spreading gain, and node density, and we show how these results can be used to provide protocol design guidelines.

1. Introduction

The inherent flexibility of wireless ad hoc networks is a highly desirable attribute for various emerging applications and for extending the range and capacity of infrastructure-based wireless networks. Exploring the capacity of wireless ad hoc networks has been a key area of investigation [1–4] which deals with finding the fundamental limits on achievable communication rates.

The multiple access and anti-multipath properties of spread spectrum have long been considered to make Code Division Multiple Access (CDMA) desirable at the physical layer of ad hoc networks [5]. Since ad hoc networks are inherently interference limited, there has been growing interest in using direct sequence CDMA (DS-CDMA) to relax interference requirements and improve spatial reuse [6–11]. However, the advantages of employing DS-CDMA seen in interference limited cellular networks [12] are yet to be proven in a multihop ad hoc setting. In fact, the capacity of wireless ad hoc networks employing DS-CDMA scales sub-linearly with the spreading gain as shown in [13]. Therefore, considering only capacity, the increase in bandwidth in DS-CDMA as compared to a narrow band system is not justified.

In this paper we investigate an optimal guard zone, defined as the region around a receiver where transmissions are inhibited, which allows efficient sharing of the wireless channel. We demonstrate that the guard zone can be realized in a simple manner especially in DS-CDMA networks, yet provide a large gain in capacity compared to networks where no scheduling is employed. The performance of the proposed scheme has also been compared to highly complex, near-optimal, and ultimately infeasible centralized schemes.

1.1. Related work: the need for guard zone-based scheduling

The scheduling problem in ad hoc networks is motivated by the requirement that the wireless channel be shared. The way this sharing is implemented has serious implications since it affects the major performance measures (end-to-end delay, outage, throughput, power levels) of the network.

The work of Baccelli et al. [14] employs a stochastic geometric model to investigate optimal scheduling in ad hoc networks. By realizing a random exclusion zone around each node, they propose a distributed medium access control (MAC) protocol that maximizes spatial reuse at the cost of an increased number of

* Corresponding author.
E-mail addresses: ahasan-cae@nust.edu.pk (A. Hasan), ahsan_ali_004@hotmail.com (A. Ali).

http://dx.doi.org/10.1016/j.comcom.2014.11.004
0140-3664/

unsuccessful transmissions (>50%) thus resulting in poor energy efficiency. In [11] no effort has been made to determine how good the proposed scheduling mechanism is in terms of spatial reuse or its ability to provide link protection as subsequent links are scheduled. A multistage contention protocol to realize spatial packing was implemented in a distributed fashion in [15] which achieves close-to optimal performance. However, the model assumes fixed transmission distances with no power control.

MAC protocols in IEEE 802.11 wireless networks [16] enable simultaneous transmissions by employing the carrier sense multiple access (CSMA) mechanism. The basic idea of carrier sense is that transmitters listen to the physical medium to detect any ongoing transmissions. If no nearby node is transmitting, the sender begins its transmission, else it defers transmission and contends for the channel again after some time. Therefore, scheduling transmissions using the CSMA mechanism ensures spatial separation among concurrent transmissions. The optimal carrier sense threshold that maximizes spatial reuse given a minimum required Signal to Interference plus Noise Ratio (SINR) was derived in [17] for regular topology and in [18] for random networks.

In contrast to the carrier sense mechanism, the proposed guard zone-based scheduling allows two nearby transmitters to transmit simultaneously as long as they do not violate the guard zone criteria. An important problem with CSMA is that it inhibits potential transmissions around an active transmitter, whereas transmissions need to be inhibited only around the active receiver. Two additional problems in carrier sense are, first, that potential interferers do not know how long to back-off as control packets cannot be decoded for nodes that are both outside the transmission range of the receiver *and* within the interference range. Second, and more importantly, carrier sensing suppresses nodes that are closer to the transmitter and not the potential interferers around the receiver. Therefore, nodes within the interference range of a receiver would eventually transmit if they are beyond the carrier sensing range of the transmitter.

A scheduling algorithm assuming global knowledge of the channel gains between every pair of nodes was proposed in [19], along with a power control algorithm, that guarantees optimal power assignment for the scheduled subset of transmissions. Although the proposed scheme is near-optimal and provides a good performance comparison to other practical algorithms, which are sub-optimal, it has two obvious short-comings.

- Such a scheme is impractical to implement in a wireless ad hoc network due to the requirement for global real-time channel state information (CSI),
- Incorporating tight power control limits the ability of the scheduling mechanism to add additional links.

This motivates the pursuit of a scheduling scheme that can get close to the global CSI case in terms of area spectral efficiency, while enabling the simple addition of links.

1.2. Main result

In this paper the effect of spatial separation among concurrent transmissions on the network capacity is studied. A scheme is proposed that enforces spatial separation among concurrent transmissions by incorporating a guard zone around active receivers where transmitters (other than the intended transmitter) are inhibited. A close to optimal guard zone, which maximizes spatial reuse, is derived which is simple to implement and well suited to a DS-CDMA physical layer. We demonstrate that the guard zone provides a huge improvement in capacity as compared to networks where no scheduling is employed. The improvement is drastic for dense networks especially under strict outage constraints. By implementing guard zone-based scheduling, we show that new links can be admitted sequentially and the attained performance comes close to a highly-complex, near-optimal, and ultimately infeasible centralized scheme.

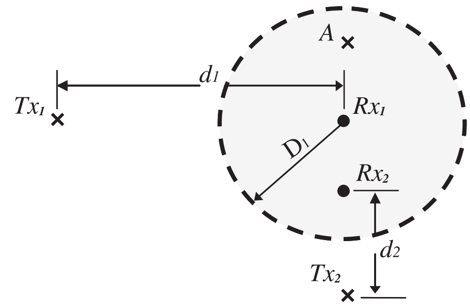

Fig. 1. Example of guard zone in a simple network. The guard zone around receiver Rx_1 inhibits node A from transmitting while Tx_2 may transmit concurrently to receiver Rx_2.

The derived results cleanly capture the variation in the optimal guard zone size under different network parameters like path loss α, spreading gain M, outage probability ϵ, and node density λ. A significant advantage of DS-CDMA is its ability to reduce the required guard zone size, with decrease on the order of $M^{\frac{-1}{\alpha}}$, that can even be smaller than the transmission range. This helps in implementing efficient scheduling and also eliminates the hidden node problem in ad hoc networks. Although the proposed scheme is sub-optimal both in terms of spatial reuse and energy efficiency, its simplicity lends itself to distributed implementation. Also, unlike centralized scheduling schemes where addition of new link initiates a global search, the proposed scheme admits new links without affecting the viability of active links.

2. Guard zone-based scheduling

Since ad hoc network capacity is inherently interference-limited, it is natural to explore mechanisms for reducing the interference. In [20] most of the capacity improvement through interference cancelation is obtained via canceling only the closest interferer, which suggests that the interference from a few nearby transmissions constitutes nearly all of the aggregate interference at a receiver. Therefore, an appropriate sized guard zone that suppresses close-by transmissions might also improve spatial reuse. Employing a guard zone of size $b(O,D)$[1] around each receiver helps limit the aggregate interference by inhibiting the nearby dominant interferers. Appropriately choosing the guard zone size is critical in order to maximize spatial reuse [21] since the guard zone also restricts the freedom of transmission of nodes within the disc $b(O,D)$. Consider the simple example shown in Fig. 1 where receiver Rx_1 is communicating with its transmitter Tx_1 at a distance d_1. Enforcing a guard zone of size $b(O,D_1)$ around Rx_1 inhibits node A from transmitting simultaneously while Tx_2, assuming it is outside every receiver's guard zone, may concurrently communicate with node Rx_2 despite the fact that Rx_2 is well within Rx_1's guard zone.

In general not all the receivers experience similar aggregate interference, especially when power control is employed. This implies that the guard zone size around each receiver should be individually chosen to maximize spatial reuse. The motivation for a fixed system-wide guard zone is to allow the scheduling algorithm to be realized in a simple distributed manner and to eliminate the need to monitor and exchange the interference conditions at each node. Therefore, we investigate a fixed system-wide

[1] A ball of radius $D > 0$ centered at origin O, i.e. the set $b(O,D) = \{x : |x| \leqslant D\}$, with slight abuse of notation, $b(O,D)$ around a receiver i implies a ball of radius D centered at receiver i.