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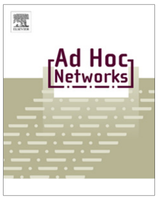

Joint effect of data rate and routing strategy on energy-efficiency of IEEE 802.11 DCF based multi-hop wireless networks under hidden terminal existence

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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.

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].

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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 regarding the IEEE 802.11g DCF in Section 3. The simulation results presented in Section 4 are followed by some concluding remarks given in Section 5.

2. Literature review

The investigation of the joint effect of data rate and routing strategy on energy efficiency of multi-hop IEEE 802.11 DCF based wireless networks under hidden terminal existence is related with three different lines of related research: energy-efficient rate adaptation, joint rate and transmit power control or routing control and energy consumption of IEEE 802.11 DCF under presence of hidden terminals. In this section, we review the literature of these research lines in the lower three protocol layers, together with some recent joint approaches.

The widespread usage of IEEE 802.11 wireless networks with multiple data rate capabilities accelerated data rate adaptation studies due to the lack of a predefined procedure in the standard specifications. Adapting the data rate according to channel characteristics in order to satisfy a minimum bit error rate is used as a method for improving energy-efficiency, rather than throughput, in IEEE 802.11 DCF based single-hop wireless networks in [7–13]. The effect of data rate on a IEEE802.11a based WLAN is examined in [7] for various number of contending stations, where energy consumption in transmit, receive and idle modes is considered. Highest data rate is shown to consume minimum energy for any number of stations and it is shown that consumption in receive mode dominates as the number of stations increase due to increased overhearing.

Rate adaptation is combined with transmit power control (TPC) in [8] considering hidden nodes, where an optimal rate-power combination table is computed offline, and then at runtime, a wireless station determines the most energy-efficient transmission strategy for each data frame transmission by a simple table lookup. Energy-efficiency of joint rate adaptation and TPC is considered for IEEE 802.11 DCF based WLANs also in [9–11]. The results of these studies show that rate adaptation provides significant energy gains, especially when combined with transmit power control. Energy-efficient rate adaptation based on frame delivery ratio and received signal strength indication is considered for long distance Wi-Fi links in a single-hop network in [12], and it is shown that energy consumption per successfully delivered bit is decreased by jointly controlling data rate and transmission power. Only transmission mode is considered to be responsible for energy expenditure in simulations for this long distance IEEE 802.11b based network, which results with lower energy consumption for lower rates and it is shown that raising transmission power is a sufficient method compared to decreasing data rate for higher energy-efficiency in this study. Another joint data rate and power control with the target of achieving energy-efficiency is proposed in [13] for a single-hop network, where again power is assumed to be consumed in the transmit mode only. The results of these two studies in [12,13] when compared with [7,8] reveal that optimum strategy whether to increase or decrease the data rate for a more energy-efficient communication is dependent on the assumed energy consumption model. Assuming that only transmit mode consumes energy favors lower data rates (since receiver sensitivity of lower rates is lower, which results with a lower transmit power for the same bit error rate), whereas also considering energy consumption in idle and receive modes favors higher rates (since energy consumed for reception by all overhearing neighbor nodes and excessive idle listening dominates and packets lasting for shorter durations consume totally lower energy). Hence, a comprehensive approach for investigation of the effect of data rate on energy-efficiency should include energy consumption in all modes, which is the approach followed in this article.

Different than these studies, we investigate energy-efficiency of various data rates in *multi-hop* networks for different routing strategies. The inequality of channel access caused by hidden terminals and increased traffic of multi-hop paths necessitate different solutions for multi-hop networks. Moreover, the target becomes minimizing the energy consumption of a successfully delivered bit from source to destination rather than a single link. The joint effect of rate adaptation and transmit power control on throughput of multi-hop networks is investigated in [14–17], whereas the effect on energy-efficiency of multi-hop networks is investigated in a few studies [18–20]. [18] proposes a distributed cooperative rate adaptation (CRT) scheme which minimizes the total transmission power over transmission data rates subject to traffic requirements of nodes. The authors show that assigning a transmission power and data rate by taking hidden terminals into account results in significant energy gains in the overall multi-hop wireless network. A IEEE 802.11 DCF based multi-hop multi-rate network is used in [19], where smaller data rates are shown to be not always advantageous due to longer busy periods in the channel. And it is shown that adjusting the transmit power and rate according to the interference level achieves lower energy consumption. Not only joint rate and transmit power, but also routing is considered for enhancing energy-efficiency in energy renewable multi-hop wireless mesh networks in [20]. This study shows that it is beneficial to consider rate control in a cross-layer architecture where network layer is included.

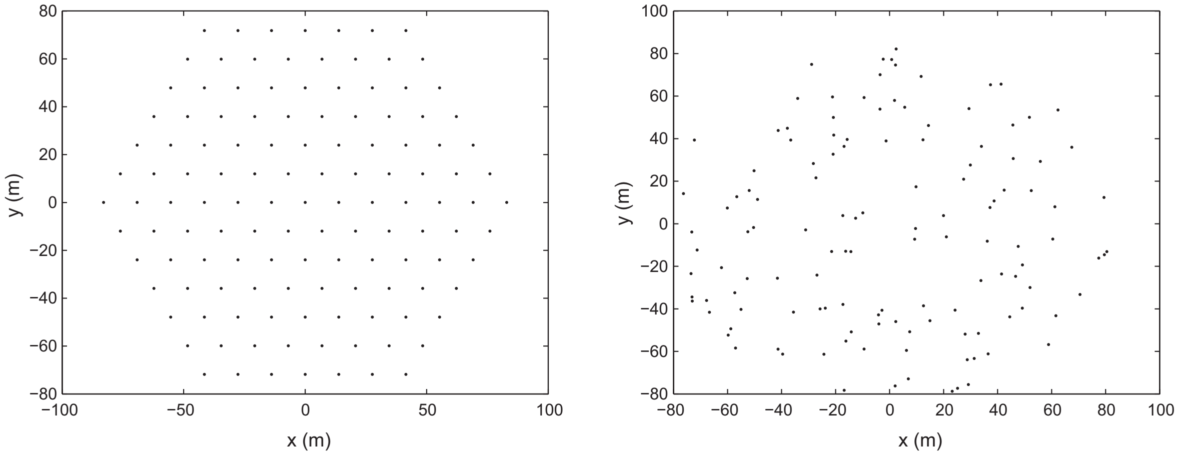
A cross-layer study conducted for multi-hop IEEE 802.11 DCF based networks shows that adapting the routing strategy according to the traffic load results in significant energy savings in [4]. This cross-layer analysis, which considers MAC layer mechanisms under hidden terminal existence, is extended in this article by inclusion of the joint effect of data rate at the physical layer and routing strategy at the network layer for different topologies and a wide range of traffic loads.

3. Modelling and simulation

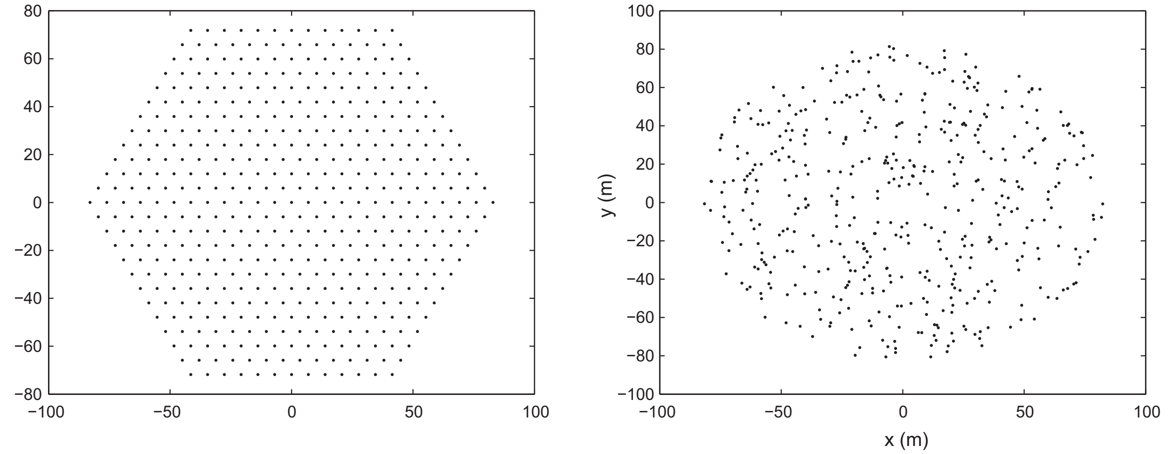
The joint effect of data rate and routing strategy on energy-efficiency is investigated for large dense multi-hop wireless networks in this study. Several example applications of such networks in the IoT world may be listed as follows: (a) A WSN formed for agriculture monitoring and activation of an irrigation system, where the environmental humidity of a field is measured by hundreds/thousands of sensors monitored over the Internet, (b) a VANET for conveying instantaneous vehicular information (position, speed, destination, etc.) of a large number of vehicles to the Internet in order to provide optimal route prediction for delay-critical emergency situations, (c) a WSN formed for industrial automation for monitoring hundreds/thousands of temperature sensors inside refrigerator chambers for detecting breaks in the cooling chain, (d) a WMN formed for smart metering of electricity consumption of several facilities/buildings in a city/campus area, (e) a MANET formed by hundreds of discovery robots, sent to a volcano/cavern/subsidence, which communicate by each other for position estimation while sustaining connectivity to the Internet through relays.

Table 1
Parameters used for simulation runs.

Data rate (DR)	6/12/24/54 Mbps
PLCP rate	6 Mbps
W_0	16
B	3
Short Retry Count (SRC)	7
Long Retry Count (LRC)	4
SlotTime	20 μs
DATA	1000 bytes
RTS	20 bytes
CTS	14 bytes
ACK	14 bytes
SIFS	10 μs
DIFS	50 μs
EIFS	412 μs
IFQ buffer size	5
path loss exponent η	3



(a) 127-node hexagonal topology (b) 127-node random topology



(c) 469-node hexagonal topology (d) 469-node random topology

Fig. 1. Node positions of (a) 127-node hexagonal topology, (b) the uniformly random distributed 127-node topology, (c) 469-node hexagonal topology, and (d) the uniformly random distributed 469-node topology.

Table 2
Receiver sensitivities and basic rates for each investigated data rate.

Data rate	6 Mbps	12 Mbps	24 Mbps	54 Mbps
Basic rate	6 Mbps	12 Mbps	24 Mbps	24 Mbps
RxSensitivity	−112.0 dB	−109.0 dB	−104.0 dB	−95.0 dB

Table 3
Power consumption values.

$P_{transmit}$	$1.425 + 0.25h^{-\eta}$ W
$P_{receive}$	1.425 W
P_{idle}	1.319 W

3.1. Simulation settings

The EPB metric, which is used in this study for investigation of the joint effect of data rate and routing strategy on energy-efficiency in large dense multi-hop wireless networks, is defined as the energy consumed in the whole network per one successful end-to-end delivered useful bit. The useful bits are the bits containing valuable data, excluding header bits, in the packets received successfully by the destination nodes. EPB is obtained by dividing the total energy consumed in the network by the successfully delivered number of useful bits throughout the simulations. This implies that the following energy expenditures are counted in the EPB metric: (a) energy spent by transmission/retransmission/reception of control and DATA packets over all links of paths for all source–destination pairs, (b) energy spent during idle listening/backoff, (c) energy spent during overhearing, i.e. reception of packets not destined to the nodes themselves.

Simulations are conducted by Network Simulator-2 (NS-2), version 2.35, which is the most recent version of the network simulation package at the time of this work. For all simulations conducted by NS-2, the following components of energy consumption is tracked for each node:

- E_{rx}: the total energy consumed for receiving a packet destined to the node itself.
- E_{tx}: the total energy consumed for transmitting a packet to the destination.
- $E_{overhear}$: the total energy consumed while overhearing a packet not destined to the node itself.
- E_{idle}: the total energy consumed during idle modes of the transceiver per packet.

The EPB metric is calculated finally by

$$EPB = \frac{E_{tx} + E_{rx} + E_{overhear} + E_{idle}}{P_{size} \cdot 8}, \tag{1}$$

where P_{size} is the number of useful bytes in a DATA packet.

The IEEE 802.11g based multi-hop networks under investigation are composed of 127 or 469 stationary nodes, which are either located in a regular hexagonal topology or distributed uniformly in a random topology shown in Fig. 1. The nodes are distributed on a fixed-size-area, hence the 469-node networks are denser compared to the 127-node networks. The diameter of the network is selected to be at least four times the transmission range in order to let hidden terminals to exist. Although most of the simulations are based on these homogeneous networks with all IEEE 802.11g nodes, a discussion of a heterogeneous network, where IEEE 802.11b nodes coexist, is carried out in Section 4.7.

Traffic load generated by each source node is distributed to several destinations over multiple paths to avoid conditions where a path is heavily loaded in a short time scale. The simulations are performed from unsaturated up to saturated traffic loads. Under the saturated

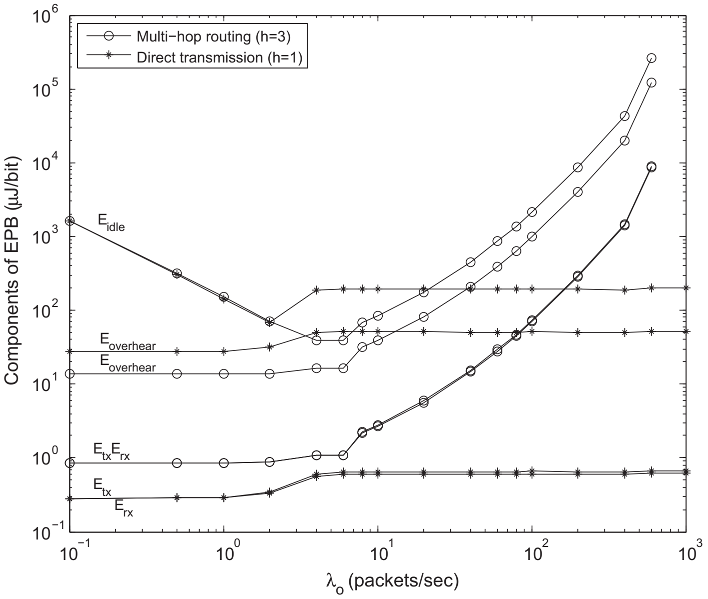


Fig. 2. Components of EPB for the 469-node hexagonal topology for $DR = 6$ Mbps.

traffic load, there is always at least one packet waiting in the queue upon finishing processing of the last packet. The traffic load is classified as light, moderate and heavy in this study based on the average number of times a frame is retransmitted, n_{rtx}, over a link as follows:

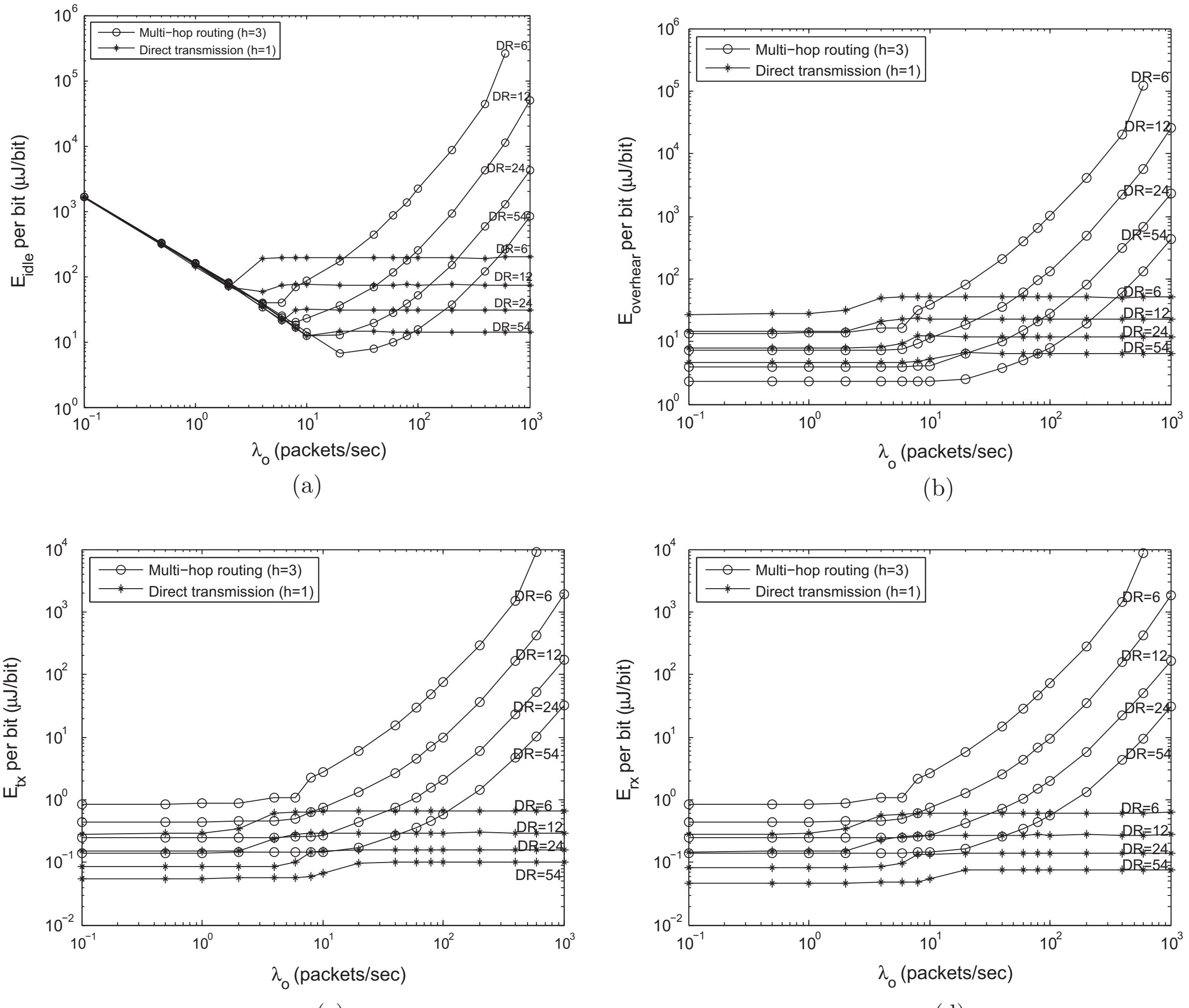
- Light traffic load: Average number of retransmitted frames is negligible ($0 < n_{rtx} < 1$).
- Moderate traffic load: Average number of retransmissions is not negligible but not high ($1 \leqslant n_{rtx} < M - 1$), where M is the maximum retry count.
- High traffic load: Average number of retransmissions is high ($M - 1 \leqslant n_{rtx}$).

Each node is assumed to generate Poisson traffic with rate λ_o packets per second for most of the results obtained throughout this study, except Section 4.8, where variable bit rate (Exponential and Pareto) and constant bit rate traffic models are considered.

In IEEE 802.11g standard, an alternative protection mechanism is defined, called CTS-to-self mechanisms to avoid collisions. However, this mechanism is not as effective as the RTS/CTS mechanism where hidden terminals exist [21]. Thus, the RTS/CTS mechanism is used in obtaining most of the results in this study. Also an investigation of the impact of deactivating RTS/CTS mechanism on energy-efficiency is carried out in Section 4.5.

In the case of a collision in the network, packets are retransmitted based on binary exponential backoff (BEB) until the node reaches the maximum retry count M. Packets are dropped after M unsuccessful retries and due to overflow of the finite sized IFQ. The simulations are performed for a duration necessary to generate an average of 6000 packets per node. The parameters used in the simulations are listed in Table 1.

The time durations of RTS, CTS, ACK and DATA frames are calculated according to ERP-OFDM specifications given by,



(a) (b) (c) (d)

Fig. 3. Components of EPB for the 469-node hexagonal topology for DR = {54,24,12,6} and h = {1,3}: (a) Idle energy per bit, (b) overhear energy per bit, (c) transmission energy per bit, and (d) reception energy per bit.

$$T_{RTS} = 20 + \left\lceil \frac{20 \cdot 8 + 22}{DR \cdot 4} \right\rceil \cdot 4, \tag{2}$$

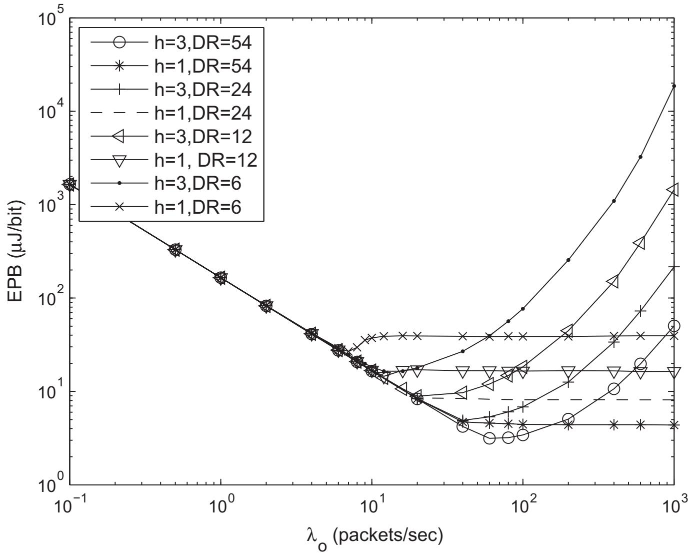
$$T_{CTS/ACK} = 20 + \left\lceil \frac{14 \cdot 8 + 22}{DR \cdot 4} \right\rceil \cdot 4, \tag{3}$$

$$T_{Data} = 20 + \left\lceil \frac{(P_{size} + 36 + 28) \cdot 8 + 22}{DR \cdot 4} \right\rceil \cdot 4, \tag{4}$$

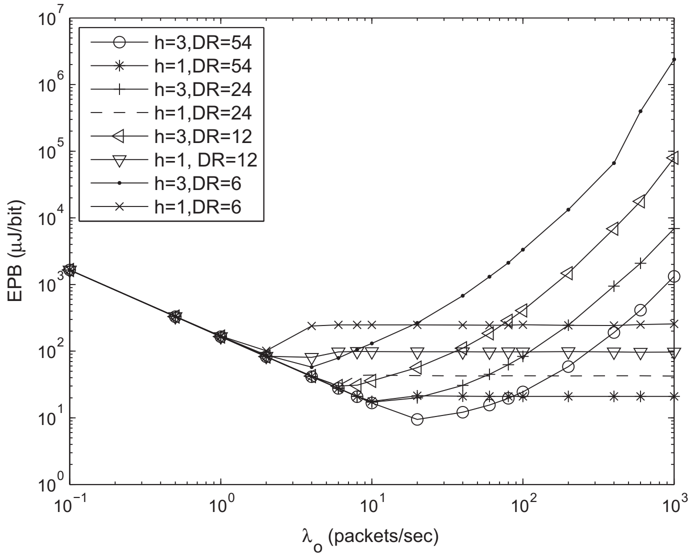
where *DR* is the transmission data rate.

According to the specifications, the basic rate set is equal to the mandatory rate set, which is {6, 12, 24} Mbps when using the 20 MHz channel spacing for an Independent Basic Service Set (IBSS), which is an ad hoc network that contains no access points. These settings are adopted since we consider multi-hop networks without access points. Since we aim to investigate the effect of data rate in 802.11g multi-hop networks, for high data rates sending the control frames at the highest basic rate is preferred for a better performance comparison. The data rates, basic rates and corresponding receiver sensitivity used in the study are shown in Table 2.

Nodes employ the maximum transmit power, $P_{txmax} = 0.25$, for direct transmission with data rate 54 Mbps. Power control is done to reduce the transmit power for lower data rates due to corresponding lower



(a)

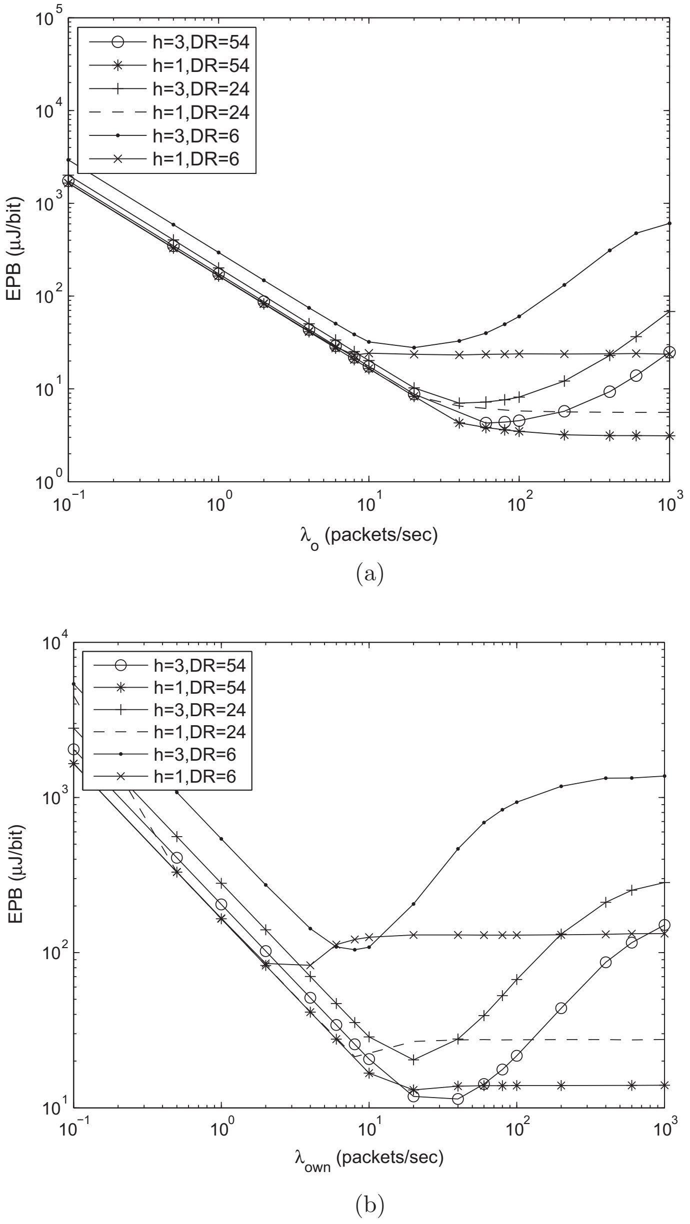


(b)

Fig. 4. EPB for data rates DR = {54,24,12,6} and routing strategies with $h = \{1,3\}$ for the (a) 127-node, and (b) 469-node hexagonal topologies.

receiver-sensitivities. Also the transmit power is reduced so to reach the next hop for multi-hop routing. The power consumption values of transmit, receive and idle modes of the IEEE 802.11g network interface card assumed are listed in Table 3.

Simulations are done for unicast traffic and fixed routing scheme, where each generated packet traverses a path of h-hops, where $h = \{1,3\}$. Hence, energy-efficiency under two different routing strategies, direct transmission versus multi-hop transmission is investigated for various data rates. The source–destination pairs are fixed during simulations for each data rate and h value for obtaining a fair comparison of the joint effect of rate and routing strategy. The source–destination pairs are determined so that one direct path and one h-hop multi-hop path are feasible. Although the discussions in this article is based on the hop count routing metric, the expected transmission count is also investigated in the simulations in Section 4.9 by assigning random link errors and including shadowing. The error-free channel assumption is used in the rest of the sections in order to focus the discussion of the impact of joint data rate and routing strategy on energy-efficiency under hidden terminal presence, so that collisions are due to hidden terminals instead of channel errors.



(a)

(b)

Fig. 5. EPB for data rates DR = {54,24,12,6} and routing strategies with $h = \{1,3\}$ for the (a) 127-node, and (b) 469-node random topologies.

3.2. Modelling assumptions

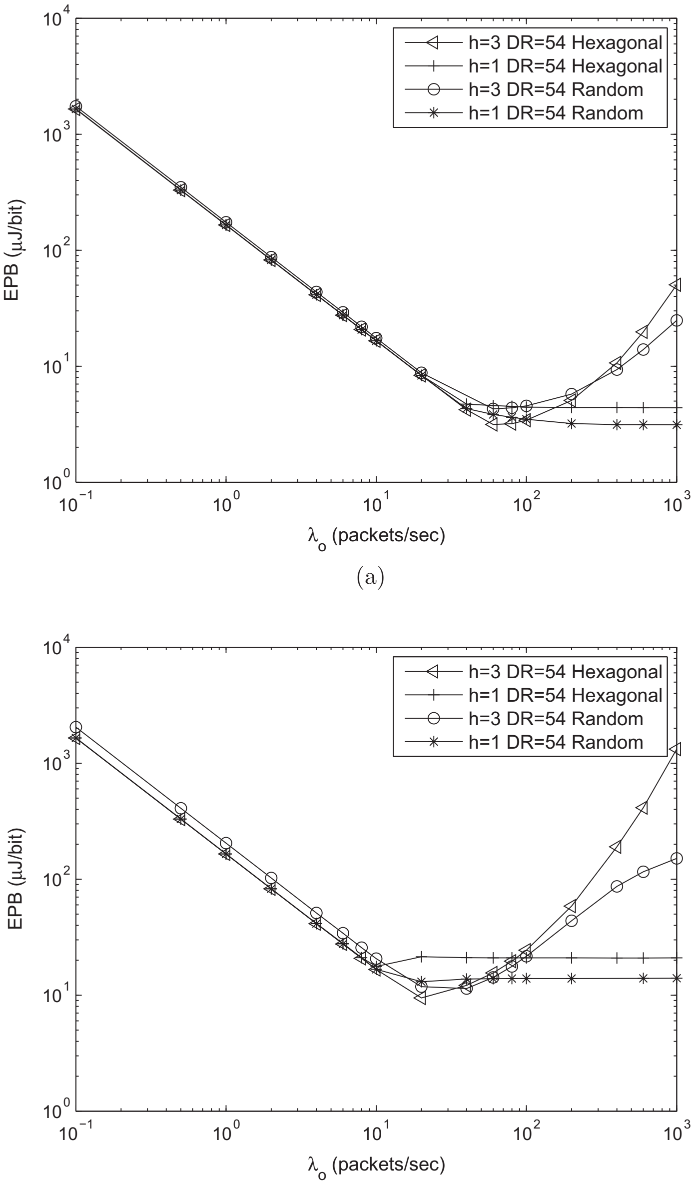
Some assumptions made by previous studies are adapted into the simulations [22–24]. The assumptions are as follows: (i) The unified disk radio model, (ii) Stationary nodes. The unified disk radio model has been widely used by many researches in wireless networking due to its simplicity in mathematical characterization of physical layer [1] and is given by

$$P_{rx} = cP_{tx}d^{-\eta} \tag{5}$$

where P_{rx} is the receiver sensitivity, P_{tx} is the transmit power, d is the distance between transmitter and receiver, η is the path loss exponent and c is a constant value. The carrier sensing range is assumed to be equal to transmission range. In this model, a successful transmission occurs if there are no simultaneous transmissions within a certain interference range from the receiver.

4. Results

In this section, the joint effect of data rate and routing strategies on EPB performance of IEEE 802.11g based multi-hop wireless networks are investigated for various traffic loads and various network sizes. Results considering different routing metrics such as hop count and expected transmission count, different technologies and with/without CTS/RTS message exchange are obtained. First of all,



(a)

(b)

Fig. 6. Comparison of EPB of hexagonal and random topologies for $DR = 54$ Mbps and $h = \{1, 3\}$ for: (a) 127-node, and (b) 469-node topologies.

consumption of energies during idle listening, overhearing, transmission and reception, which constitute the energy components of the EPB metric is analyzed for acquiring an understanding of the EPB behavior.

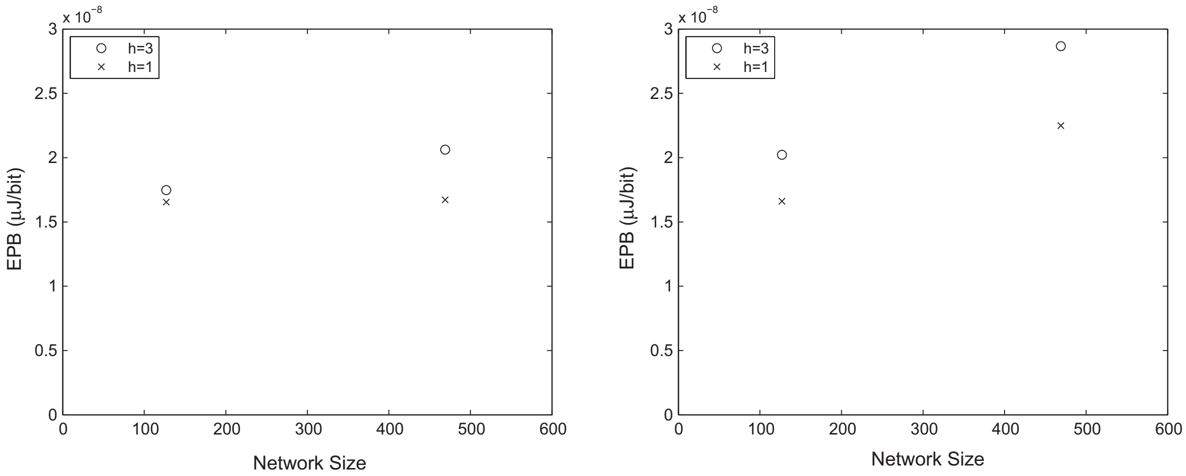
4.1. Energy components

In order to highlight the underlying EPB behavior, energy components of the 469-node hexagonal topology is analyzed as a representative scenario. Fig. 2 shows the energy components of EPB for $DR = 6$ Mbps, whereas the joint effect of data rate and routing strategy on the consumption of energies during idle listening (Fig. 3(a)), overhearing (Fig. 3(b)), transmission (Fig. 3(c)) and reception (Fig. 3(d)) are illustrated in Fig. 3 for the 469-node hexagonal topology.

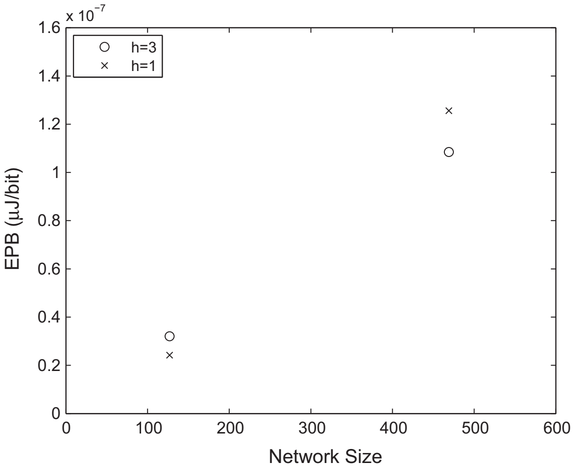
Fig. 2 shows that EPB depends highly on traffic load and E_{idle}, idle energy consumption, is the major source of energy consumption for the considered IEEE 802.11g multi-hop wireless network. E_{idle} is followed by the overhear energy consumption, transmit and receive energy consumptions sequentially. This result indicates that an energy-efficiency investigation of the IEEE 802.11 DCF in multi-hop networks should consider not only transmit and receive mode consumptions, but also idle mode energy consumption together with the reception energy consumed by overhearing contending nodes.

Fig. 3(a) illustrates the joint effect of data rate and routing strategy on the idle energy consumption. The results shows that under light traffic loads idle energy consumption is equivalent for any data rate and routing strategy, whereas highest data rate with multi-hop routing results with minimum E_{idle} under moderate traffic loads and highest data rate with direct transmission results with minimum E_{idle} under moderate traffic loads.

The joint effect of data rate and routing strategy on the overhear energy consumption is given in Fig. 3(b). The results shows that highest data rate always achieves



(a) $DR = 54$ Mbps, λ_o=10 packets/sec (b) $DR = 24$ Mbps, λ_o=10 packets/sec



(c) $DR = 6$ Mbps, λ_o=10 packets/sec

Fig. 7. EPB for the 127-node and 469-node random topologies for $\lambda_o = 10$ packets/s, $h = \{1, 3\}$ and various data rates: (a) $DR = 54$ Mbps, (b) $DR = 24$ Mbps, and (c) $DR = 6$ Mbps.

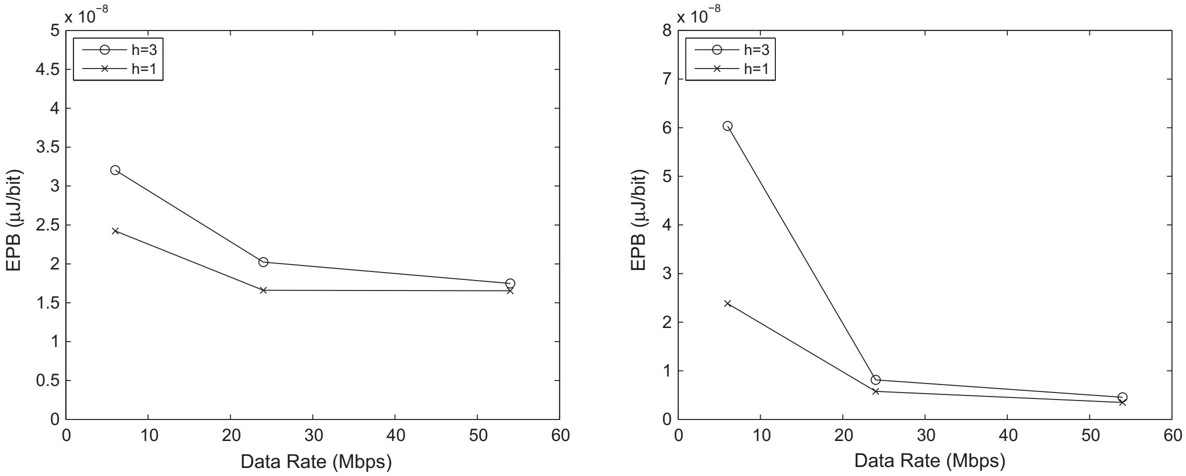
the minimum overhear energy consumption, whereas multi-hop routing under light traffic loads and direct transmission under heavy traffic loads result with minimum $E_{overhear}$. $E_{overhear}$ is obtained by multiplying packet durations, reception power, the number of overhearing nodes and number of packets per each useful end-to-end successfully transmitted bit. Hence it decreases with decreasing interference, which is provided by increasing data rate and jointly using multi-hop routing under moderate traffic loads and direct transmission under heavy traffic loads.

Fig. 3(c) and (d) illustrate the transmit and reception energy per bit for the 469-node hexagonal topology for various data rates and routing strategies. These two energy components are minimized with lower packet durations and lower number of packet transmissions, hence using $DR = 54$ jointly with direct transmission minimizes E_{tx} and E_{rx}.

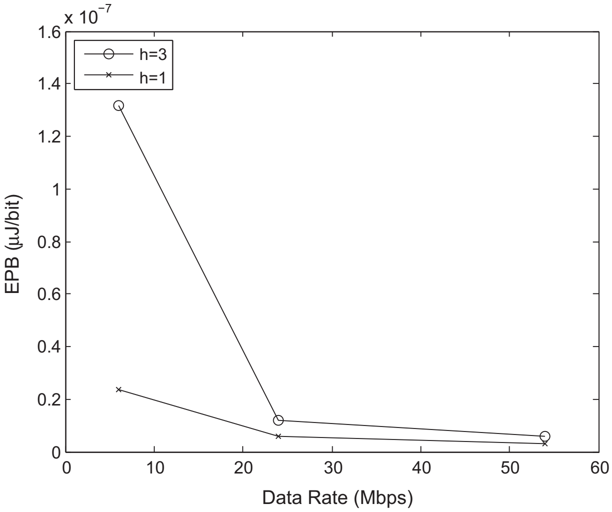
These results show that energy is not only consumed during transmissions and receptions, but also and mostly during idle listening and overhearing of neighbor nodes, the timing of which is governed by the MAC protocol and is affected by the traffic load of the multi-hop wireless network [4]. Hence, this study shows that a comparison of EPB for various data rates and routing strategies 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.

4.2. Energy per bit

The joint effect of data rate and routing strategy on the energy consumed per useful bit is shown in Fig. 4 for the 127-node and 469-node hexagonal regular topologies, in Fig. 5 for the random topologies for a wide range of traffic loads from unsaturated up to saturated.



(a) λ_o=10 packets/sec (b) λ_o=100 packets/sec



(c) λ_o=200 packets/sec

Fig. 8. EPB for the 127-random topology for $h = \{1, 3\}$ under various traffic loads (a) $\lambda_o = 10$ packets/s, (b) $\lambda_o = 100$ packets/s, and (c) $\lambda_o = 200$ packets/s.

EPB obtained by NS-2 simulations includes the energy consumed by: (i) transmit, receive and idle modes, (ii) any related control packets, (iii) packet drops due to IFQ overflow and maximum retry count, (iv) hidden terminal collisions, (v) retransmissions, (vi) IEEE 802.11 specific backoff durations and carrier listening, etc.

The results obtained for both the hexagonal and the random topologies 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 due to concurrent transmissions or hidden terminals are negligible, various data rates and the routing strategies have no effect on EPB for hexagonal topologies, whereas highest data rate with direct transmission is more advantageous for random topologies. The independence of EPB from data rate and routing strategy for hexagonal topology under light traffic loads stems from the fact that the idle power consumption dominates during the IEEE 802.11g DCF as shown in Fig. 3(a) and from the fact that the source–destination distance of each direct transmission path is equally divided for the *h*-hop multipath for the hexagonal topologies. Switching to random topologies, multi-paths always traverse a longer total distance than direct paths, hence direct transmissions result with lower EPB as observed in Fig. 5. This fact also affects

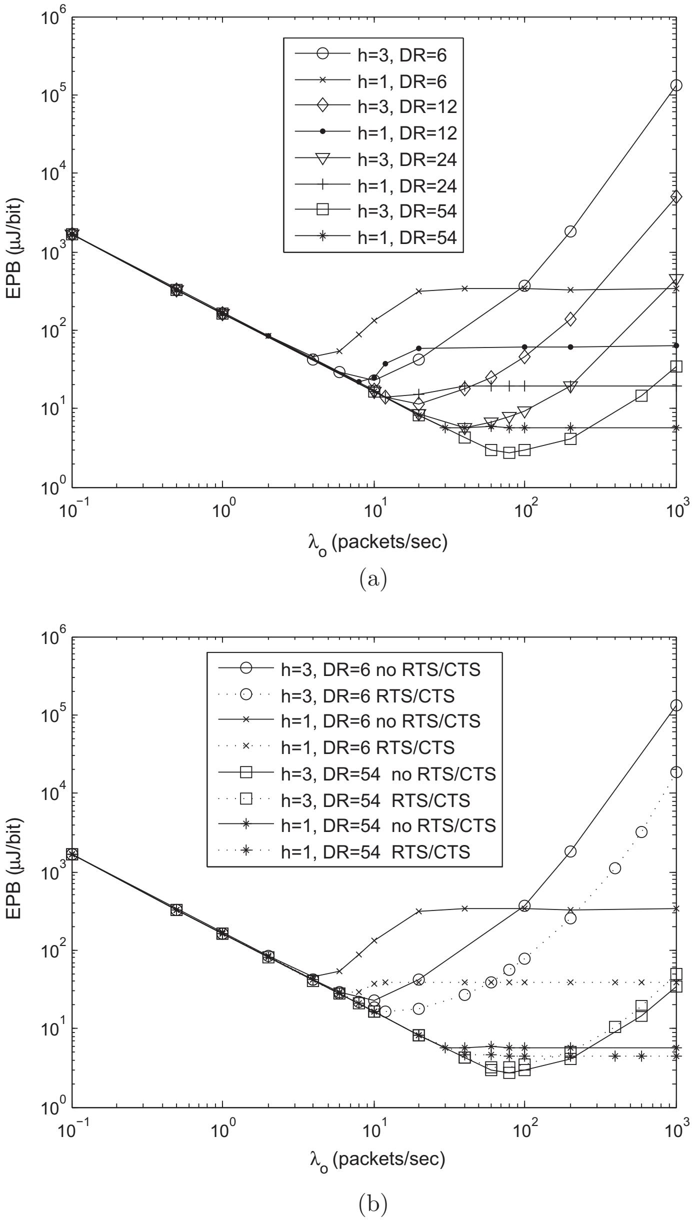


Fig. 9. EPB for the 127-node hexagonal topology for routing strategies with $h = \{1,3\}$ (a) without RTS/CTS exchange mechanism for DR = {6,12,24,54} and (b) with and without RTS/CTS exchange mechanism for DR = {6,54}.

the idle power consumption, which becomes lower for higher data rates due to shorter interference durations for the random topologies.

As the traffic load increases, collisions due to hidden terminals and retransmissions increase. For moderate traffic loads, the optimum EPB is achieved by transmitting at higher data rates jointly with multi-hop routing strategy for hexagonal topologies, whereas it is achieved by transmitting at higher data rates jointly with direct transmission strategy for random topologies. The superiority of direct transmission over multi-hop routing is again due to the fact that multi-hop routes traverse a higher total end-to-end distance compared to direct transmissions in random topologies. The superiority of higher data rates stems from the fact that higher rate packets last for shorter duration and hence shorter transmit, receive and overhear energies per bit are consumed. Moreover, idle energies per bit are consumed less for higher data rates due to IEEE 802.11g DCF operations since idle energy is consumed mostly during backoff under moderate traffic loads and shorter packets transmitted in the channel cause shorter backoff durations at all contending nodes.

Under heavy traffic loads, using the highest data rate jointly with direct transmission strategy achieves the minimum EPB for all considered topologies. Under heavy traffic loads, hidden terminal collisions become severe and packet drops at IFQs increase so that using multi-hop transmission strategy occupies the channel more than direct transmission for one end-to-end successfully transmitted useful bit. Hence, joint use of high data rate with direct transmission strategy reliefs the channel ending up with lower EPB.

These 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, when data rate reduction becomes a necessity, the data rate can be decreased jointly by adapting the routing strategy. For example, for the 127-node random topology shown in Fig. 5(a), switching from multi-hop routing with $DR = 54$ to direct transmission with $DR = 24$ would decrease EPB by about 50% for $\lambda_o = 400$ packets/s, whereas switching to multi-hop routing with $DR = 24$ would increase the EPB more than twofold. Likewise, by jointly adapting the data rate with routing strategy, EPB can be saved by up to 250% under moderate traffic loads and much more under heavy traffic loads for the considered topologies.

4.3. Effect of the topology

The effect of regularity of the topology on EPB performance is illustrated in Fig. 6 for $DR = 54$ Mbps over a wide range of traffic loads. These results suggest that as the regularity decreases EPB increases, but the overall behavior of the EPB versus traffic load is observed to be similar for hexagonal and random topologies.

The effect of density of the topology on EPB is illustrated in Fig. 7 for various data rates and a representative moderate traffic load taken as $\lambda_o = 10$ packets/s. As the network density increases, the EPB increases by 17% for $DR = 54$, by 40% for $DR = 24$ and 4-fold for $DR = 6$ Mbps.

4.4. EPB versus data rate

EPB versus data rate for the 127-node random topology is given under various traffic load in Fig. 8. For each traffic load, the lowest energy consumption is obtained always at the highest data rate for direct transmission. The EPB gap between direct transmission and multi-hop routing strategy is observed to increase with increasing traffic load.

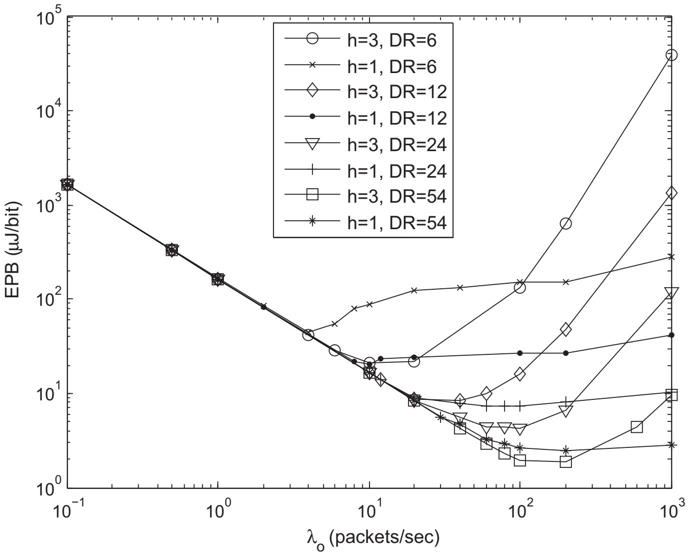
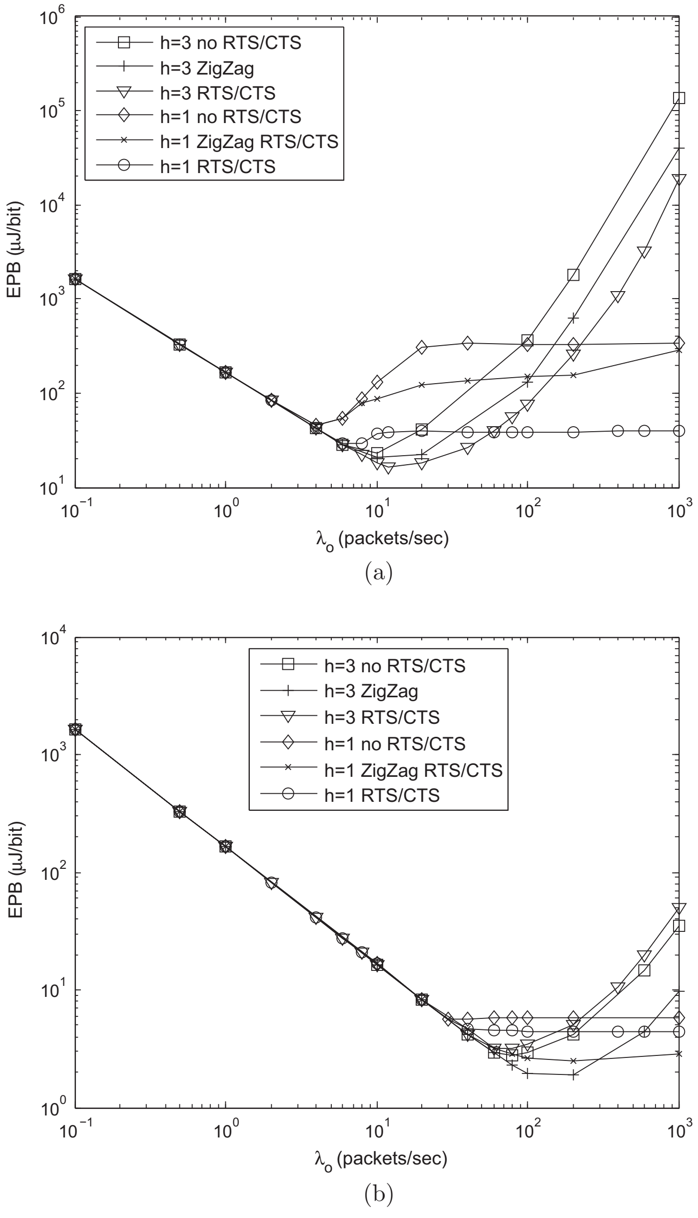


Fig. 10. EPB for the 127-node hexagonal topology for routing strategies with $h = \{1,3\}$ with ZigZag decoding for DR = {6,12,24,54}.

4.5. Effect of deactivation of RTS/CTS exchange mechanism

The numerical results presented in Fig. 2–8 are obtained by using the RTS/CTS exchange mechanism of IEEE 802.11 DCF. Using the RTS/CTS exchange mechanism decreases collisions under existence of hidden terminals. However, many applications deactivate the RTS/CTS exchange mechanism in IEEE 802.11 networks in practice. Hence, the joint effect of data rate and routing strategy on EPB performance is investigated in Fig. 9 for the 127-node hexagonal topology. EPB of various data rates without RTS/CTS exchange mechanism is given in Fig. 9(a), which illustrates that deactivating the RTS/CTS mechanism introduces the following differences compared to the case with RTS/CTS exchange given in Fig. 1(a): (i) the gap between EPB curves of $h = 1$ and $h = 3$ for the same data rate increases (this is because direct transmission is more prone to hidden terminal collisions without RTS/CTS exchange), (ii) EPB performance gap between various data rates increases significantly under moderate to saturated traffic loads (The EPB of DR = 6 Mbps is about 30 times the EPB of DR = 54 Mbps without RTS/CTS, whereas it is about 10-fold with RTS/CTS exchange).

Fig. 9(b) gives a comparison of EPB with and without RTS/CTS mechanism for DR = {6,54}. The intermediate data rates are not shown in order not to complicate the figures.



(a)

(b)

Fig. 11. Comparison of EPB with RTS/CTS Exchange, without RTS/CTS exchange and ZigZag decoding (without RTS/CTS exchange) for the 127-node hexagonal topology for $h = \{1,3\}$ for (a) DR = 6 Mbps and (b) DR = 54 Mbps.

Deactivating the RTS/CTS mechanism is found out to increase the EPB up to about 8 times for all data rates and routing strategies, except joint use of DR = 54 Mbps with multi-hop routing. The smaller packet durations of DR = 54 Mbps combined with the smaller number of hidden stations with multi-hop routing constitute the reason of a 36% decrease in EPB without RTS/CTS exchange. As a result, when deactivating RTS/CTS mechanism is an option, the best strategy for energy-efficiency can be stated as follows: (a) under moderate traffic loads, joint use of higher data rates with multi-hop transmissions, without RTS/CTS exchange, (b) under heavy traffic loads, joint use of higher data rates with direct transmissions, with RTS/CTS exchange.

4.6. Effect of adaptive decoding

Further recent new work has shown that if the adapter gets synchronized with one packet and receives the header correctly it can still receive the data even in presence of collision by ZigZag decoding, if the same set of packets collide during retransmissions [25]. Repeating collisions of same set of packets are not treated as collisions with ZigZag decoding, which is proposed for use without the RTS/CTS exchange mechanism.

The data packet collisions in Section 4.5 without the RTS/CTS exchange mechanism end up with packet losses and retransmissions. Adapter behavior, specifically the effect of ZigZag decoding, is also considered in the simulations. The joint effect of data rate and routing strategy on EPB performance with ZigZag decoding is given in Fig. 10 for the 127-node hexagonal topology, which illustrates that in case of ZigZag decoding the joint effect of data rate and routing strategy on EPB under various traffic loads exhibits the same behavior (EPB is independent from data rate and routing strategy under unsaturated traffic loads, maximum for high data rate and multi-hop transmissions under moderate traffic loads, maximum for high data rate and direct transmissions under saturated traffic loads). The benefit of using ZigZag decoding is shown in Fig. 11(a) for DR = 6 Mbps and in Fig. 11(b) for DR = 54 Mbps, where a comparison with and without RTS/CTS exchange mechanism is given. ZigZag decoding is observed to increase energy-efficiency more for higher data rates and multi-hop transmissions under moderate and saturated traffic loads, where collisions take place. ZigZag decoding is effective in recovering colliding packets in case of repetitive collisions of the same set of packets. For the 127-node considered topology, the number of contending stations is 7 for multi-hop routing, whereas it is 37 for direct transmissions. Hence, collisions with the same set of packets is more probable with multi-hop routing (due to smaller number of contending stations) and with higher data rates (due to smaller packet durations). As a result, the best strategy is to use RTS/CTS exchange with DR = 6 Mbps and to use ZigZag decoding with DR = 54 for enhanced energy-efficiency; jointly with multi-hop routing under moderate traffic loads and direct transmission under heavy traffic loads.

4.7. Effect of coexistence of different IEEE standards

In general, IEEE 802.11g coexists with other technologies or standards. The results up to this point, are obtained based on a homogeneous wireless network composed of only IEEE 802.11g nodes. The impact of coexistence of different IEEE 802.11 standards, specifically IEEE 802.11b and IEEE 802.11g, on EPB performance is investigated in this section. The EPB performance of an heterogeneous 469-node hexagonal topology, where about 23% of the nodes are of type IEEE 802.11b and the rest are of type IEEE 802.11g, is investigated when different IEEE standards

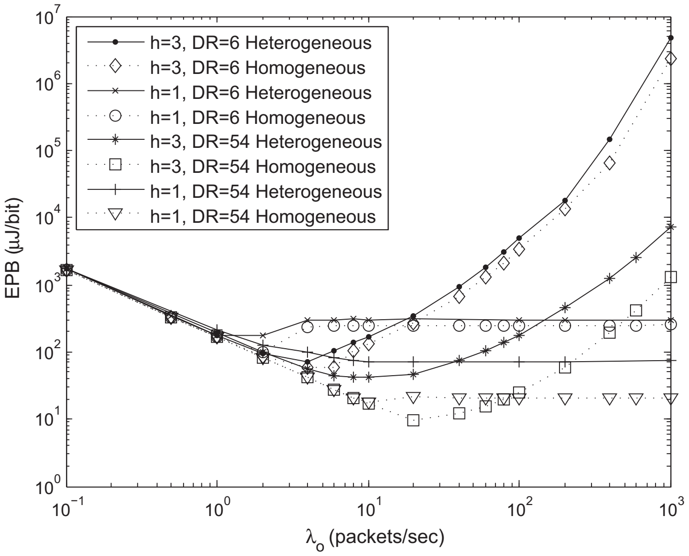


Fig. 12. EPB for the homogeneous (all IEEE 802.11g nodes) and heterogeneous (23% IEEE 802.11b nodes) 469-node hexagonal topologies for $DR = \{6, 54\}$ Mbps and $h = \{1, 3\}$.

share the medium. In the heterogenous network, IEEE 802.11b nodes communicate with each other at data rate 11 Mbps, basic and PLCP rates 1 Mbps; whereas IEEE 802.11g nodes communicate with each other at the data and basic rates given in Table 1. RTS/CTS exchange is used in obtaining the results.

The EPB of the 469-node-hexagonal IEEE 802.11b/g heterogeneous and IEEE 802.11g homogeneous networks are compared in Fig. 12 for data rates 6 and 54 Mbps. A degradation in energy-efficiency is observed for the heterogeneous network for moderate-to-high traffic loads for all the data rates. Even if the 802.11b data rate is higher than the 802.11g 6 Mbps data rate, a degradation of EPB is present. This reveals that the colliding control packets during the RTS/CTS exchange constitute the reason for a more energy-efficient homogeneous 802.11g network, due to the 6-fold basic and PLCP rates compared with that of the heterogeneous 802.11b/g network. The energy-efficiency decrease is observed to be more for higher data rates and multi-hop routing in the heterogeneous network compared with the homogeneous network. The EPB increases up to 2-times for DR = 6 Mbps, whereas it increases up to 7-times for DR = 54 Mbps for the heterogeneous network compared with the homogeneous network. The increase in EPB in the heterogeneous network is more for higher data rates and multi-hop transmissions, since the lower data and basic rates of the IEEE 802.11b nodes in the heterogeneous network occupy the channel more for one end-to-end successfully transmitted useful bit when compared to the homogeneous network. Hence, introducing different types of nodes into a large multi-hop network decreases the energy-efficiency more for joint high data rate and multi-hop routing strategy. But despite this increase, using high data rate jointly with multi-hop routing under moderate traffic loads and with direct transmission under heavy traffic loads remains to be the best strategy for minimum EPB performance for the considered heterogeneous network.

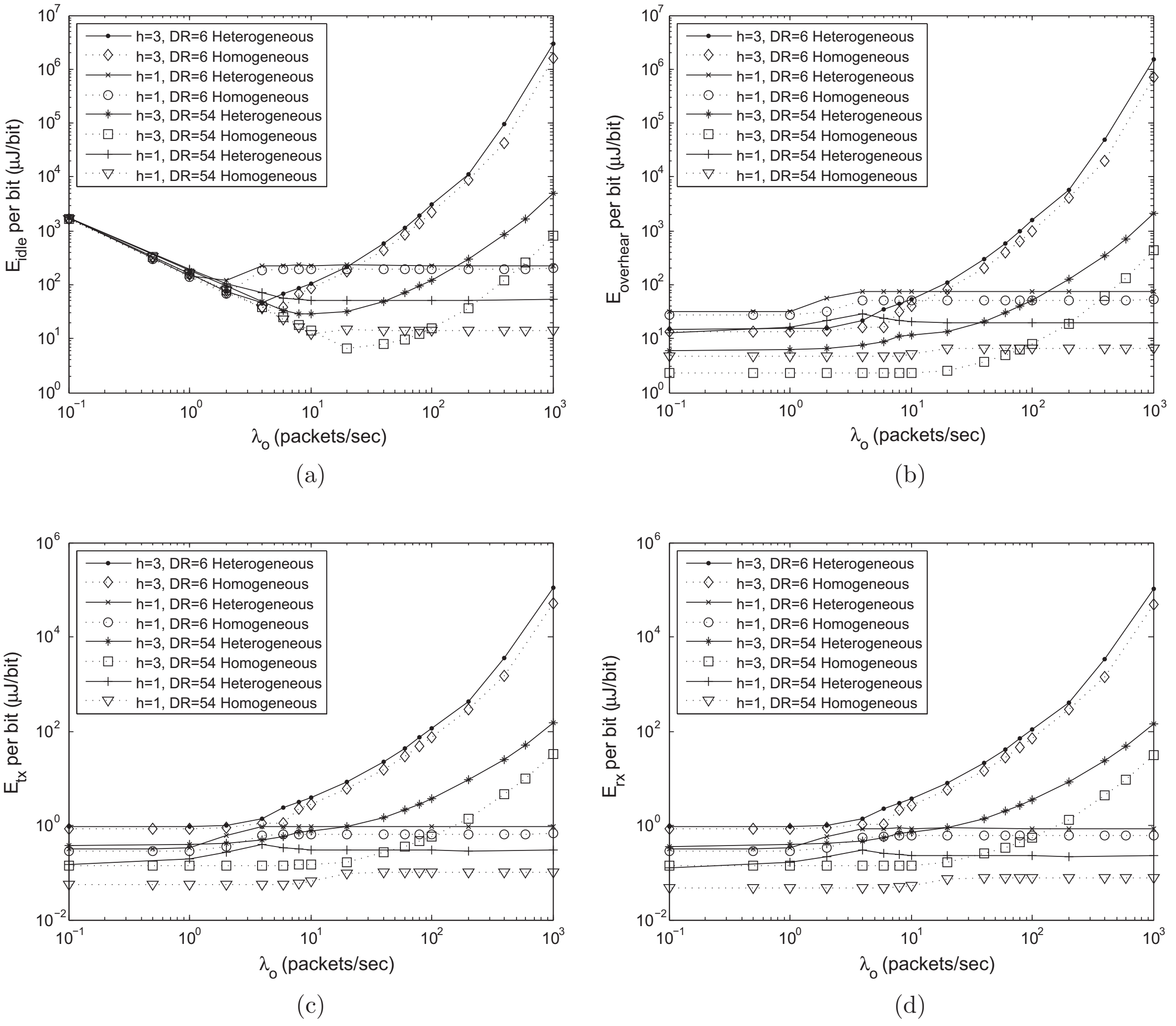


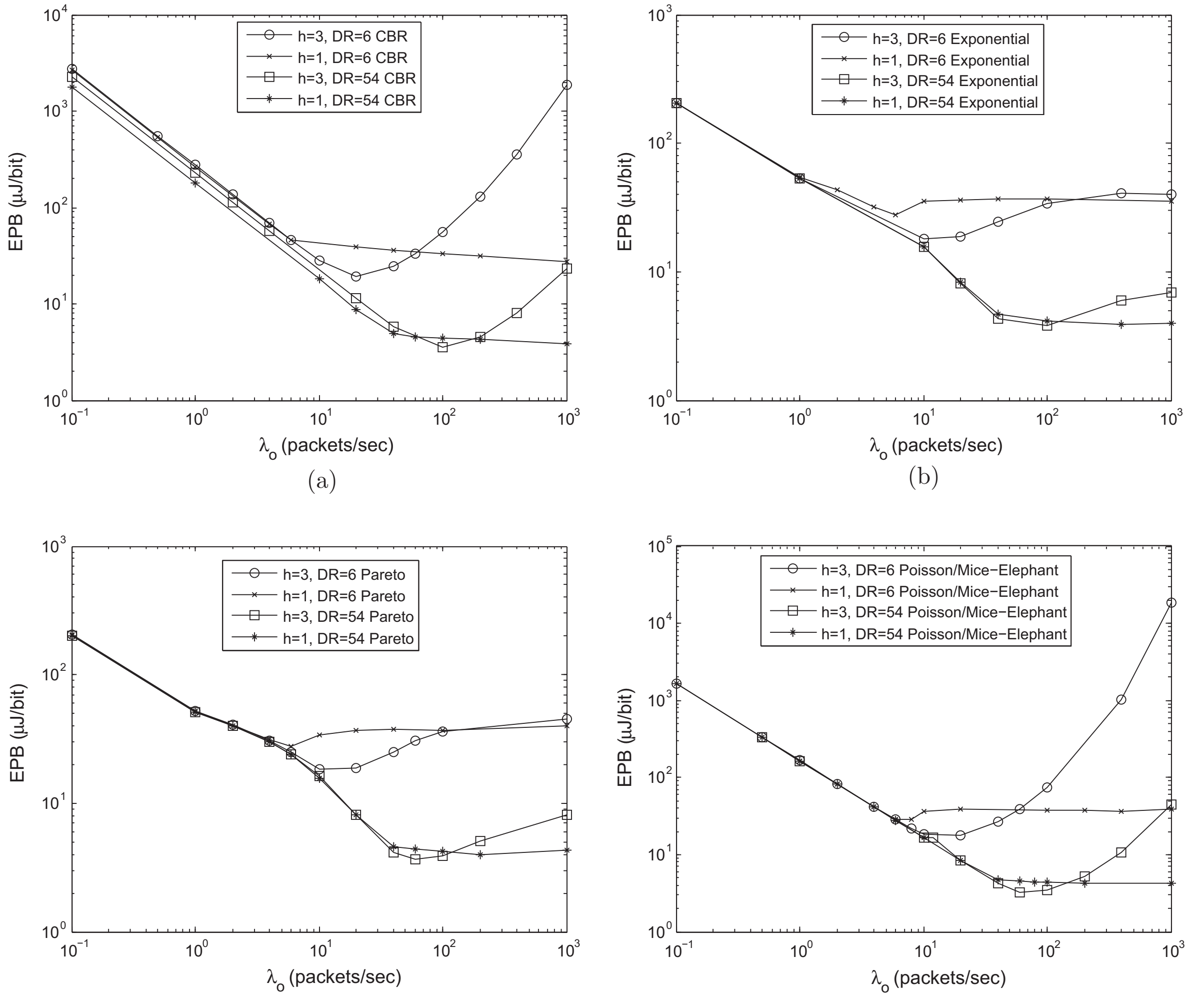
Fig. 13. Components of EPB for the homogeneous and heterogeneous 469-node hexagonal topologies for DR = {6,12,24,54} and *h* = {1,3}: (a) Idle energy per bit, (b) overhear energy per bit, (c) transmission energy per bit, and (d) reception energy per bit.

The energy components of heterogeneous network is compared with the energy components of the homogeneous network for DR = {6, 54} Mbps in Fig. 13, where the joint effect of data rate and routing strategy on the consumption of energies during idle listening (Fig. 13(a)), overhearing (Fig. 13(b)), transmission (Fig. 13(c)) and reception (Fig. 13(d)) are given. The energy components of the heterogeneous network are all shifted up and to the left when compared with the homogeneous network components given in Fig. 3. The up-shift implies an overall increase in energies per bit and the left-shift implies collisions and retransmissions starting under lower traffic loads, which stem from longer control and data packet durations of the IEEE 802.11b nodes sharing the medium. Hence, the average number of retransmissions, which determines the starting point of moderate and heavy traffic loads should be calculated for heterogeneous networks, for jointly using data rate and routing strategy in a correct manner for enhanced energy-efficiency.

4.8. Effect of different traffic types

The joint effect of data rate and routing strategy on EPB consumption is analyzed by assuming a Poisson traffic model up to this section. The effect of different traffic models on EPB performance is investigated for the following additional traffic models:

1. Constant bit rate (CBR): Each node generates a traffic with constant rate of λ_0 packets/s.
2. Exponential: Each node generates a variable bit rate traffic with ON/OFF periods. Traffic is generated during ON periods and no packets are generated during OFF periods. The ON and OFF periods are derived from an exponential distribution with an 100 ms average ON period and 900 ms average OFF period. The average rate is λ_0 packets/s.
3. Pareto: The packet arrival process is similar to the Exponential traffic model, except that both ON and OFF periods are derived from a Pareto distribution. In the simulations, the shape parameter of the Pareto distribution is set as 1.5.



(a) (b)

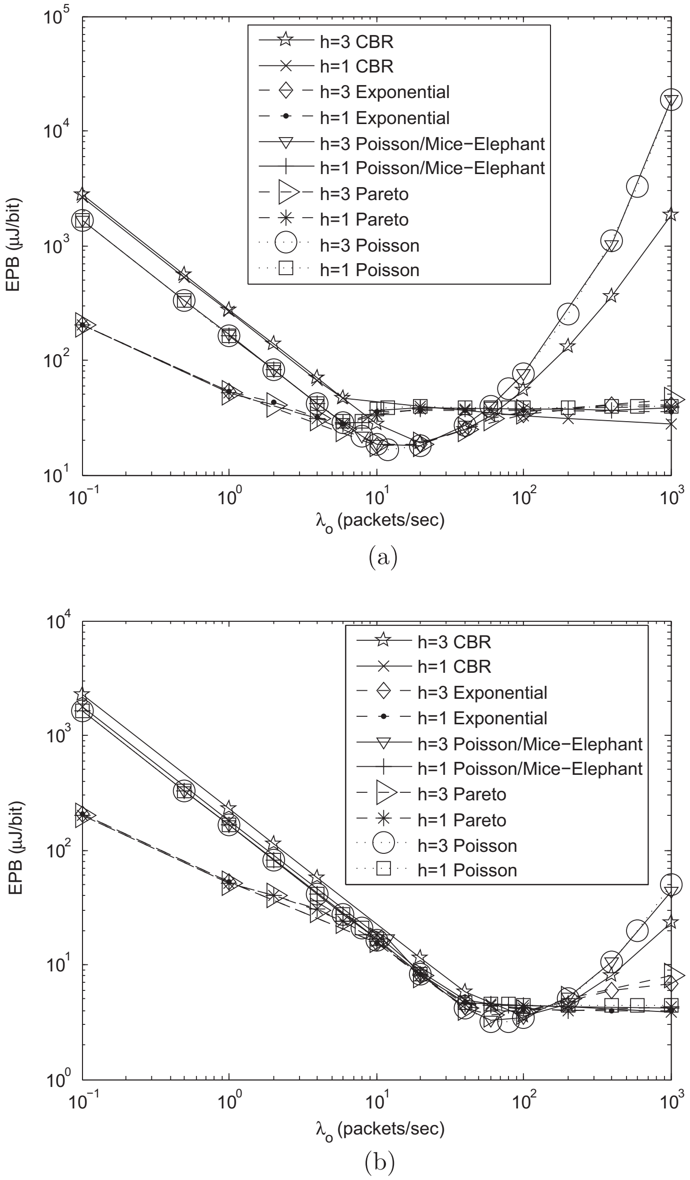
(c) (d)

Fig. 14. EPB for the 127-node hexagonal topology for DR = {6,54} and h = {1,3} for traffic types: (a) CBR, (b) exponential, (c) Pareto, and (d) Poisson with mice and elephant users.

4. Poisson with mice and elephant users: Poisson traffic model is used with a difference in user behaviors. Half of the nodes generate Poisson traffic with an average rate of 100-times that of other nodes.

The joint effect of data rate and routing strategy for the above traffic types is investigated for the 127-node-hexagonal homogeneous network and is given in Fig. 14. The results show for all traffic types, the general behavior of EPB curves still holds for joint data rate and routing strategy, i.e. the highest data rate provides the minimum EPB with multi-hop transmissions under moderate traffic loads and with direct transmissions under saturated traffic loads. All the data rates and routing strategies perform the same under unsaturated traffic loads, except with the CBR traffic, which provides minimum EPB with DR = 54 Mbps with direct transmission.

A comparison of all traffic types is given in Fig. 15(a) for DR = 6 Mbps and in Fig. 15(b) for DR = 54 Mbps. It is observed that under moderate traffic loads, the joint effect of data rate and routing strategy on EPB is almost independent of the traffic type. Different traffic types result with different EPB under unsaturated and saturated traffic loads. The Exponential and Pareto traffic models achieve significantly lower EPB consumption under unsaturated traffic loads compared to the Poisson and CBR traffic models. This is due to the lower idle and overhear energy consumption during the ON/OFF periods adopted by these



(a)

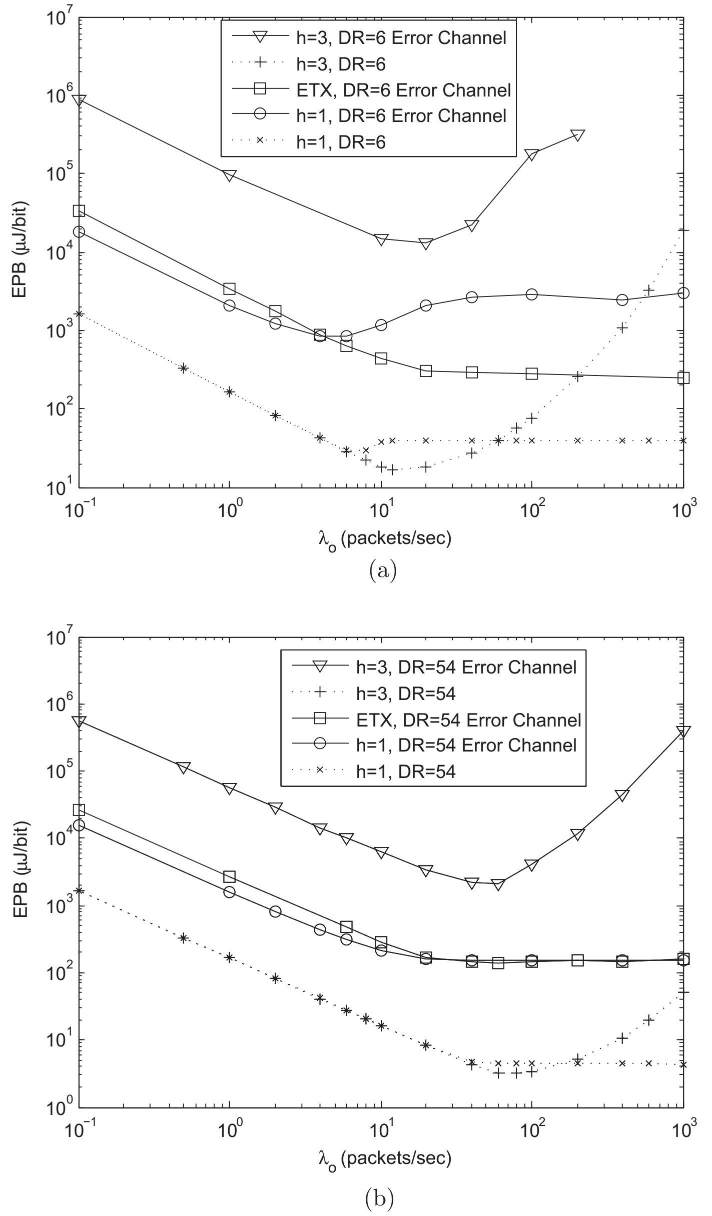
(b)

Fig. 15. A comparison of impact of different traffic models on EPB of the 127-node hexagonal topology for $h = \{1,3\}$ and for data rates (a) DR = 6 Mbps, and (b) DR = 54 Mbps.

models. The CBR traffic model is observed to consume the highest EPB under unsaturated traffic loads, due to collisions experienced by the decreased spontaneity of traffic generation. Under saturated traffic loads, the ON/OFF periods of the Exponential and Pareto traffic models are observed to introduce a control on the injected packets into the channel, providing a level of collision control and hence, the EPB consumption of these traffic types with multi-hop transmissions becomes almost constant as with direct transmissions. The mice and elephant user behavior is observed to have a negligible impact on EPB, which shows that the IFQ already provides a control on the packets injected into the channel.

4.9. EPB with another routing metric: expected transmission count

The joint effect of rate adaptation and routing strategy on energy-efficiency of multi-hop wireless networks is investigated by considering the Hop Count as the routing metric up to this point in this article. The hop count as the routing metric does not take into account the



(a)

(b)

Fig. 16. A comparison of impact of hop count and ETX routing metric in perfect channel and error channel on EPB of the 127-node hexagonal topology for $h = \{1,3\}$ and for data rates (a) DR = 6 Mbps, and (b) DR = 54 Mbps.

Table 4
The best joint data rate and routing strategies for minimizing EPB for different topologies and traffic loads.

EPB		Traffic load		
		Low	Moderate	High
Topology	127-node hexagonal	any h, any DR	$h = 3$, DR = 54	$h = 1$, DR = 54
	469-node hexagonal	any h, any DR	$h = 3$, DR = 54	$h = 1$, DR = 54
	127-node random	$h = 1$, DR = 54	$h = 1$, DR = 54	$h = 1$, DR = 54
	469-node random	$h = 1$, DR = 54	$h = 3$, DR = 54	$h = 1$, DR = 54

differences between wireless links since it considers all links to be equally good [16]. In this subsection, we consider another routing metric, the expected transmission count (ETX) introduced in [26], in order to investigate its effect on EPB jointly with data rate. We assigned random link qualities, where error is introduced to each packet with a uniform random distribution of mean 0.5. Hence, a harsh error channel is obtained where half of the packets are dropped on the average due to channel errors, additional to the IEEE 802.11 MAC collisions, hidden terminal collisions and IFQ buffer overflows. Moreover, long-scale fading, i.e. shadowing, is assumed in the channel in order to reflect real life propagation losses. The ns-2 implementation of the shadowing model is used to produce path losses of normal random distribution with zero mean and 2 dB standard deviation.

The ETX of a path is found out by summation of the number of data transmissions (including retransmissions) for a single successful transmission over all links of the path. The path with the lowest ETX routing metric is selected as the routing path. In order to attain a fair comparison among hop count and ETX metric, the same source–destination pairs are used with the same errors assigned to the same links. Uniform random errors are assigned to links independent from the length of the links and data rate in the simulations. The ETX routing metric is observed to result with routes with an average hop count of 1.8 hops and an average link length of 31.34 m, whereas the link length of $h = 3$ routes is 13.96 m.

EPB obtained by the hop count metric in Fig. 4(a) is compared with the hop count metric in error channel (with shadowing and random channel errors) and the ETX metric in Fig. 16(a) for DR = 6 Mbps and in Fig. 16(b) for DR = 54 Mbps.

Owing to the harsh error channel introduced, it is observed that energy expenditure of hop count routing with $h = 3$ increases more than 10-fold in the error channel, and even worse under saturated traffic loads. The EPB increase for $h = 3$ is more than the EPB increase for $h = 1$, so that direct transmission becomes energy-efficient for all traffic loads. ETX routing metric is observed to be advantageous under saturated traffic loads. In case of imperfect channel conditions, $DR = 54$ with hop count routing metric $h = 1$ provides the minimum energy consumption under unsaturated and moderate traffic loads, whereas ETX routing metric provides minimum EPB under saturated traffic loads.

5. Conclusion

In IEEE 802.11 DCF based networks, various data rates can be exploited in an adaptive manner depending on channel conditions to maximize the system performance. Many rate adaptation schemes proposed for single-hop networks decrease the data rate upon corrupted receptions assuming improper channel conditions. However, large and dense multi-hop wireless networks are expected to form the structure of the Internet of Things world in near future, where the hidden terminal problem emerges and constitutes the reason for a significant number of packet collisions and energy losses. Identification of the reason of packet losses, either collision or channel error, and reacting accordingly becomes important in multi-hop wireless networks.

This article aims to investigate the joint effect of data rate and routing strategy on energy per bit performance of IEEE 802.11g DCF based multi-hop wireless networks under hidden terminal existence under perfect channel conditions in order to highlight the best strategy for energy-efficiency when packet losses occur due to collisions rather than channel error. The behavior of IEEE 802.11g based multi-hop networks in an error-free, non-fading channel is observed by considering MAC contention and hidden terminals over a large range of traffic loads ranging from unsaturated to saturated by Network Simulator-2.

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 energy per bit 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 best joint data rate and routing strategies for minimizing EPB are summarized in Table 4 over a wide range of traffic loads in hexagonal and random topologies. Moreover, our results show that energy is consumed mostly during idle mode in multi-hop networks, rather than transmit and reception modes. Since the timing of idle listening is governed by the MAC protocol and is affected by the traffic load of the multi-hop wireless network, a comparison of EPB for various data rates and routing strategies is shown to require consideration of not only power ratings of transmit, reception and idle modes, but also the MAC dynamics over a large range of traffic loads. Moreover, when deactivating RTS/CTS mechanism is an option, the best strategy for energy-efficiency becomes joint use of higher data rates with multi-hop transmissions without RTS/CTS exchange under moderate traffic loads and with direct transmissions with RTS/CTS exchange under heavy traffic loads. The effect of adaptive decoding, different types of traffic models, coexistence of different standard nodes, effect of different routing metrics and error channel is investigated in this article.

In real life, channel conditions are not ideal and the packet is lost due to either hidden terminal or channel errors. If a packet is lost due to hidden terminals, adapting to a higher rate increases energy-efficiency; but if the packet is lost due to channel errors, the rate should be decreased. The results presented in this paper lay out that significant energy savings can be obtained if the reason of collisions is discriminated by rate adaptation schemes. One method for discrimination of the reason of collisions for WLANs is introduced in [3], which is an indication of the possibility of identification of the reason of packet collisions also for multi-hop wireless networks.

As a conclusion, the results of this study provides guidelines on how data rate and routing strategy jointly affect energy-efficiency, which enable designers to enhance the energy per bit performance of IEEE 802.11 DCF based multi-hop wireless networks. As a future work, we suggest that a load-aware joint data rate and routing strategy adaptation scheme, which discriminates the reason of packet drops and acts according to the results obtained in this article, might provide significant EPB gains in IEEE 802.11 DCF based multi-hop wireless networks.

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