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Performance analysis of CSMA/CA protocols with multi-packet transmission

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ABSTRACT

Wireless objects equipped with multiple antennas are able to simultaneously transmit multiple packets by exploiting the channel's spatial dimensions. In this paper, we study the benefits of such Multiple Packet Transmission (MPT) approach, when it is used in combination with a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol for fully interconnected networks, addressing the interactions between the two mechanisms and showing the performance gains that can be achieved. To this end, a very simple Media Access Control (MAC) protocol that captures the fundamental properties and trade-offs of a CSMA/CA channel access protocol supporting MPT is introduced. Using this protocol as a reference, a new analytical model is presented for the case of non-saturated traffic sources with finite buffer space. Simulation results show that the analytical model is able to accurately characterize the steady-state behavior of the reference protocol for different number of antennas and different traffic loads, providing a useful tool for understanding the performance gains achieved by MAC protocols supporting MPT.

1. Introduction

MIMO techniques allow for a more efficient use of transmission resources by making the channel's spatial dimension available, using simple and effective signal processing techniques [1]. This new spatial dimension can be used to enhance coverage and reliability (spatial diversity) or to boost the system throughput (spatial multiplexing) [2]. In this paper, we will focus on the spatial multiplexing feature, which can be used to transmit multiple packets at the same time, referred to as Multi-Packet Transmission (MPT). MPT by using Spatial Multiplexing can be seen as a packet-based extension of the Space Division Multiple Access (SDMA) or Multi-user MIMO concepts [3].

Although the benefits and drawbacks of MPT in point to point links are well-known, there is still a lack of results focusing on the new challenges and benefits that can arise by combining MPT capabilities with random-access MAC protocols. On the one hand, using MPT will reduce the number of transmission attempts and therefore decrease the collision probability in a contention scenario. On the other hand, in order to make the MPT work properly, the MAC protocol needs to be modified, at the expense of some extra temporal overhead, e.g., to include the necessary procedures for estimating the channel state between the transmitter and each receiver, required for isolating the different spatial streams, or to feed the CSI (Channel State Information) back to the transmitter when necessary. There will also be a need for extra acknowledgments to confirm the reception of all spatial streams. The negative impact of the extra temporal overhead imposed by these modifications on the system performance needs to be quantified and contrasted with the performance boost gained by enabling the simultaneous transmission of multiple packets.

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This paper intends to provide insight on the interactions between CSMA/CA random access MAC protocols and the MPT scheme. We study and characterize these interactions by introducing a basic MAC protocol that combines these mechanisms and includes all the required features to make it work properly. The performance of the overall system is evaluated using an analytical model, whose accuracy is validated using simulations. The applied analysis strategy and the resulting model are general enough to provide deep insight into the analysis of any CSMA/CA MAC protocol with MPT capabilities.

In this context, the main contribution of this paper is to present a queueing model for wireless objects with MPT capabilities using a CSMA/CA protocol for channel access. We show that the considered approach provides a suitable path to modeling packet-based, multiple-antenna access protocols in non-saturation conditions. The presented results confirm the accuracy of the presented model and show the performance benefits of such protocols, as well as providing insights on how the system parameters have to be configured in order to achieve better performance gains.

CSMA/CA-based MAC protocols with MPT capability have been recently considered for WLANs due to their ability to improve the network performance, while keeping both the simplicity and the efficiency that random access MAC protocols possess [4,5]. In addition, the upcoming appearance of the IEEE 802.11ac amendment for WLANs [6], which only enhances the Access Points with the MPT capability, is also pushing in that direction.

In [4], a MAC protocol for WLANs supporting MPT at the Access Point (AP) is presented. The RTS/CTS handshake procedure is extended to both coordinate the transmission of multiple packets from the AP to different STAs, and to provide the AP with the required CSI. An analytical model of the presented protocol in non-saturation conditions is introduced, although the authors only focus on the MAC performance, as queueing is not included in the model, hence not allowing for metrics such as average waiting delay per packet or the packet-loss probability due to buffer overflow to be computed. In [5], the performance of MPT in the downlink for the upcoming IEEE 802.11ac standard is evaluated. An accurate physical-layer and channel model is provided when a zero-forcing precoding scheme [3] is used to create the multiple spatial streams. To evaluate the system performance, an analytical model in saturation conditions is presented, where it is assumed that the AP can always transmit as many packets as the number of antennas it has, thus also not considering the queueing dynamics.

However, MPT can be also applied to a wider set of scenarios in which the use of CSMA/CA MAC protocols is common, such as in Wireless Multimedia Sensor Networks that may have high bandwidth demands to transmit audio and video signals [7], in cluster-based Wireless Networks [8], to enhance the cluster-head capabilities to transmit to multiple nodes simultaneously, or in vehicular networks [9], to improve the car-to-car communication, among others. As these scenarios usually include a large number of nodes contending for the channel, they are more interesting from the point of view of the interactions between the MPT and CSMA/CA protocols, and for that reason we focus on them in this paper.

The rest of the paper is structured as follows. Section 2 presents the considered reference scenario, i.e., a single-hop network where N nodes compete for the channel. Section 3 details the reference protocol. In Section 4, the analytical model is presented. The analytical model validation and performance results are discussed in Section 5. Finally, the main conclusions of the paper are summarized in Section 6.

2. System model

A single-hop network with N nodes is considered. Each node is assumed to be within the transmission range of all the other nodes and close enough to have negligible propagation delay. Every node is equipped with M antennas as shown in Fig. 1, which allow it to simultaneously transmit up to M packets to a single or multiple destination nodes.

2.1. Node operation and link layer

Each node has a finite buffer of length K packets, to which packets arrive according to a Poisson process of rate λ. Each packet has a fixed length of L bits and can be directed to any of the other nodes. Packets depart from the node in batches, called space-batches, and are selected for transmission following a First-In First-Out (FIFO) policy, regardless of their destination(s). The space-batches are scheduled immediately following departure instants, i.e., when the previous space-batch is purged from the queue. The number of packets included in a space-batch, $s(q)$, depends on $q \in [0,K]$, the queue occupancy at the moment the new transmission is scheduled, and two system parameters $s_{\min}$ and $s_{\max}$, as follows:

$$s(q) = \begin{cases} s_{\min}, & q < s_{\min} \\ q, & s_{\min} \leqslant q < s_{\max} \\ s_{\max}, & s_{\max} \leqslant q \end{cases} \tag{1}$$

which can be written more concisely as $s(q) = \max\{s_{\min}, \min\{q, s_{\max}\}\}$. Note that if just after a departure $q < s_{\min}$, the scheduler waits until enough packets have arrived and a space-batch containing $s_{\min}$ packets can be constructed. The parameters $s_{\min}$ and $s_{\max}$ can take values between *1* and M, with $s_{\min} \leqslant s_{\max}$. They are design parameters that can be carefully chosen, depending on the arrival rate and the channel conditions, to improve the system performance. Choosing a high value for $s_{\min}$ reduces the number of transmission attempts on the channel, thus reducing the probability that a transmission results in a collision but at the cost of a larger average waiting delay, specially at low traffic rates. The $s_{\max}$ value has to be adjusted considering the channel state. In general, for any multi-user beamforming scheme, under good channel conditions (high Signal-to-Noise Ratio (SNR)), $s_{\max}$ can be increased towards M as the system can benefit from a larger number of parallel transmissions with reasonably low transmission error probability. However, at low SNR, high $s_{\max}$ values may result in a high packet error rate (PER), hence limiting the system throughput.