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Fast track article

Mitigating collisions through power-hopping to improve 802.11 performance[☆]

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ABSTRACT

In this article, we introduce a power-hopping technique (PH-MAC) that, by alternating between different transmission power levels, aims to deliberately cause packet capture and thereby reduce the impact of collisions in 802.11 WLANs. We first devise an analytical model of the 802.11 protocol with heterogeneous capture probabilities, and show that, depending on the network load, the capture effect can enhance the throughput performance of all nodes. We base the design of PH-MAC on the findings following from this analysis and demonstrate that important performance improvements can be achieved by exploiting the interactions between the MAC and PHY layers to mitigate collisions. Finally, to understand the feasibility of this technique in practical deployments, we present a prototype implementation of PH-MAC which relies on commodity hardware and open-source drivers. We evaluate the performance of this implementation in an indoor testbed under different network conditions in terms of link qualities, network loads and traffic types. The experimental results obtained show that our scheme can provide significant gains over the default 802.11 mechanism in terms of throughput, fairness and delay.

1. Introduction

In practical IEEE 802.11 deployments, when two or more simultaneous transmissions occur on the channel, if frames arrive at the destination with different power levels, it is often the case that the one received with the strongest signal can be demodulated despite the interference caused by the others, provided the difference in their signal strength is sufficiently large. This phenomenon is referred to as the *capture effect* and has been widely neglected when modelling the IEEE 802.11 protocol behaviour, the common assumption being that simultaneous transmissions result in collisions [1–4].

Recent works show both analytically and experimentally that the capture effect can potentially reduce the number of failures due to collisions and thus increase the throughput performance of the network [5–11]. However, we argue that the interactions between the MAC and PHY layers in the presence of the capture effect have not been yet deeply understood, since existing studies neglect the impact of traffic load and postulate that only nodes that deliver frames at high signal levels (generally due to their better placement relative to the access point) benefit from capture.

In contrast to previous works, in this paper we first devise an analytical model of the 802.11 operation under the capture effect and show that this phenomenon can not only improve the overall throughput of the network, but may also enhance the performance of the nodes that deliver frames at a low signal level, when the stations experiencing better link qualities with the receiver are lightly loaded. Specifically, we show that, depending on the network load, the throughput attained

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by the stations residing further away from the access point (AP) is not always degraded due to nodes located near the AP capturing the channel, but, on the contrary, the capture effect can also reduce the collision rate encountered by the distant users, thereby providing them with larger throughput. Our model adopts a renewal-reward process [3] to model the binary exponential backoff scheme of the MAC protocol and extends our previous analysis of [12] by considering a fully heterogeneous network, i.e. distinguishing multiple classes of nodes that experience dissimilar capture probabilities.

Based on the valuable insights that follow this analysis, we introduce a *power-hopping* MAC/PHY scheme (PH-MAC) that exploits the identified protocol behaviour to boost the WLAN performance. Specifically, our proposal preserves the 802.11 MAC rules, but selects among different power levels with certain probabilities when transmitting frames, deliberately causing capture to mitigate collisions. This design extends our earlier work [12], which assumed that stations could only choose among a high and a low power level. Here, we allow for multiple discrete power levels and also investigate the impact of their number. We model this enhancement using a Bianchi-type Markov chain [1] and show that, by choosing the power levels with equal probabilities, PH-MAC reduces the impact of collisions, providing significantly better throughput performance as compared to the standard 802.11 protocol.

To evaluate the potential gains of our mechanism, we implement a practical approximation of PH-MAC using open-source drivers and off-the-shelf 802.11 hardware. We assess the performance of this prototype by conducting extensive experiments in a small-scale indoor testbed, under different conditions in terms of link qualities, network loads and traffic types. The obtained results show that PH-MAC can achieve noteworthy performance gains over the default 802.11 scheme in terms of total throughput, fairness and delay, without requiring any changes to the existing hardware, but only small modifications to the available device drivers.

The rest of the paper is organised as follows: in Section 2, we review relevant related work; in Section 3 we present the network model considered for our analysis; in Section 4 we undertake an analytical and numerical study of the 802.11 performance with heterogeneous capture; in Section 5, we present the power-hopping MAC scheme that we implement and validate both numerically and via experiments with real devices; finally, Section 6 concludes the paper.

2. Related work

Aspects of the capture effect have been widely studied in the past in the context of mobile radio environments, e.g. [13,14]. Despite the significant effort devoted to modelling the performance of 802.11 DCF (see e.g. [1–4]), the capture effect is largely ignored in these studies, as well as in recent publications that investigate the behaviour of the EDCA protocol enhancement [15–17]. To date, few analytical models of the capture probability in Rayleigh fading channels have been proposed and used to predict the impact of this effect on the capacity of 802.11 networks, e.g. [6,7]. Ge et al. [5] take a further step towards understanding how capture affects the back-off mechanism of the protocol, while Sutton et al. [8] introduce a more detailed 3-dimensional Markov chain model that incorporates capture and serves estimating not only failure probability, but also several QoS metrics. However, the failure probability is computed by subtracting a capture probability from the collision probability. Instead, in our analysis we treat a fraction of the collisions as resulting in capture.

Experimental studies have examined the capture phenomenon comprehensively with real deployments, identifying the throughput unfairness that may arise due to this effect [9,18]. A deeper understanding of how frame timing and signal strength influence the occurrence of capture in practice is provided in [10,11]. Based on the arrival time of a frame with a stronger signal relative to the arrival of weak signal packet, Manweiler et al. distinguish between capture and message-in-message phenomena, and exploit the latter to improve network throughput [19]. To the best of our knowledge, no previous approaches adjust the transmission power to purposely cause capture and benefit from this effect.

Transmit power control techniques have been employed to improve the energy-efficiency of the 802.11 DCF [20] or for mitigating interference in multi-AP deployments [21]. A combined rate and power control scheme is proposed in [22] to improve battery-life of mobile devices, while avoiding link asymmetries and improving capacity. These works confirm the feasibility of dynamically adapting the transmission power with current 802.11 devices, which constitutes one of the motivations behind the design of the power-hopping technique that we propose herein for reducing the impact of collisions. However, as compared to these approaches, our objective is to understand better the PHY/MAC interactions under the capture effect and exploit those in dense environments to enhance network performance.

3. Network model

In this section, we provide an overview of the network model and the assumptions used in the performance analysis that we conduct. We consider the case of infrastructure 802.11 wireless networks, i.e. all transmissions are to/from the AP. We start by introducing relevant aspects of the IEEE 802.11 protocol with the DCF (Distributed Coordination Function) operation, which is the default channel access scheme currently employed in WLANs [23] and then explain how capture is accounted for in our system.

3.1. IEEE 802.11 DCF

DCF uses a CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) MAC protocol with binary slotted exponential backoff. Briefly, when a station having packets to send senses the wireless medium idle for a period of *DIFS*