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Joint effect of data rate and routing strategy on energy-efficiency of IEEE 802.11 DCF based multi-hop wireless networks under hidden terminal existence



Canan Aydogdu*, Sibel Sancakli

Electrical and Electronics Department, İzmir Institute of Technology, 35430 Urla, İzmir, Turkey

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ABSTRACT

We investigate the joint effect of data rate and routing strategy on energy-efficiency of multi-hop wireless networks incorporating a comprehensive behavior of the IEEE 802.11 DCF under the presence of hidden terminals. Two basic routing strategies, direct transmission versus multi-hop routing, are considered over a large range of traffic loads. The goal of this study is to layout guidelines for a cross-layer energy-efficient rate adaptation algorithm, which takes medium access control and network layer dynamics into account together with the hidden terminal effect.

Our results show that, for the low-power wireless IEEE 802.11g standard considered in this article, the highest data rate consumes the least power in multi-hop wireless networks when hidden terminals mostly constitute the reason of collisions. In case of channel impairments, adapting the rate jointly with the routing strategy can save the energy consumed per bit by up to 250% under moderate traffic loads and much more under heavy traffic loads.

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1. Introduction

The Internet of Things (IoT) vision and emerging 4G services, fuelled with the flexibility of mobility, is expected to transform the structure of wireless networks from the current single-hop access networks to large dense multi-hop wireless networks. Multi-hop wireless networks have the capability of conveying information through multiple hops and include the wireless mesh networks (WMN), mobile ad hoc networks (MANET), wireless sensor networks (WSN), vehicular ad hoc networks (VANET), etc., which are envisioned to be formed among large number of nodes in the near future.

One major challenge of multi-hop wireless networks is the limited or costly energy, which is further reduced by

the additional load imposed by multi-hop transmissions [1]. Energy-efficiency is a cross layer issue and is affected by the following three major functions at the protocol stack differently in multi-hop wireless networks compared to single-hop networks: (1) the data rate at the physical layer, (2) medium access control protocol at the data link layer and (3) routing protocol at the network layer. The goal of this article is to layout guidelines for energy-efficiency in multi-hop wireless networks considering these three functions at the lower three layers.

In single-hop networks, packet errors occur mostly due to imperfect channel conditions and rarely due to concurrent transmissions, which are minimized by medium access control (MAC) functions such as carrier sensing, backoff, etc. Hence, in single-hop networks rate adaptation has the potential of improving the achievable throughput compared to fixed rate transmission, since rate adaptation mitigates the effects of link quality fluctuations [2].

* Corresponding author. Tel.: +90 2327506528; fax: +90 2327506599.
E-mail address: cananaydogdu@iyte.edu.tr (C. Aydogdu).

However, in multi-hop networks, the hidden terminal problem emerges and constitutes the reason for a significant number of packet collisions and energy losses. Moreover, packet errors also stem from the increased number of concurrent transmissions of multi-hop paths. Identification of the reason of packet losses, either collision or channel error, and reacting accordingly is shown to enhance the performance of rate adaptation in WLANs in [3]. Higher data rate, i.e. lower packet durations, decrease the probability of packet error rate (PER) due to concurrent transmissions caused by the hidden terminal effect and increased multi-hop traffic for multi-hop networks. Briefly, achieving a minimum PER is possible by decreasing the data rate in single-hop networks, whereas increasing the data rate may result with a smaller PER in multi-hop networks if packet errors due to hidden terminals and concurrent transmissions exceed packet errors due to channel errors. For multi-hop networks, the optimal data rate for a minimum PER is affected by the reason of packet errors, which is related to the MAC and routing protocols. Errors due to channel impairments necessitate a decrease in data rate, whereas errors due to collisions of concurrent transmissions of hidden terminals or multi-hop routes necessitate an increase in data rate.

Higher data rates are coupled with lower receiver sensitivities and consume more transmission power than lower data rates for achieving the same signal to noise ratio at the receiver. On the other hand, packets sent at higher data rates last for lower duration decreasing the transmission energy consumption, which is equal to transmission power times packet duration. Moreover, energy is not only consumed during transmissions and receptions, but also during idle listening and overhearing of neighbor nodes, the timing of which is governed by the MAC protocol and is affected by the traffic load of the multi-hop wireless network [4]. Hence, a comparison of energy-consumption of various data rates is not straight forward and requires consideration of not only power ratings of transmit, reception and idle modes, but also the MAC dynamics over a large range of traffic loads.

Multi-hop wireless networks differ also from the single-hop networks from the network layer aspect, because energy cost of end-to-end, rather than node-to-node, successfully delivered bits becomes an important performance metric in multi-hop wireless networks. Moreover, a path from the source to the destination typically consists of multiple hops and accumulation of packets on intermediate nodes causes packet drops or delays at the interface queues (IFQ) of nodes, which again has an energy cost. Evaluation of energy consumption of end-to-end delivered bits requires consideration of collisions and retransmissions at each link, together with accumulations at the IFQ of nodes of a multi-hop path, which are the responsibility of the MAC layer. Hence, the evaluation of the effect of data rate necessitates the routing protocol to be jointly considered for a comprehensive energy-efficiency analysis in multi-hop wireless networks.

The primary contribution of this study is the investigation of the joint effect of data rate and routing strategy on energy-efficiency of multi-hop wireless networks by inclusion of a comprehensive MAC protocol under hidden

terminal existence. Our goal is to figure out design guidelines for rate adaptation algorithms for the large and dense multi-hop networks of the future IoT world.

IoT vision is coupled with green networking, which is defined as a way to reduce energy required to carry out a given task while maintaining the same level of performance [5]. Hence we selected Energy Per Bit (EPB) as the energy-efficiency metric in this study, which provides an absolute comparison among different data rates [6].

In this article, the widespread IEEE 802.11 Distributed Coordination Function (DCF) is chosen as the MAC protocol for energy-efficiency evaluation of multi-hop wireless networks. Since we focus our discussion here on the impact of data rate on energy-efficiency, we have chosen the IEEE 802.11g version due to the wide range of supported rates and inter-operability with former IEEE 802.11b and legacy standards.

In this study, we focus our discussion to the investigation of the effect of data rate in perfect channel conditions in order to focus our attention to the MAC and routing protocol dynamics, which become important in multi-hop wireless networks. We also include a discussion of an error channel with shadowing and random link errors, where we present guidelines for jointly decreasing the rate and adapting the routing strategy in case of imperfect channel conditions when rate reduction becomes a necessity.

Our results show that the joint effect of data rate and routing strategy is traffic load and topology dependent for the low-power wireless communications standard IEEE 802.11g considered in this article. Under light traffic loads, where MAC collisions are negligible, the idle power consumption dominates and the EPB consumption becomes independent from data rate for regular topologies. For random topologies, either single-hop routing with any data rate or multi-hop routing strategy with highest data rate increases the EPB under light traffic loads. This suggests that for random topologies, where multi-hop routes traverse a higher total end-to-end distance compared to direct transmissions, long lasting packets with low data rates should not be preferred even under light traffic loads. As the traffic load increases, collisions due to hidden terminals and retransmissions increase, favoring higher data rates. The EPB of the lowest rate considered in this study becomes about 10-fold of the highest rate for the regular topologies and 7-fold for the random topologies for single-hop routing. The gap between EPB of various rates is observed to be more for multi-hop routes due to increased number of transmissions.

The main conclusion of this study is that under perfect channel conditions, where collisions stem from concurrent transmissions due to hidden terminals rather than channel errors due to wireless propagation, the best strategy for minimizing EPB is to jointly increase the data rate and decrease the hop-count of the routing strategy under moderate-to-heavy traffic loads. Under light traffic loads, there is no need to adapt rate due to packet errors stemming from concurrent transmissions and hidden terminals, but multi-hop routing with low data rates should be avoided.

The remainder of this article is organized as follows: firstly, we present a literature review in Section 2 and describe the simulation settings and assumptions

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