EFFECTS OF TRANSMISSION RATE ON THE PERFORMANCE OF IEEE 802.11 DCF BASED MULTI-HOP WIRELESS NETWORKS

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ABSTRACT

EFFECTS OF TRANSMISSION RATE ON THE PERFORMANCE OF IEEE 802.11 DCF BASED MULTI-HOP WIRELESS NETWORKS

Multi-hop wireless networks offer promising applications for future communications and they differ from widespread single-hop networks. Throughput (node-to-node successfully transmitted bits per second) is an important performance metric in single-hop wireless networks, whereas goodput (end-to-end successfully delivered bits per second) becomes an indication of the performance in multi-hop networks. Energy-efficiency is another important performance metric due to the limited battery life of mobile devices. Main factors that affect the network performances are packet collisions that occur due to the hidden terminal problem and blocking of packets at interface queues at intermediate nodes in multi-hop networks. In this dissertation, the effect of transmission rate on goodput, throughput and energy performances of IEEE 802.11g DCF based on multi-hop wireless networks are investigated over a large range of traffic loads. The performances are observed under direct transmission and multi-hop transmission, considering MAC contention such as binary exponential backoff, retransmissions, collisions and overhearing of nodes. IEEE 802.11g DCF is used because it supports high data rates and has interoperability with the older version of IEEE standards. Network Simulator 2 is modified to compute the goodput, throughput and energy per bit (EPB) performance metrics under perfect channel conditions. The results reveal that varying the data rate has no effect on goodput, throughput and energy under light traffic loads. Under moderate-to-heavy traffic loads, goodput and energy efficiency performances drop sharply whereas throughput remains constant. Hidden terminals and interface queue blocking is observed to be the reason for performance reduction of increasing goodput and EPB which increase with traffic load under moderate-to-heavy traffic loads. This suggests that a rate adaptation algorithm, which discriminates the reason of packet drops and keeps the transmission rate at the maximum can improve goodput and energy performances significantly for multi-hop wireless networks.

ÖZET

IEEE 802.11 DCF BAZLI ÇOK-SEKMELİ TELSİZ AĞLARDA VERİ HIZININ PERFORMANSA ETKİLERİ

Çok-sekmeli telsiz ağlar, gelecek nesil haberleşme sistemleri için umut verici uygulamalar sunmakta ve yaygın olarak kullanılan tek sekmeli ağlardan farklılaşmaktadır. Üretilen iş (düğümler arası saniyede iletilen başarılı bit sayısı) tek sekmeli ağlarda kullanılan önemli bir performans ölçütüyken ulaştırılan iş (uç düğümler arası saniyede ulaştırılan bit sayısı) çok sekmeli ağlarda kullanılan belirgin bir performans ölçütü olmuştur. Enerji verimliliği telsiz cihazlardaki sınırlı batarya ömründen dolayı bilinen diğer bir önemli performans ölçütüdür. Çok sekmeli ağlarda saklı terminal probleminden ve arayüz kuyruğundaki ara düğümlerden dolayı paket kayıpları oluşur. Bu tezde, IEEE 802.11g DCF' e dayalı çok sekmeli telsiz ağlarda veri hızının ulaştırılan iş, üretilen iş ve enerji performanslarına etkileri geniş bir trafik yük aralığında incelenmektedir. MAC seviyesinde kanal çarpışmalarını, ikili üstel geri çekilme, yeniden iletimler, çarpışmalar ve düğümlerin kulak misafiri olmalarını göz önüne alarak performanslar doğrudan gönderim ve çok-sekmeli gönderim altında gözlemlenmiştir. Yüksek veri hızını desteklediği ve önceki IEEE standartlarıyla uyumlu olduğu için IEEE 802.11 DCF kullanılmıştır. Ağ Simülatörü 2 geliştirilerek ideal kanal koşulları altında ulaştırılan iş, üretilen iş ve her birim bit başına harcanan enerji performansları hesaplanmıştır. Sonuçlar, hafif trafik altında değişen veri hızının ulaştırılan iş, üretilen iş ve enerji üzerinde etkisi olmadığını göstermiştir. Orta şiddetten ağır şiddete doğru olan trafik yükünün altında, ulaştırılan iş ve enerji verimliliği performansları hızlıca düşerken üretilen iş sabit kalmıştır. Orta trafikten ağır trafik yüküne doğru, saklı düğümler ve arayüz kuyruk engellemesinin, trafik yüküyle artan ulaştırılan işin ve her bitteki enerjinin performans düşüşüne sebep olduğu gözlemlenmiştir. Orta ve ağır trafik yükü altında, saklı düğümler ve arayüz kuyruk engellenmesinin sebep olduğu paket kayıpları ideal kanal koşullarında ulaştırılan işi artan trafikte düşmeye zorlamaktadır. Bu sonuç paket kayıplarının sebebini ayrıştıran ve veri hızını maksimum seviyede tutan bir hız uyarlama algoritmasının ulaştırılan iş ve enerji performanslarını önemli ölçüde iyileştireceğini önermektedir.

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LIST OF ABBREVIATIONS

B	Maximum counter value
BEB	Binary Exponential Backoff
$CSMA-CA$	Carrier Sense Multiple Access with Collision Avoidance
DCF	Distributed Coordination Function
DR	Data Rate
ERP	Extended Rate Physical
EPB	Energy Per Bit
E_{tx}	Transmit energy per bit
E_{rx}	Receive energy per bit
$E_{overhear}$	Overhear energy per bit
E_{idle}	Idle energy per bit
IFQ	Interface queue between physical and MAC layers
G	Node goodput of node i
$G_n(i)$	Average node goodput
h	Number of all paths in a network
N	Total number of nodes in wireless network
n_{succ}	Number of successful transmission per path
$n_{delivered}$	Number of delivered packets
$n_{dropifq}$	Number of packets dropped at IFQ
n_{ifq}	Total number of packets dropped at IFQ
$n_{dropPackets}$	Number of dropped packets
$n_{totalPackets}$	Total number of packets
p	The probability of collision
p_{ifq}	The average interface queue blocking probability
R_{txmax}	Maximum transmission range for DR=54Mbps
S	Number of successful transmission per path
$S_n(i)$	Average node throughput
$Tsim$	Simulation duration
λ_o	Traffic load
λ_{route}	The average packet generation rate

CHAPTER 1

INTRODUCTION

A communication network can be described as a set of equipment and facilities that provide a service by which the information is transferred between users located at various geographical points. Telephone networks, computer networks, television broadcast networks, cellular telephone networks and the internet are examples of networks that use electronic or optical technologies. The Internet of Things (IoT) vision and emerging 4G services, fueled with the flexibility of mobility, leads to a world of large multi-hop wireless networks, which have the capability of conveying information through multiple hops, different from the widespread single-hop infrastructure dependent wireless access networks. Multi-hop wireless networks include networks such as the Wireless Mesh Networks (WMN), Mobile Ad Hoc Networks (MANET), Wireless Sensor Networks (WSN) and Vehicular Ad Hoc Networks (VANET), where nodes have the functionality of forwarding packets.

Wireless multi-hop networks are expected to play a significant role in future communications world, regarding emergency, military, health and vehicular applications as given in Fig 1.1. To broaden the applications, the network should be designed carefully and network performance should be improved. The demand for higher data rates in wireless networks increases each decade with increasing user needs. Hence, goodput, the amount of data delivered successfully to the destination nodes is a major challenge in the design and operation of wireless networks due to the shared wireless channel. In the shared wireless channel, simultaneous transmissions cause interference to each other and degrade the goodput performance severely compared to wired networks.

In wireless networks goodput is an important performance metric in order to provide the required quality of service, whereas energy efficiency is another major metric. Energy-efficiency studies for wireless networks, initiated first by the need of optimization of battery lifetimes in mobile ad-hoc networks and wireless sensor networks, have also focused on decreasing the comparable energy costs introduced by the infrastructure (access points/base stations) deployed at the user-end of the Internet.

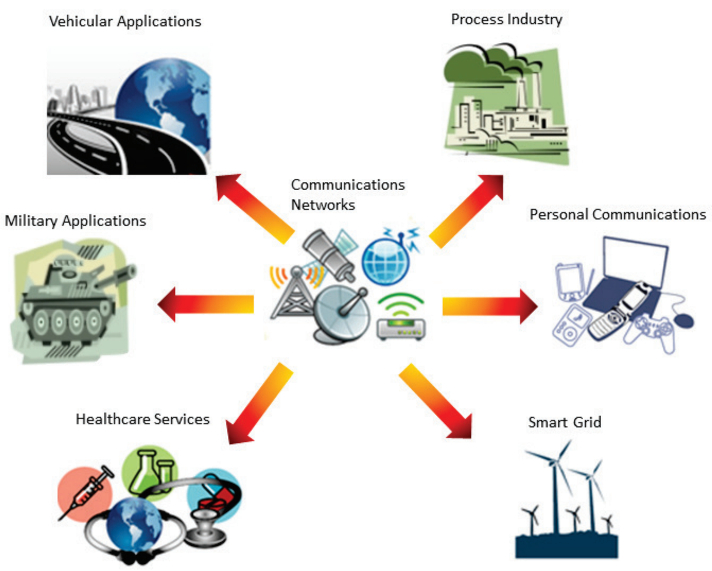


Figure 1.1. Various application areas of wireless networks

Recent studies have shown that the majority of the energy used by the Internet today is consumed in the wireless end, which is expected to increase even further in the future with increasing data rate demands and number of users, leading to multi-hop wireless networks (Al-Hazmi et al. 2011). Moreover, information and communication technology is reported to account for 2-2.5% of all harmful global carbon emissions, which is equal to the global aviation industry (Hodges and White 2008) and a decrease in emission volume of 15-30% is reported to be necessary before year 2020 to keep global temperature increase below 2^oC (Pamlin and Szomolányi 2006).

Energy per bit (EPB) performance metric provides an absolute comparison (Han et al. 2011) and green networking is defined as a way to reduce energy required to carry out a given task while maintaining the same level of performance (Bianzino et al. 2012). In comparison of direct transmission and multi-hop routing, the most energy-efficient routing strategy is the one that uses less energy to deliver the same packets successfully to the same destinations from the same sources but over different routes. Therefore, EPB is selected as the energy-efficiency metric in this study. In multi-hop wireless networks, some node-pairs can not communicate directly because the communication range of the links is limited, as a result the nodes must forward data to each other via intermediate nodes. The source node transmits a packet to a neighbouring node and the neighbouring node in turn transmits the packet to one of its neighbours until the packet is received at its destination where the rules of this forwarding is set by a chosen routing algorithm.

Multi-hop wireless networks differ from the widespread single-hop networks in three major aspects: 1) Throughput (node-to-node successfully transmitted bits per second) is an important performance metric in single-hop wireless networks, whereas goodput (end-to-end successfully delivered bits per second) becomes an indication of performance in multi-hop wireless networks; 2) A path from the source to the destination typically consists of multiple hops and accumulation of packets on intermediate nodes causes buffer overflows and packet drops at the InterFace Queue (IFQ) where IFQ is between physical and MAC layers; 3) Hidden terminal problem emerges in multi-hop wireless networks and constitutes the reason for a significant number of packet collisions. Hidden terminal effect is a problem in multi hop networks and it may degrade the performance. The collisions can occur because of the hidden terminal, since each node behaviour depends not only on the nodes which are placed in the carrier sensing range but also the nodes placed outside the carrier sensing range.

Multi-hop wireless networks are important in the wireless networks because they can be used to extend the coverage when the maximum transmit power of the source is not enough to send packets to the destination. However, there are some challenges in multi-hopping. One major challenge of wireless multi-hop networks is the limited capacity which is further reduced by the additional load imposed by multi-hop transmissions (Gupta and Kumar 2000).

Rate adaptation is considered to be one of the basic techniques to enhance capacity in multi-hop wireless networks. The basic mechanism of a Rate Adaptation Algorithm (RAA) is to adapt the transmission rate at the physical layer to channel conditions by changing the modulation and coding scheme. The RAAs in the literature are proposed for single-hop wireless networks where packet collisions occur due to changing channel conditions and the aim is to maximize the throughput. Hence, these RAAs may not be optimal for achieving maximum goodput and minimum energy in multi-hop wireless networks, where packet collisions also occur due to hidden terminals and IFQ blocking.

The fundamental question underlying this dissertation is as follows: " What is the effect of transmission rate on the goodput, throughput and energy performances of multi-hop wireless networks for changing traffic loads, network size and routing strategies ? ". To answer this question, Network Simulator 2 (NS-2) (Simulator 2001) simulations are conducted on various size and density of regular and random topologies in which the nodes have any functionality: any combination of source, sink and relay. The hidden terminals are considered in order to incorporate multi-hop characteristics.

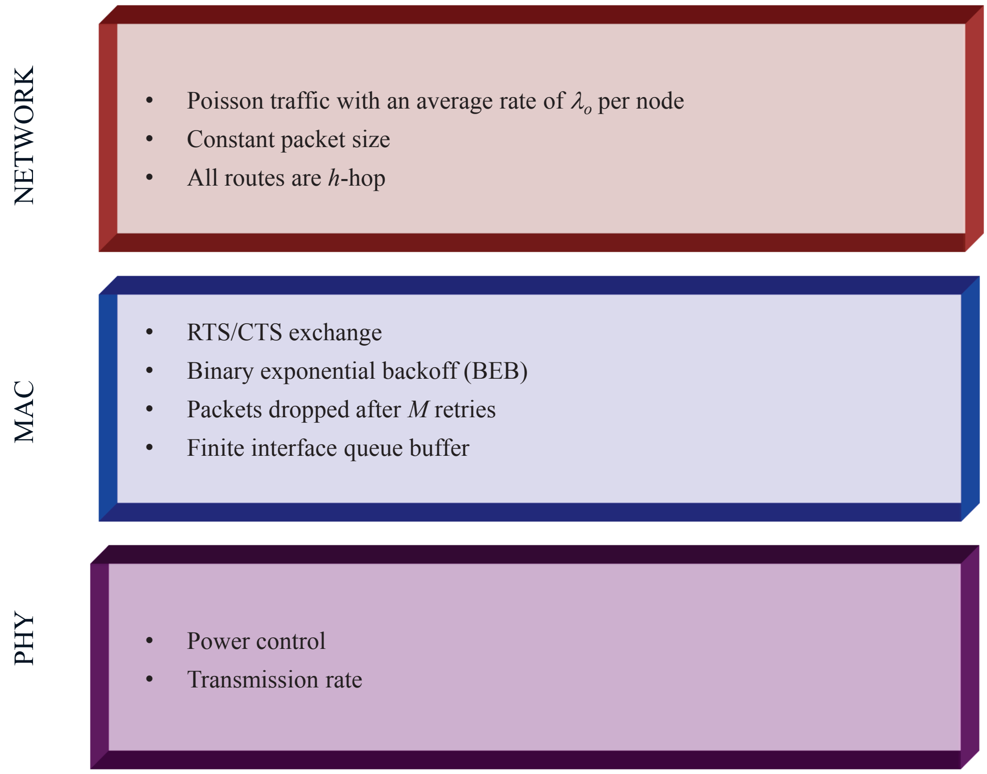


Figure 1.2. The mechanisms considered in physical, MAC and network layers

The mechanisms considered in each layer are shown in Fig. 1.2. At the physical layer, various transmission rates and power control are considered. IEEE 802.11g DCF is used as a Medium Access Control (MAC) protocol, and the dynamics of MAC such as retransmission, Binary Exponential Backoff (BEB) and collisions are considered. Various routing strategies are adopted in order to include the effect of the network layer. Fixed routing is used where either multi-hop routing or direct transmission is used between any source and destination nodes.

1.1. Thesis Organization

In Chapter 2, we introduce multi-hop wireless networks, the IEEE 802.11 DCF and IEEE 802.11g ERP-OFDM standards. The literature review which focuses on studies about goodput, throughput and energy performances is given in Chapter 3. Chapter 4 contributes the backbone of the dissertation where the analytical background on calculation of goodput, throughput and energy performances is provided. Moreover, the metrics and basics used for large scale fading, power control mechanisms, medium access control mechanisms, network layer routing protocol are given. Finally, assumptions and simulation settings are provided, which are followed by simulation results. Chapter 5 gives some concluding remarks which also includes a brief summary, implications of the study and suggestions for further research.

CHAPTER 2

BACKGROUND

In this chapter, we will first describe multi-hop wireless networks. Then, the features of IEEE 802.11 DCF and IEEE 802.11g ERP-OFDM standards that are relevant to this dissertation will be given respectively.

2.1. Multi-Hop Wireless Networks

An multi-hop wireless network is a collection of wireless mobile nodes where packets from source to destination traverse multiple hops. A packet is transmitted from the source node to a neighbouring node and the neighbouring node in turn transmits the packet to one of its neighbours. This process continues till the packet is transmitted to its destination. A "hop" is described as each link that a packet is sent over, and a "route" or "path" is described as the set of the links that a packet travels over from the source to the destination. These kind of networks are called "mesh networks". Multi-hop wireless networks constitute a general class of wireless networks which includes WMNs, VANETs, etc., where routes are composed of more than one hop.

Multiple nodes are required to reach other nodes in the network because the transmission range of the nodes are limited. Each node in the multi-hop wireless network wishing to participate must be willing to forward packets to the other nodes which indicates that each node acts as a router and host. This is an advantage of multi-hop wireless networks because the network may not require the construction of expensive infrastructure and network administration.

Figure 2.1 is a multi-hop wireless network in which the source node S sends data to node D via R_1 and R_2 nodes, using multiple hops. Multi-hop networks are used to extend the coverage when the maximum transmit power of the source station is not enough to reach the destination.

Multi-hopping functionality becomes optional in denser wireless networks where possible intermediate nodes exist in between source and destination and the transmit

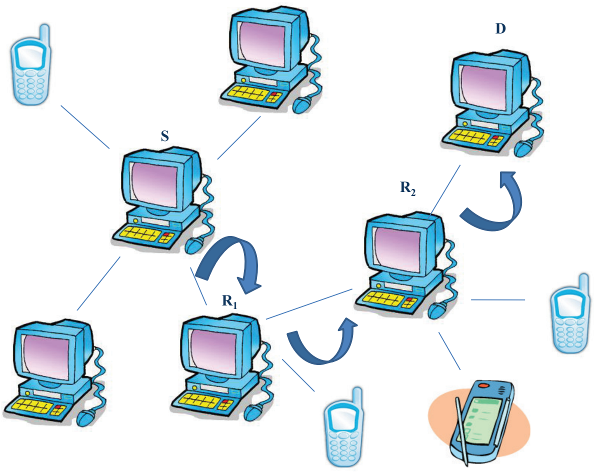


Figure 2.1. A multi-hop network

power of the source station is enough to transmit directly to the destination.

However, there are some challenges in multi-hopping such as the limitation of the two substantial resources, the energy and the bandwidth. Energy is limited for mobile stations due to battery supplied appliances and bandwidth is limited due to the shared error-prone-time-varying wireless nature of the communication channel. Innovative cross-layered designs for energy and bandwidth efficient protocols are required to overcome these challenges. Thus, an investigation of how different protocol layers and basic principles affect performance of multi-hop wireless networks should be conducted with an extensive consideration of the layers of the OSI Model protocol stack.

2.2. IEEE 802.11 DCF

IEEE 802.11 (Committee et al. 1999) is the most popular WLAN standardized technology which plays an important role in the next generation of wireless communication systems. The initial IEEE 802.11 standard specifies radios that can operate at 1Mbps and 2Mbps in the 2.4 GHz frequency range. The standard describes three different physical layers: direct sequence spread spectrum (DSSS), frequency hopping spread spectrum (FHSS), and infrared (IR) layers. IEEE 802.11a, 802.11b and 802.11g specify additional bit-rates and packet formats. The standards are summarized briefly in Table 2.1.

802.11b provides additional higher data rates at 2.4 GHz by using DSSS and

Table 2.1. IEEE 802.11b/a/g Standards

Standard	Release	Frequency (GHz)	Bandwidth (MHz)	Data rate per stream (Mbps)	Range (m)
IEEE 802.11b	Sep 1999	2.4	20	1 2 5.5, 11	38-140
IEEE 802.11a	Sep 1999	5	20	6, 9, 12, 18, 24, 36, 48, 54	35-120
IEEE 802.11g	Jun 2005	2.4	20	6, 9, 12, 18, 24, 36, 48, 54	38-140

802.11g provides higher data rates that uses Orthogonal Frequency Division Multiplexing (OFDM). 802.11a standard also uses OFDM to split an information signal across 52 separate subcarriers to provide higher data rates at the 5 GHz unlicensed national information infrastructure (U-NII) band.

Table 2.2 illustrates the modulations and channel coding for the bit-rates used in the 802.11 standards. Some form of error correction is used by each bit rate with a coding rate, shown as k/n, where n coded bits are transmitted for every k data bits. The bit-rate is calculated by multiplying the coding rate, bits per symbol, and the number of symbols per second. While DSSS bit rates send one symbol at a time, OFDM bit rates send 48 symbols in parallel, so 6 megabits sends fewer bits per symbol and more redundancy for each bit than 5.5 megabits even though it has a higher bit rate.

All of the 802.11 packets include a small preamble which has a low bit rate before the data payload. The preamble includes the packet length, the bit-rate for the data payload, and some equivalence information calculated over the preamble contents. For instance, the preamble is sent at 1 megabit in 802.11b and 6 megabits in 802.11g and 802.11a.

The 802.11 MAC standard specifies two access mechanisms, the Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF is the basic MAC mechanism, based on the carrier sensing multiple access with collision avoidance (CSMA-CA) protocol, which is introduced to avoid the collision. A channel can be monitored by carrier sensing which determines whether the medium is idle or busy. If the medium is busy, it does not make sense for a station to transmit its frame and cause a collision which means waste bandwidth. To avoid the collisions, each station should wait for

Table 2.2. A summary of the IEEE 802.11g bit-rates. Each bit-rate uses a specific combination of modulation and channel coding

Bit-rate	802.11 Standards	DSSS or OFDM	Modulation	Bits per Symbol	Coding Rate	Mega-Symbols per second
1	b	DSSS	BPSK	1	1/11	11
2	b	DSSS	QPSK	2	1/11	11
5.5	b	DSSS	CCK	1	4/8	11
11	b	DSSS	CCK	2	4/8	11
6	a/g	OFDM	BPSK	1	1/2	12
9	a/g	OFDM	BPSK	1	3/4	12
12	a/g	OFDM	QPSK	2	1/2	12
18	a/g	OFDM	QPSK	2	3/4	12
24	a/g	OFDM	QAM-16	4	1/2	12
36	a/g	OFDM	QAM-16	4	3/4	12
48	a/g	OFDM	QAM-64	6	2/3	12
54	a/g	OFDM	QAM-64	6	3/4	12

the channel to be available before making an attempt to transmit. However, other stations also wait for the channel to become idle. If the station transmits immediately after the channel becomes idle, the collisions are likely to occur and the channel is occupied for a long time due to the lack of collision detection. To solve this problem, the time during which the contending stations attempt to seize the channel is randomized. This random time is called as backoff time.

The binary exponential backoff (BEB) procedure adopted by DCF is given by

$$W_b = \begin{cases} W_o, & b = 0 \\ 2^b W_o, & 0 \leq b < B \\ 2^B W_o, & B \leq b < M \end{cases} \tag{2.1}$$

where W_b is the maximum value of backoff counter, B is the collision number, W_o is minimum contention window size, M is maximum retry count and b is the backoff stage. After every failed transmission, the backoff stage is doubled, whereas reset to zero after a successful transmission. The back-off counter is decremented until the medium becomes

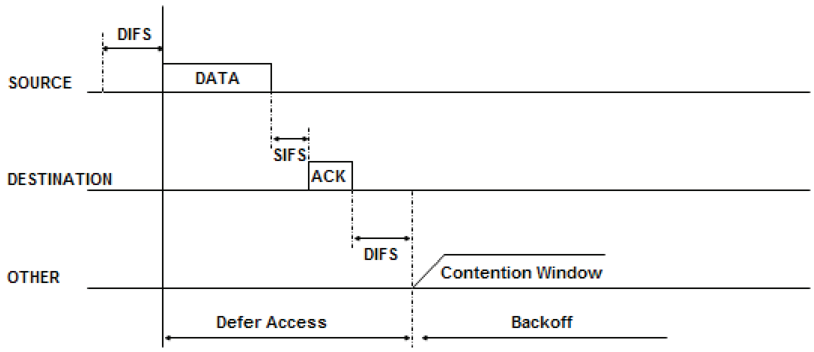


Figure 2.2. The basic access procedure of DCF

busy or until the timer reaches zero.

Fig. 2.2 illustrates the basic access procedure of DCF. After a transmission has been completed, all stations should remain quiet for a certain minimum period which is called Interframe space (IFS). The type of the frame defines the length of the IFS. High priority frames should only wait the short IFS (SIFS) period before they contend for the channel. The PCF interface space (PIFS) is another interframe space which is less than DIFS and greater than SIFS. The DCF interframe space (DIFS) is applied by used the DCF to transmit data. The station starts transmission if the station detects the medium is idle for a period DIFS or greater. On the other hand, if the station detects the medium is busy, it must calculate a random backoff time to perform a reattempt.

During this schedule, the station monitors the medium and decrements a counter. The station is allowed to transmit when its backoff timer expires during the contention period. If there is another station which transmits during the contention period before the given station, then the backoff procedure stops and resumes the next time a contention period takes place. When a frame transmission is completed successfully and the station has another frame to transmit, the station must first execute the backoff procedure. The station which has already been contending for the channel tends to access the medium sooner than stations with new frames.

Fig. 2.3 shows a hidden-station problem in which both A and C are in the range of B but they are not in the range of each other. If C wants to send B a data packet while A has already started transmitting, C can not realize that B is busy. As a result, a collision occurs at B and the transmission fails.

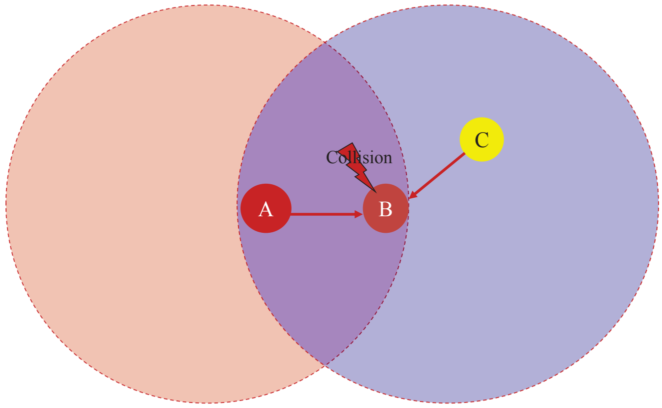


Figure 2.3. The hidden-terminal problem: C is a hidden terminal for A → B transmission

A handshake procedure was developed to operate with CSMA-CA to overcome the hidden-station problem. If a station (source) wants to send a data frame to another station (destination), it first sends a request-to-send (RTS) frame. If the destination receives the RTS frame, then it issues a clear-to-send (CTS) frame.

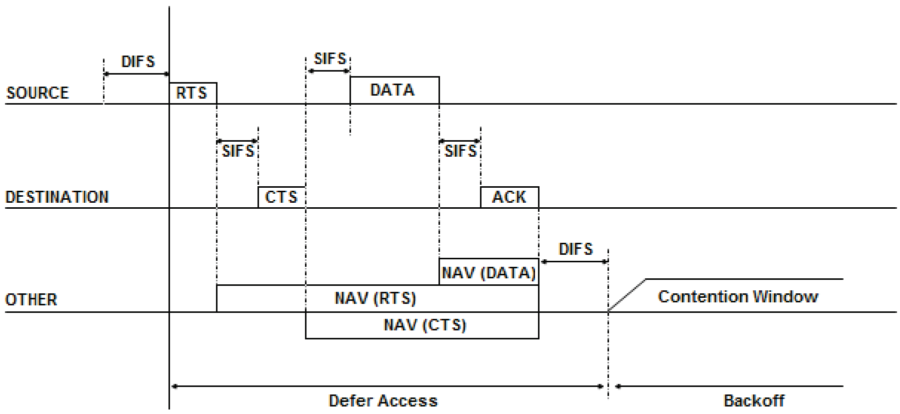


Figure 2.4. The RTS/CTS mechanism

All of the stations within the range of destination receive the CTS frame and they remain quite while this transmission. If the data is transmitted without error, destination responds with an acknowledgement (ACK). During this procedure, CSMA-CA coordinates stations, by considering hidden stations, so collisions are avoided. Two stations can still send RTS frames at the same time so they can collide at the destination. In this case, a backoff timer is executed by the stations to schedule a later attempt. Having RTS frames collide is preferable to having data frames collide because RTS frames are much shorter than data frames. The stations which detect a duration field in a transmitted data frame adjust their network allocation vector (NAV), which shows the amount of time that must elapse until the current transmission is complete and the channel becomes idle. The scheme of an RTS/CTS mechanism is shown in Fig. 2.4.

2.3. IEEE 802.11g ERP-OFDM

In this dissertation, IEEE 802.11g standard (Committee et al. 2003) which supports data rates up to 54 Mbps at 2.4GHz ISM band is used, and it is based on Direct Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplexing (OFDM). In 802.11g, four different physical layers are provided as Extended Rate Physicals (ERPs): ERP-DSSS/CCK, ERP-OFDM, ERP-DSSS/PBCC and DSSS-OFDM, where the first two layers are mandatory.

The first one, ERP-DSSS with complementary code keying (CCK) is the old physical layer used by IEEE 802.11b standard. In this layer, DSSS technology is used with CCK modulation. The second one, ERP-OFDM physical layer is introduced by IEEE 802.11g in which OFDM is used to provide higher date rates at 2.4GHz band. The third one, ERP-DSSS/PBCC is developed by IEEE 802.11b which provides the same data rate as the first layer by using DSSS technology with the packet binary convolutional coding (PBCC) algorithm. IEEE 802.11g standard extends the set of data rates of this layer by adding 22Mbps and 33Mbps. The last one, DSSS-OFDM is a new physical layer in which a hybrid combination of DSSS and OFDM is used. In this layer, DSSS is used in preamble and header transmission while OFDM is used in the payload transmission. This hybrid approach covers the interoperability aspects. The 2.4 GHz ISM band is a shared medium, so interoperability with other devices is an important issue for maintaining high performance.

In IEEE 802.11 standards, the physical layer packet overhead of a packet consists of two parts: the Physical Layer Convergence Protocol (PLCP) preamble is used for synchronization, and the PLCP header in which packet information about physical layer is held. Due to the fact that PLCP preamble is too long, an option to support a shorter type of preamble has been introduced to reduce packet overhead by IEEE 802.11 group. Even though the mandatory use of the short preamble option is recommended by IEEE 802.11g, there are both short and long options for the ERP-DSSS/CCK, ERP-DSSS/PBCC and DSSS-OFDM physical layers. However, there is only one type of preamble and header for ERP-OFDM physical layer.

The IEEE 802.11g standard defines an ERP network attribute to incorporate dynamic adjusment of the slot time and minimum contention window values. The ERP network attribute can be described as a flag which is published to the stations via a beacon frame. Beacon frame is known as a control frame which contains information of the network. If all of the stations in a WLAN have a capability to support ERP-OFDM data rates (6Mbps-54Mbps), ERP attribute is enabled. In this case, the slot time and minimum contention window values depend on the WLAN mode of operation which is either basic service set (BSS)or independent basic service set (IBSS). In the first one, BSS operation, the slot time is set to 9us and the minimum contention window is set to 15 slots if the ERP attribute is enabled. In the second case, IBSS operation, the slot time is set to 20us and the minimum contention window is set to 15 slots if the ERP is enabled.

CHAPTER 3

GOODPUT, THROUGHPUT AND ENERGY PERFORMANCES OF IEEE 802.11 DCF

IEEE 802.11 WLANs have became one of the most important technologies for wireless communications recently. As users' demand for higher data rated, lower latency and higher energy-efficiency wireless services increase and wireless technologies need more development in the quality of service supplied.

Our essential quality of service metric is the data rate of the information, which is an indication of the speed of information flow. However, the wireless channel is a shared medium and has limited bandwidth. Federal communications commissions regulate the access to the spectrum for different uses which results in bandwidth limitation for mobile wireless networks.

Information speed performance in wireless networks is fundamentally different from traditional networks. In wireless networking applications, it is complicated to provide adequate information speed due to the lack of accurate knowledge of the state of the network [e.g. availability of routers, the quality of the radio links and their resources] (Chakrabarti and Mishra 2001). In addition to this, information speed is also decreased by the time varying conditions and error-prone wireless channel. Moreover, providing an adequate goodput/throughput is impossible if the nodes are too mobile or a node looses its connectivity with the rest of the network. In order to indicate information speed, the terms throughput and goodput are mostly used.

Another important performance goal in wireless networks is energy efficiency which is related to the limited battery life of mobile devices. There are many exciting wireless networking applications where energy-efficiency is an important design issue. The reason for this is that many wireless services depends on battery powered devices. Portable, lightweight devices often access wireless medium and those devices are only supported by a local battery. The amount of energy available is limited for each user, requiring energy-efficient protocols in order to maximize node lifetime. Moreover, green networking concerns have increased during the last decade targeting at a lower gas emission and cost.

3.1. Goodput and Throughput Performance

The goodput definitions vary between different disciplines.In computer networks, goodput is defined as the application level throughput which is the number of effective bits per unit. The duration starts from the time that a packet is forwarded by the network from a source to a destination, excluding retransmitted data packets, packet headers and protocol overheads. In communication systems theory, goodput is the information transmission rate times the probability of success which is assumed that there is no change in channel statistics. This approach is problematic when it comes to increase the channel error rates and error bursts (Giovanidis 2010). Also, goodput is defined as the ratio of completed user data rate over channel data rate (Ci and Sharif 2005).

In this dissertation, we specially consider average node goodput which is identified as *the number of data bits per second received successfully by the destination from any source, averaged over all nodes in the wireless network*. The average goodput is shown to be proportional to the offered load under unsaturated traffic loads whereas it is proportional to the constant C under saturated traffic loads as given by (Aydogdu 2010).

$$C = \begin{cases} (1-p^M)^{h-1}(1-p_{ifq})^{h-1}, & \text{if } h > 1 \\ \dfrac{p^M}{(1-p^M)}, & \text{if } h = 1 \end{cases} \tag{3.1}$$

where h is the number of hop counts, p is the conditional probability, p_{ifq} is packet drop with probability, M is the maximum retry count and $h = 1$ implies direct transmissions and h>1 is multi-hop routing. Each packet in every transmission attempt of a node collides with a conditional probability p regardless of the number of retransmissions. Packets are dropped after unsuccessful retries with probability of p^M. Moreover, the overflow of the finite sized IFQ, identified between MAC and physical layers, results in packet drops. As the collision and IFQ blocking probabilities increase, i.e. contention increases, the average goodput decreases significantly for multi-hop transmissions compared to direct transmissions.

Throughput is defined as the link layer data rate of successful transmissions. The average node throughput is *the data rate of successful transmissions of a node, including retransmission because of collisions*. The dropped data packets at some intermediate hops are not counted in calculation of goodput whereas they are counted in calculation of throughput. In multi-hop wireless networks, the goodput is much lower than throughput, compared to single-hop networks since packets are also dropped at intermediate nodes. Hence, goodput is normally employed to give a more accurate performance evaluation rather than throughput in multi-hop networks. Both goodput and throughput performances are vulnerable to channel quality and packet length, lower layer protocol efficiency, network load, network topology, hardware speeds, network design protocols, etc., are factors that affect goodput and throughput performances.

In this dissertation, we specially consider average node goodput and average node throughput. The average node throughput is the data rate of successful transmissions of a node, including retransmission due to collisions (Bianchi 2000), (Alizadeh-Shabdiz and Subramaniam 2006) whereas average node goodput is the number of data bits per second received successfully by the destination, averaged over all nodes in the wireless network.

Transmission rate is the rate in bits per second that data can be transmitted. IEEE 802.11 terminology, there are two different rates: data rate (DR) and basic rate (BR). Data rate is the transmission rate of data packets, whereas basic rate is the transmission rate of control packets, such as RTS, CTS, etc. In 802.11g, DR and BR can take the following values: DR={6,9,12,24,36,48,54} and BR={6,12,24} (Committee et al. 2003). Whenever we use the transmission rate in this dissertation, we mean the (DR, BR) pair.

In the literature, it is assumed that increasing the transmission rate increases the goodput and throughput. Various rate adaptation algorithms proposed in the literature are all based on this assumption and increase the transmission rate when channel conditions are good and decrease the transmission rate whenever channel quality is poor.

In this dissertation, we aim to investigate the validity of this assumption in case of hidden terminals for various routing strategies and a large range of traffic loads ranging from unsaturated to saturated.

3.2. Energy Performance

The improvements in wireless services such as mobile data, personal communications services (PCS) and wireless LANs show that accessibility and portability has a significant value as key feature of communications. The utility of wireless devices has a maximum value when they are useful in anywhere but finite power supplies limit the value of wireless devices.

Communication between two mobile nodes can be provided either in a single hop transmission if each node is within the transmission range of the other or in multi-hop transmissions where intermediate mobile nodes are used to relay the message.

In multi-hop wireless networks, two important issues are discussed:

1 The lightweight mobile devices such as smart-phones have relatively limited battery power.

2 The cost of the transmission energy required are much more than computing cost for individual devices (Banerjee and Misra 2002).

The effective usage of power devices is defined as energy efficiency which aims to maximize the network lifetime or each individual node lifetime, or to minimize energy per bit (EPB) delivered. The network lifetime is the time duration until the first node failure because of battery depletion (Chang and Tassiulas 2000), (Kang and Poovendran 2003) since the network can be partitioned by a single node failure and the further services can be interrupted. The individual node lifetimes can be prolonged by maximizing i) the fraction of surviving nodes in a network (Wattenhofer et al. 2001), (Xu et al. 2001), ii) the minimum residual battery available among all of nodes (Liang 2005), and iii) the mean expiration time (Liang 2005).

EPB is minimized to achieve energy efficiency and EPB is defined as the energy consumed at all layers of protocol stack for delivering one bit of information to the destination. The energy consumption is affected by various modulation techniques, MAC techniques, retransmission strategies and routing.

In this dissertation, we will use *energy per bit (EPB)* as a energy performance metric because it is more important than the network lifetimes in an wireless network. Energy Per Bit (EPB) is defined as the total energy cost of transmitting one successful bit over a path, the formula of EPB in multi-hop wireless networks is given by

$$EPB = E_{tx} + E_{rx} + E_{overhear} + E_{idle} \tag{3.2}$$

where E_{tx} and E_{rx} is the total energy per bit consumed by all path nodes for transmitting and receiving, respectively. $E_{overhear}$ is the total energy per bit consumed by all path and neighbour nodes while overhearing, and E_{idle} is the energy spent during idle modes of the transceiver. Path nodes are defined as the source and destination nodes plus any relay nodes in between. The nodes which are inside the union of transmission areas of all path nodes are called as neighbouring nodes, excluding the path nodes. The energy is consumed by the path nodes while transmitting, receiving and overhearing, and it is consumed by neighbour nodes while overhearing. During the idle mode, energy is spent if the nodes do not sleep.

3.3. Related Work

To the best of our knowledge, there is no study on investigation of the effect of transmission rate on goodput and/or throughput performance of multi-hop wireless networks. This is understandable because in single-hop wireless networks where no hidden terminals exist, the more information you pump into the network the more you receive at the end nodes per second. But the situation may be different for multi-hop networks where the hidden terminal problem emerges and it may be different for various routing strategies under various traffic loads. Hence, rate adaptation algorithms proposed for single-hop wireless networks may fail in multi-hop networks with hidden terminals under different traffic loads. This dissertation includes a simulative performance analysis of the effect of transmission rate on goodput, throughput and energy performances in IEEE 802.11 DCF based multi-hop wireless networks.

This section discusses previous researches related to the goodput/throughput performances of IEEE 802.11 DCF and the rate adaptation algorithms which have been proposed to improve the system performance. Moreover, the energy-efficiency in the literature will be discussed at the end of the Section 3.3..

The wide deployment of IEEE 802.11 devices has caused an increase in the demand of multi-hop networks. The applications have been extended to multi-hop networks to carry out the need of high speed connectivity. In the literature, there are some approximate models or simulations, proposing to investigate the throughput in wireless single-hop and multi-hop networks.

The performance of single-hop wireless networks is studied in (Bianchi 2000) and many others following works (Chatzimisios et al. 2002), (Duffy et al. 2005), (Barowski et al. 2005), (Carvalho et al. 2004a), (Carvalho et al. 2004b). All of them consider single-hop wireless networks with random-access MAC protocols while none of them has included the hidden-terminal problem in their analytical models. In Bianchi (2000), the throughput performance of IEEE 802.11 DCF is evaluated under the assumption of ideal channel conditions and finite number of terminals in single-hop saturated networks.

A simple analytical model is proposed to derive the saturation throughput of collision avoidance protocols with given transmission probability of a node in multi-hop wireless networks (Wang and Garcia-Luna-Aceves 2002). A two dimensional Poisson distribution is assumed for node locations and a limiting probability is used to simplify the backoff behaviour and the channel busy status. Due to the fact that setting the transmission probability is difficult in experiments or simulations, it is difficult to verify the analytical results.

An analytical model is presented for the IEEE 802.11 DCF in multi-hop networks that considers hidden terminals and works for a large range of traffic loads (Aydogdu and Karasan 2011). The authors also propose a goodput model which consider rate reduction due to collisions, retransmissions and hidden terminals and use the model to analyse the goodput of various routing strategies in IEEE 802.11 DCF based multi-hop wireless networks.

In addition, there are some studies about the effects of rate adaptation on the goodput/throughput performance of wireless networks. The authors present the capacity of wireless ad-hoc networks by assuming a fixed transmission rate in (Gupta and Kumar 2000). In Liu and Hanzo (2005), the effects of rate adaptation on the throughput of random ad-hoc networks are investigated. The analysis shows that rate adaptation has a potential of improving the achievable throughput in compared to fixed rate transmission, since rate adaptation mitigates the effects of link quality fluctuations. The authors consider a random ad hoc network which includes n nodes uniformly and independently distributed in a unit area, which is a planar disk as in (Gupta and Kumar 2000). All nodes in the network share the same bandwidth and all packet-transmissions are slotted into perfectly synchronized time slots. The power of each transmitting node is fixed while the power control is not used.

In Xia et al. (2011), the impact of the bit-rate on the performance of IEEE 802.11 WLANs is analysed in terms of the performance metrics: effective data rate, packet loss rate and round trip time (the average time difference between the points when a packet is sent and when an acknowledgement of that packet to be received). The effective data rate is described to evaluate the link bandwidth utilization which reflects the resource efficiency as well as dependability of networks and packet loss rate is the ratio of the number of packets dropped by the network to the total number of packets sent by all hosts. Bit-rate is described as the number of bits that are conveyed or processed per unit of time which is also known as data rate or bandwidth. In the simulations, the performance metrics are calculated as a function of the number of hosts for different data-rates of 802.11b, 11 Mbps, 5.5 Mbps, 2 Mbps and 1 Mbps. According to the results, as fewer nodes compete to access the channel whereas the effective data rate is the same for various bit rates. On the other hand, as the number of hosts increases, the effective data rate increases for large bit rate of 11 Mbps. It first grows and then decreases for 5.5 and 2 Mbps and slumps for a small bit-rate of 1 Mbps. The reason is that small bit rates only can satisfy bandwidth requirements for a few hosts.

Laddomada et al. (2010) focus on multi-rate IEEE 802.11 DCF standard. The simulation results are presented for some sample scenarios in which each station generates data packets with a constant rate which depends on the channel quality performance. A modified Proportional Fairness (PF) criterion is proposed, it is suitable for mitigating the rate anomaly problems of multi-rate loaded IEEE 802.11 DCF. The authors provide a DCF model for networks with multi-rate stations derive the saturation throughput in (Yang et al. 2006). The fairness issue in 802.11 multi-rate networks is investigated by analysing various time-based fairness criteria in (Babu and Jacob 2007).

Furthermore, there has been a significant amount of research on rate adaptation algorithms in recent years. These adaptation mechanisms rely on strategies that can be broadly categorized as either physical layer measurements or frame-based estimations. In the physical layer measurements, the channel quality is measured directly by using the information from physical layer. This information includes the received signal-to-noise-ratio (SNR). The mean of a larger SNR is a higher probability of receiving data with a low bit error rate (BER).

Recent researches illustrate that adapting rates based on direct channel measurement is difficult to perform so that frame-based estimation is a good alternative. This estimation techniques are used to make decision on rate increase or decrease based on the success or failure. Some of the most known rate adaptation algorithms are the following: Automatic Rate Fallback (ARF) (Kamerman and Monteban 1997), Adaptative ARF (AARF) (Lacage et al. 2004), Collision-Aware Rate Adaptation (CARA) (Kim et al. 2006).

The studies on rate adaptation algorithms are classified in two major categories: closed loop and open loop algorithms. In closed loop algorithms, the transmitter adapts the transmission rate according to feedback from receivers. In open loop algorithms, the rate adaptation decision is made by the transmitter and there is no interactions between the transmitter and receiver, which is required in open loop algorithms. The receiver sends an Ack frame upon successful reception of a data frame. The transmitter assumes the delivery of the corresponding data frame is successful if an Ack frame receives correctly. Otherwise, the transmitter assumes that the corresponding data transmission fails if there is no Ack frame received or the Ack frame is received in error. ARF is one of the most well-known open loop algorithm (Kamerman and Monteban 1997).

In ARF, each sender increases the transmission rate if they can achieve a number of successful transmissions at a given rate. If there is 1 or 2 consecutive failures in the transmission, the rate is switched back to a lower rate. Either the number of the successfully received packets acknowledgements reaches 10 or the timer expires, the algorithm increases the transmission rate to a higher data rate. The timer expiry starts when two consecutive transmissions fail in a row.

In IEEE 802.11 standard, multiple stations contend for the shared wireless channel so that many frame collisions can occur in the channel. Many open loop rate adaptation algorithms cannot differentiate frame collisions from frame transmission failures which is caused by channel errors. The transmission rate might be decreased over-aggressively even if the channel condition is quite good. On the other hand, the closed loop rate adaptation algorithms do not suffer from collisions because the receiver dictates the rate adaptation.

One open loop algorithm is Collision-Aware Rate Adaptation (CARA) (Kim et al. 2006), used to distinguish the frame transmission failures due to poor channel conditions from frame collisions. Two methods are specified in CARA to distinguish collisions from channel errors, RTS Probing and CCA Detection. It is assumed that the transmission error probability of an RTS frame is negligible; thus, all of the RTS transmission failures are due to collisions. However, if the data transmission fails in spite of a successful RTS/CTS exchange, the failure is due to channel errors because the wireless channel has already been reserved by a successful RTS/CTS exchange and it has been guaranteed that there is no collision during the data transmission. Thereby, if the RTS/CTS frames are exchanged before each data transmission and then ARF algorithm is applied, there will be no data frame collisions so that it can be differentiated the data frame collisions from the channel-error-caused data frame transmission failure. Consequently, unnecessary rate decrements are totally avoided.

On the other hand, this approach can be the reason of the added RTS/CTS overhead which occupies the valuable wireless bandwidth. Taking into consideration, CARA proposes RTS Probing which enables RTS/CTS exchange only when there is a data frame transmission failure instead of mandating an RTS/CTS exchange before each data transmission. In RTS Probing, RTS/CTS exchange is enabled only when a data frame transmission fails. The consecutive transmission failure count, n, is compared with two different thresholds, the probe activation threshold (P_{th}) and the consecutive failure threshold (N_{th}) to make rate adjustment. The RTS/CTS frames are exchanged before the next data transmission when n reaches (P_{th}) and the data rate is lowered for the next data retransmission when n reaches N_{th}. The RTS Probing procedure works differently according to the different values of P_{th} and N_{th}, and the default values are 1 for P_{th} and 2 for N_{th}. In the default case, a data frame is transmitted without RTS/CTS support. In the case of a failure in transmission, the RTS/CTS exchange is activated for the next transmission attempt. The transmission rate is decreased if more failures are detected in data retransmission.

The second method, CCA detection, serves as a supplement to RTS Probing. After data transmission is finished, the wireless station starts assessing the channel using CCA at SIFS time and expects an Ack reception at this point of time. The collision is detected if the channel is not busy or the station has not received the ACK. In this case, there would be a retransmission without increasing failure count and lowering the transmission rate. This shows that CARA achieves better performance than other open loop rate adaptation algorithms, such as ARF, in a hidden terminal environment.

In Li et al. (2012), the proposed rate adaptation algorithm, Multiple Metrics based Rate Adaptation (MMRA), combines the metrics of expected packet transmission time, ETT, and the average number of frozen slots, ANFS. For the current channel, they try to estimate the quality and level of contention. The algorithm uses locally available information to estimate packet transmission time and level of contention for the current channel. In the system design, it is assumed a single hoop wireless LAN with fully connected topology and all the nodes are in radio range. There are totally N terminals. All of them are identical and stationary. Moreover each terminal has saturated traffic to transmit to one of its neighbours. Additionally, it is assumed that a single transceiver at each node and simultaneous transmission from more that one node will result in collision. When a source gains the channel access and starts transmitting, they assume that others will not transmit until the transmission is over.

MMRA is based on two main functionalities. First one is calculating the ETT and ANFS, and the second one is inferring the channel state and sampling-based rate adaptation algorithm. The ETT takes into consideration the mixed effects from wireless channel condition and collision. The ANFS is considered a simple metric while it is able to estimate the contention level in the channel. The algorithm starts with the highest possible data rate. Then, the ETT and ANFS are calculated by the proposed model in Li et al. (2012). Using these calculated values, it is determined that MMRA is still in the transmission mode or not. The current data rate is set to the one with the smallest calculated values if MMRA is still in the transmission mode. Conversely, MMRA switches to the sampling mode and the rate probing procedure is started.

In addition to the various studies about goodput and throughput performances, there are some studies which investigate the effect of energy performance on wireless networks. Cross-layered design of energy-efficient routing protocols play a dominant role in reducing power consumption Kozat et al. (2004), Singh et al. (1998)- Park et al. (2003). Contention at MAC layer and relaying at Network layer affect each other and energy-efficiency. Under transmit power, the energy consumed at the PHY layer decreases when switching from direct transmission to multi-hopping which decreases the number of stations in the transmission range. The decreased number of contending stations means less contention, less collisions, retransmission, backoff and freezing mechanism at MAC layer, and less overhearing which decrease the overall energy consumption. However, multi-hopping requires successful transmissions at all hops of the path and energy is lost when packet is lost at some hop. In Aydogdu and Karasan (2011), an energy model is proposed which considers energy consumption due to collisions, retransmissions, exponential backoff and freezing mechanisms, and overhearing of nodes and this model is used to analyze the energy performance of various routing strategies in IEEE 802.11 DCF based multi-hop wireless networks.

Besides all the above mentioned schemes which concern energy performance, an energy-efficiency rate adaptation algorithm is proposed in (Dou et al. 2011). ERAA (Energy-efficient Rate Adaptation Algorithm) has been designed for the WiLD (WiFi-based Long Distance) networks.

Firstly, FDR-RSSI envelope mapping has been obtained by using the proposed probing algorithm. FDR (Frame Delivery Ratio) is the probability of the frame received successfully. Then an energy-efficiency rate adaptation algorithm is proposed in which bit rate and the transmission power are selected according to the FDR-RSSI mapping to maximize the link throughput but by considering a minimal energy consumption level.

Finally, (Vassis et al. 2005) presents the features of IEEE 802.11g and evaluates the performance and effectiveness of IEEE 802.11g compared to the older IEEE 802.11 standard versions. According to the results of this article, IEEE 802.11g standard is undoubtedly the most complete of IEEE 802.11 standards family. The most important feature of 802.11g is that supports four different physical layers and combines 802.11a data rates together with backward compatibility to the old IEEE 802.11 standards.

3.4. Our Contribution

This dissertation aims to answer the following fundamental question: “How do goodput, throughput and energy performance of wireless multi-hop IEEE 802.11 DCF based networks change by variations of data rate?”

The approach used in this study differs from the literature in two aspects:

- The dynamics of medium access control such as collisions, retransmissions, and exponential backoff are considered, by using IEEE 802.11g.
- The question is analyzed for different routing strategies: direct transmission and multi-hopping.

Moreover, the effect of transmission rate is investigated over

- a large range of traffic loads,
- two-dimensional hexagonal and random topologies where hidden terminals exist and nodes may have any functionality: any combination of source, sink and relay.

The effect of transmission rate on goodput, throughput and energy performance of IEEE 802.11g DCF based multi-hop wireless networks are investigated for changing network size, traffic load and routing strategies. This investigation is limited to networks with perfect channel conditions in order to highlight the effects of packet drops due to hidden terminals, concurrent transmissions and IFQ blocking.

CHAPTER 4

PERFORMANCE EVALUATION

In this dissertation, all simulations for IEEE 802.11g are performed, using NS-2 and MATLAB. This chapter introduces the simulation settings as well as the achieved results. Firstly, the network simulator, used to obtain the results, is described. Then, the simulation settings and the results is presented in Section 4.2. and 4.3..

4.1. Network Simulator

The simulations are performed using Network Simulator 2, version ns-allinone-2.34 (Simulator 2001). NS-2 is a discrete event simulator, developed at UC Berkely. The simulator aims at providing support to networking researches. It implements networking protocols such as TCP and UPD, router queue management mechanism such as Drop Tail, CBQ and RED, traffic source behavior such as FTP, Web, CBR, Telnet and VBR and routing algorithms such as Dijkstra, DSR, etc.

NS-2 tool is useful to learn fundamentals of evaluating network performance via simulation. This object oriented simulator is written in C++, with an OTcl interpreter as a frontend. A class hierarchy is in C++ and a similar hierarchy within the OTcl interpreter are supported by the simulator. Both of these hierarchies are related to each other.

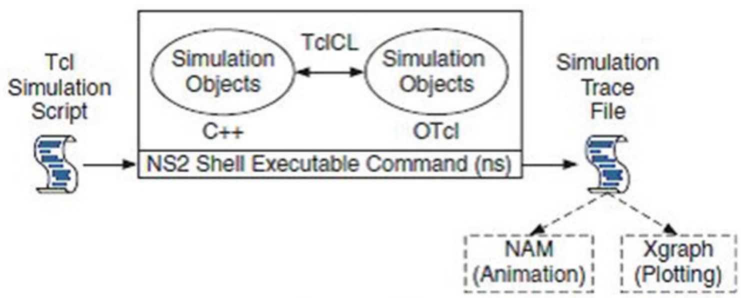


Figure 4.1. NS-2 basic architecture [Source: isi.edu (Simulator 2001)].

In the interpreted hierarchy, there is a one-to-one correspondence between a class hierarchy in C++ and a similar class hierarchy within the tcl interpreter. New simulator objects are created by using interpreter (tcl), are instantiated within the interpreter and are mirrored by corresponding objects in the class hierarchy in C++. Figure 4.1 shows us the structure of the NS-2. A tcl script file which describes the network, the traffic, node properties, wireless MAC protocol, etc., is input to the NS-2 simulator.

4.2. Assumptions and Simulation Settings

Some assumptions made by previous studies are adapted into the simulations (Ye et al. 2007), (Hsieh et al. 2001) and (Yu et al. 2008). The assumptions are as follows:

- The unified disk radio model,
- Error-free channel,
- Poisson offered traffic,
- Stationary nodes

The unified disk graph model has been widely used by many researches in wireless networking due to its simplicity in mathematical characterization of physical layer (Gupta and Kumar 2000). In this model, a successful transmission occurs if there are no simultaneous transmissions within a certain interference range from the receiver. An error-free, non-fading channel where noise is neglected, is assumed. The received power decreases with d^{η}, where d is the distance and η is the path loss component.

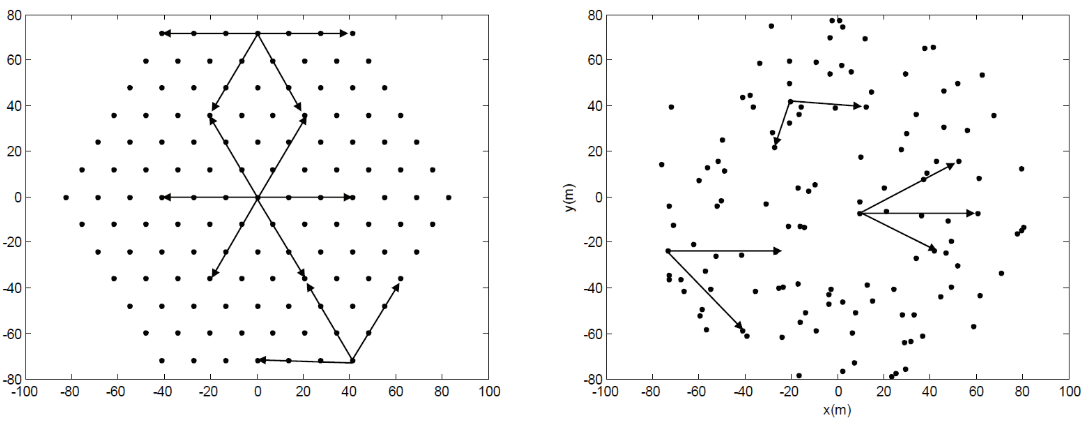
The effect of data rate is investigated for various routing strategies for a fixed traffic pattern and topology. Simulations are done for unicast traffic. All nodes in the network use the same routing strategy during a simulation and each generated packet traverses a path of h hops.

Thus, the source destination pairs with a reasonable h-hop path are computed and used in the simulations of random topologies. The source-destination pairs are chosen so that all possible linear paths carry Poisson traffic for hexagonal topologies. We use fixed routing with two different options: packets are either directly transmitted to the destination or traverse through several hops up to the destination.

Each node is assumed to generate Poisson packets with rate λ_o packet per second in all simulations. For hexagonal topologies, this generated traffic is equally divided to six and transmitted over six paths if any node is around the center of hexagonal area. Nodes at the edge of the network divide the generated traffic equally and transmit over three or four paths due to geometry of the hexagonal topology. Fig. 4.2 shows some of the selected paths for the 127-node hexagonal and random topologies, in which arrows indicate the path. In other words, traffic load over multiple paths is distributed to avoid conditions where a path is heavily loaded in a short time scale. In random topologies, the average generated packets for each node is calculated as below:

$$\lambda_{route} = \frac{N}{N_{route}} \lambda_o \tag{4.1}$$

where N is the total number of nodes in the network, N_{route} is the total number of routes in the network and λ_{route} is the average packet generation rate for a single path for random topologies.



(a) (b)

Figure 4.2. Some of the selected paths for a) 127-node hexagonal and b) 127-node random topologies (h=1)

The behavior of 802.11g is observed by considering hidden terminals in multi-hop networks for various network topologies in order to include hidden terminal effect, nodes are distributed on a circular area with radius $2R_{txmax}$. The topologies are deployed in a fixed area and different traffic pattern: two hexagonal topologies, 127 nodes and 469 nodes with multi-hop transmission and single hop transmission, h={1,3}, three randomly generated 127 node topologies and a randomly generated 469 nodes with multi-hop transmission and single hop transmission, h={1,3}. The X-Y positions of each node (X_{list}, Y_{list}) and routing list (R_{list}) between each source-destination pair are computed in MATLAB. The whole topologies are created by using MATLAB. Fig. 4.4 shows the node positions for each topology.

The source-destination pairs are chosen so that all possible linear paths carry traffic. In random topologies, the nodes are uniformly distributed within a circle of radius $2R_{txmax}$ using polar coordinates. $2R_{txmax}$ is equal to the half of the width of the hexagonal topology. To generate uniformly distributed nodes within a circle, a radius r uniformly distributed in [0, $2R_{txmax}$] and an angle theta θ uniformly distributed in [0, 2π] should be picked. However, it could result in a high density of points near the origin (0, 0), as illustrated in Fig. 4.3. More points should be generated when r increases. The polar coordinates (r, θ) of each node is determined by

$$r = 2(R_{txmax-\epsilon}) \cdot sqrt(rand()) \tag{4.2}$$

$$\theta = 2\pi \cdot rand() \tag{4.3}$$

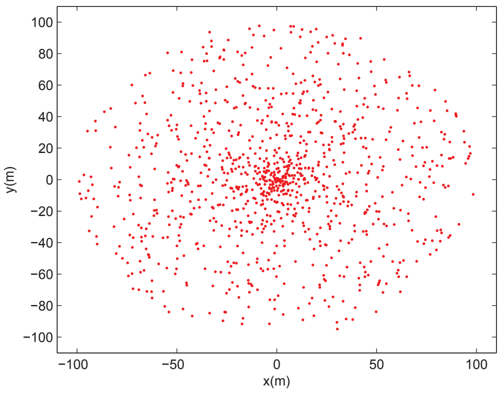
The cartesian coordinates are as follows:

$$(X, Y) = (rcos\theta, rsin\theta) \tag{4.4}$$

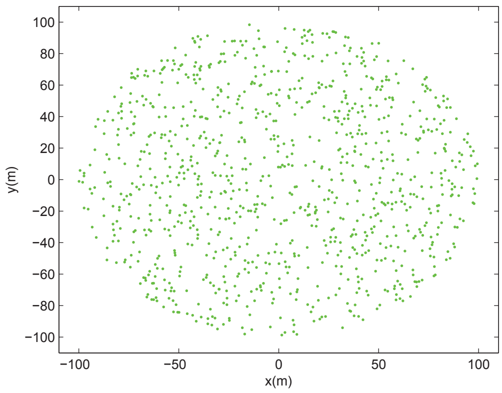
where ϵ is a small number and $rand()$ is a uniform (0,1) generator.

The simulations for IEEE 802.11g are performed for both single-hop and multi-hop routing strategies from unsaturated upto saturated traffic loads. Under the saturated traffic load, there is always at least one packet waiting in the queue upon finishing processing of the last packet.

In the case of a collision in the network, packets are retransmitted based on BEB until the node reaches the maximum retry count M. Packets are dropped after M unsuccessful retries with probability of p^M and due to overflow of the finite sized IFQ with prob-



(a)



(b)

Figure 4.3. Comparison of uniform distribution in a circular area with a) uniformity in polar coordinates r and θ b) uniformity in X and Y coordinates

ability of P_{ifq}. In the simulations, the probability of collision p and the average interface queue blocking probability p_{ifq} are calculated by the following equations respectively,

$$p = \frac{n_{dropPackets}}{n_{totalPackets}} \tag{4.5}$$

where $n_{dropPackets}$ is the number of the dropped packets for all nodes and $n_{totalPackets}$ is the total number of transmitted packets during the simulation.

$$p_{ifq} = \frac{n_{dropifq}}{n_{ifq}} \tag{4.6}$$

where $n_{dropifq}$ is the number of packets dropped at IFQ and n_{ifq} is the total number of packets which are sent to the IFQ. 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 (Vassis et al. 2005). Thus, RTS/CTS mechanism is used in this study.

The time durations of RTS, CTS/ACK and DATA are calculated according to ERP-OFDM specifications and given in Eq. 4.7, Eq. 4.8 and Eq. 4.9 respectively.

$$T_{RTS} = 20 + \lceil \frac{20 \cdot 8 + 22}{DR \cdot 4} \rceil \cdot 4 \tag{4.7}$$

$$T_{CTS/ACK} = 20 + \lceil \frac{14 \cdot 8 + 22}{DR \cdot 4} \rceil \cdot 4 \tag{4.8}$$

$$T_{DATA} = 20 + \lceil \frac{(Psize + 36 + 28) \cdot 8 + 22}{DR \cdot 4} \rceil \cdot 4 \tag{4.9}$$

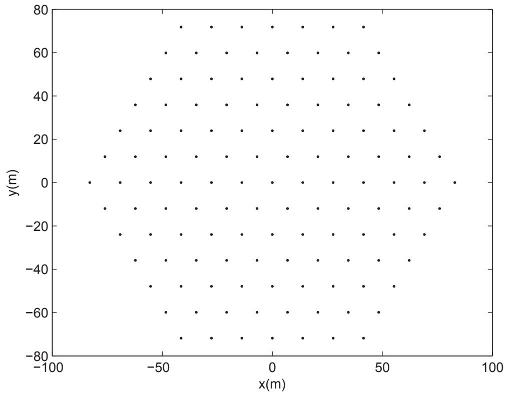
DR is the Data Rate, 4 μs is the symbol duration, and $Psize$ is the packet size and taken as 1000 bytes in all simulations.

According to the specifications, the basic rate set is equal to the mandatory rate set, which is {6, 12, 24}Mbps when using 20MHz channel spacing for an IBSS (Independent Basic Service Set). IBSS is an ad-hoc network that contains no access points. These settings are adopted since we consider the 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 4.1.

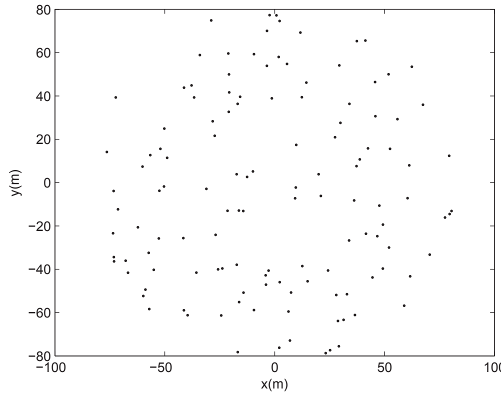
Table 4.1. Receiver sensitivities and basic rates for each data rate

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

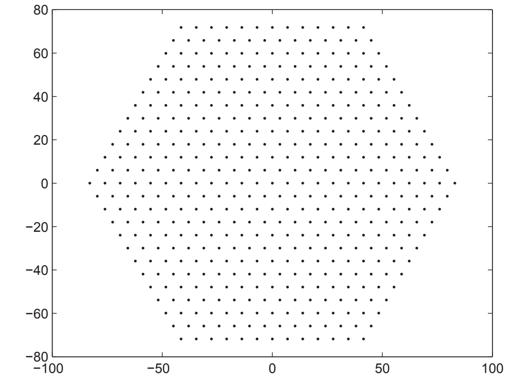
The performance evaluation of IEEE 802.11g is discussed in (Athanasopoulos et al. 2006) which concerns a variety of different data rates. The channel capacity is defined as the channel throughput under the absence of hidden terminals and clear channel conditions. Four different physical layers of the 802.11g are evaluated for a variety of different rates in various simulation scenarios. It is proved that channel throughput performance is improved using the new physical layer features while every station is provided with IEEE 802.11g wireless interface.



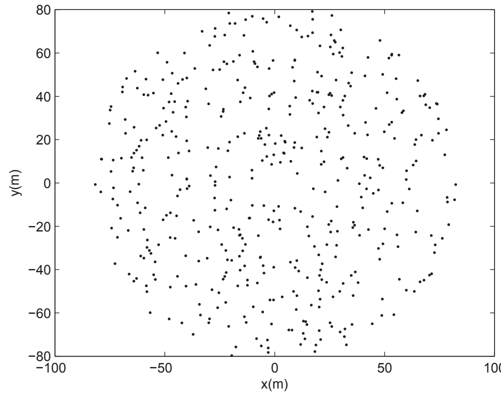
(a) 127-node hexagonal topology



(b) 127-node random topology



(c) 469-node hexagonal topology



(d) 469-node hexagonal topology

Figure 4.4. Node positions of a) 127-node hexagonal topology, b) the uniformly random distributed 127-node topology c) 469-node hexagonal topology, d) the uniformly random distributed 469-node topology

Nodes transmit at the maximum rate of 54Mbps while they reduce the transmit rate for decreasing data rates to meet the corresponding receiver-sensitivities at each data rate. In multi-hop networks, the transmission power is reduced to reach the next hop. We use the unified disk radio model where carrier sensing range is taken to be equal to transmission range.

The maximum distance between transmitter and receiver is calculated as following:

$$P_{rx} = cP_{tx}d^{-\eta} \tag{4.10}$$

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 receiver sensitivity is selected by considering the data rate as 54Mbps, -95.0 dB, and the maximum distance is found between receiver and the transmitter, then transmit power is calculated for each data rate according to this distance. Constant c is calculated as below:

$$c = \frac{G_t G_r}{L}(\frac{\lambda}{4\pi})^2 \tag{4.11}$$

where λ is wave-length while G_t is the antenna gain, G_r is the antenna reception gain and L is noise floor.

Table 4.2. Power consumption values

Pwr_{tx}	$1.425 + 0.25h^{-\eta}$ W
Pwr_{rx}	1.425 W
Pwr_{idle}	1.319 W

The simulation time is equal to a duration required to generate an average of 6000 packets per node. The parameters used in NS-2 simulations are listed in Table 4.3 which are obtained using 802.11g standard; the energy specific parameters are listed in Table 4.2 where $P_{txmax} = 0.25$ W .

```
#DSSS (IEEE802.11g)
Mac/802_11 set SlotTime_          0.000020        ;# 20us
Mac/802_11 set SIFS_              0.000010        ;# 10us
Mac/802_11 set PreambleLength_    96              ;# 96 bits=16us
Mac/802_11 set PLCPHeaderLength_  24              ;# 24 bits=4us
Mac/802_11 set PLCPDataRate_      6.0e6           ;# 6Mbps
Mac/802_11 set dataRate_          $DR             ;
Mac/802_11 set basicRate_         $BR             ;
Phy/WirelessPhy set freq_         2.472e+9
set wavelength                   [expr (3.0e+8 / 2.472e+9)]
```

Figure 4.5. The setting MAC parameters in tcl code

Fig. 4.6 illustrates the general flowchart for goodput, throughput and energy performances. In the flowchart, the entire steps in the simulations are summarized. Firstly,

Table 4.3. Parameters used for simulation runs

Data rate	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

the specific parameters such as SIFS, DIFS and slot time, are set in NS-2. The parameter setting part of the tcl code is given in Fig. 4.5.

The power settings, poisson traffic settings and fixed routing settings are done in tcl file. To use poisson traffic and fixed routing, $ns - 2.34/fixtr/fixtr \cdot cc$ and $ns - 2.34/tools/poisson.cc$ files are fed into NS-2.

The goodput, throughput and EPB performances are computed by modifying the $ns - 2.34/mac/mac - 80211.cc$ and $ns - 2.34/mac/mac - 80211.h$ files in NS-2. Firstly, the total number of delivered packets, successful transmission per path and energy consumptions are counted for each node. *Goodput* of each node i is calculated by Eq. 4.12 and Eq. 4.13, respectively.

$$G_n(i) = \frac{n_{delivered}}{T_{Sim}} \tag{4.12}$$

where $n_{delivered}$ is the number of delivered data packets to node i and T_{sim} is the total simulation duration.

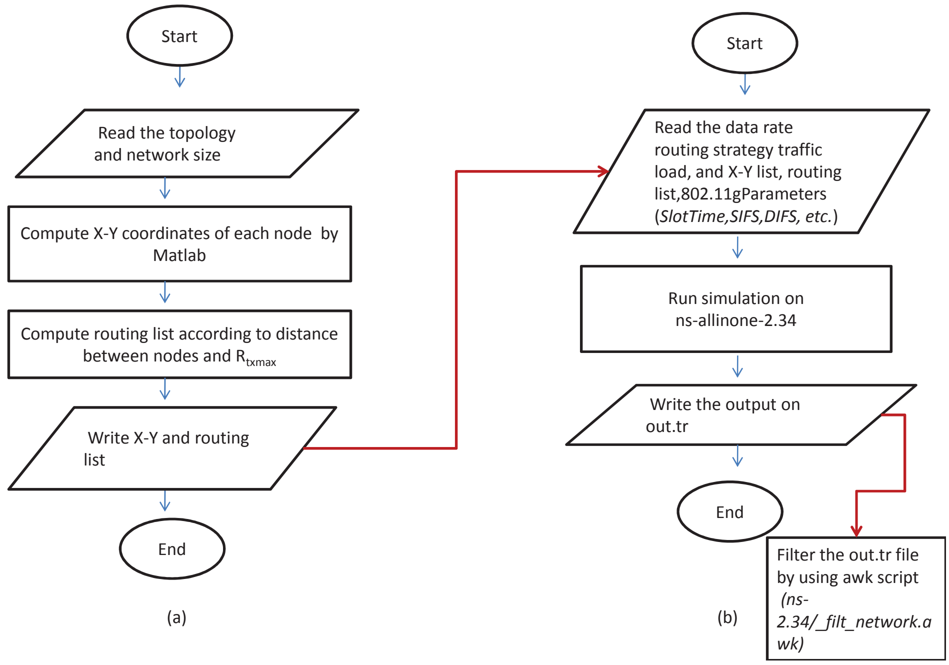


Figure 4.6. General flowchart for goodput, throughput and energy performance simulations a) MATLAB and b) NS-2

The average goodput averaged over all nodes in the network is given by

$$G = \frac{1}{N}\sum_{i=1}^{N} G_n(i) \tag{4.13}$$

where G is the average node goodput, which is computed by using filterNetwork.awk code. Awk scripts are written so as to filter the output of the simulations which include node specific information, in order to obtain average values of performance metrics.

Throughput of each node i, $S_n(i)$ is given by

$$S_n(i) = \frac{n_{success}}{T_{Sim}} \tag{4.14}$$

where $n_{success}$ is the number of successful transmission per path. The average throughputs is given by

$$S = \frac{1}{N}\sum_{i=1}^{N} S_n(i) \tag{4.15}$$

and is computed by using filterNetwork. awk code.

Energy consumption in NS-2 is computed for transmitter energy, receiver energy, idle energy and overhear energy for each node.

$$EPB = \frac{rxEnergy + txEnergy + overhearEnergy + idleEnergy}{P_{size} \cdot n_{delivered} \cdot 8} \tag{4.16}$$

where P_{size} is the number of useful bits of a $DATA$ packet, $rxEnergy$ is the total energy consumed for receiving a packet destined to itself, $txEnergy$ is the total energy consumed for transmitting a packet to the destination, $overhearEnergy$ is the total energy consumed while overhearing and $idleEnergy$ is the total energy consumed during idle modes of the transceiver.

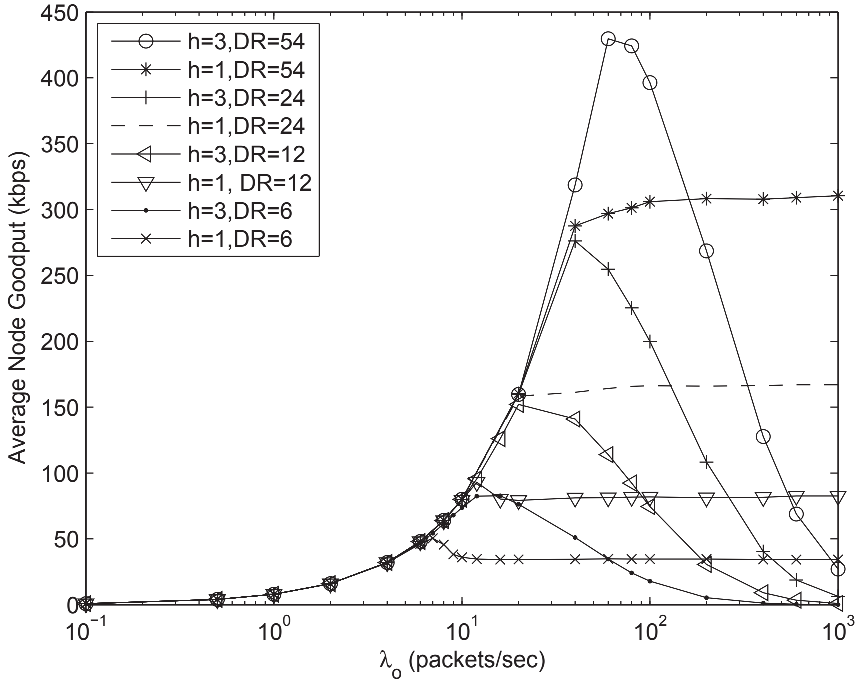
4.3. Results

In this section, the effects of data rate on goodput, throughput and EPB performances together with probability of collision (p), average interface queue blocking probability (p_{ifq}), are investigated for various traffic loads, various network size and routing strategies.

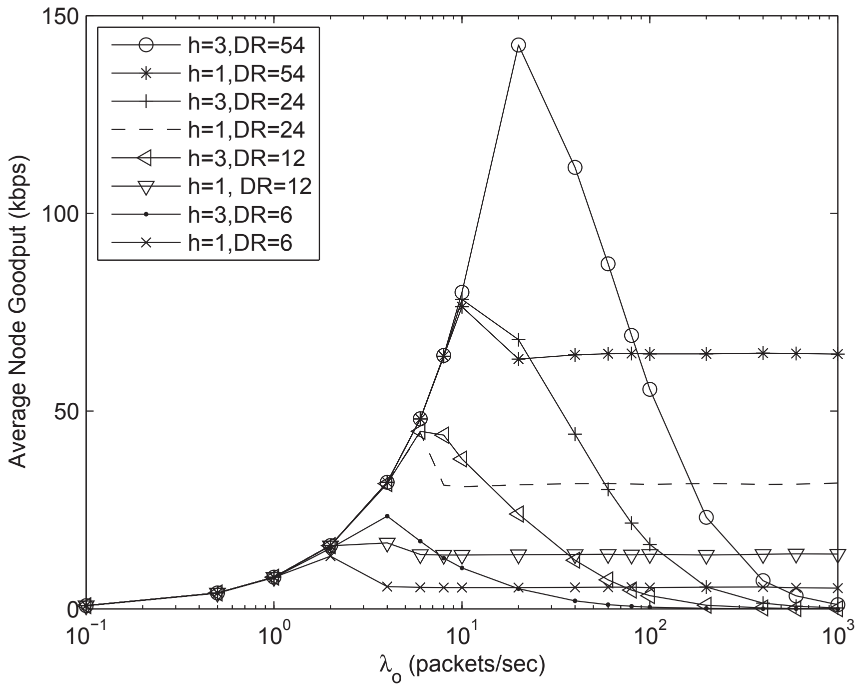
4.3.1. Average Node Goodput Performances

Average node goodput is illustrated for hexagonal topologies in Fig. 4.7. It is observed that the highest available data rate is optimum for moderate-to-heavy traffic loads, whereas any data rate maximizes goodput under light traffic loads.

The results indicate that direct transmission and multi-hopping have very close goodput performances for each data rate under light traffic loads. Under moderate traffic loads, the highest goodput is obtained at 54Mbps data rate by multi-hopping whereas goodput is maximized at 54Mbps by direct transmission for heavy traffic loads. The average of IFQ blocking probability and the average collision probability of IEEE 802.11g are pointed out in Fig. 4.8 and Fig. 4.9, respectively. It is observed that medium access



(a)



(b)

Figure 4.7. Average node goodput for the a) 127-node and b) 469-node hexagonal topologies (hop count h={1,3}, data rate DR={54,24,12,6})

control related packets drop due to concurrent transmissions while hidden terminals occur under moderate-to-saturated traffic loads with the relation given in Equation 3.1.

Under unsaturated traffic loads, changing the data rate has no effects on the goodput. Packet drops due to hidden terminals, concurrent transmissions and IFQ blocking may cause a load-unaware RAA to change data rate unnecessarily under unsaturated loads in wireless multi-hop networks.

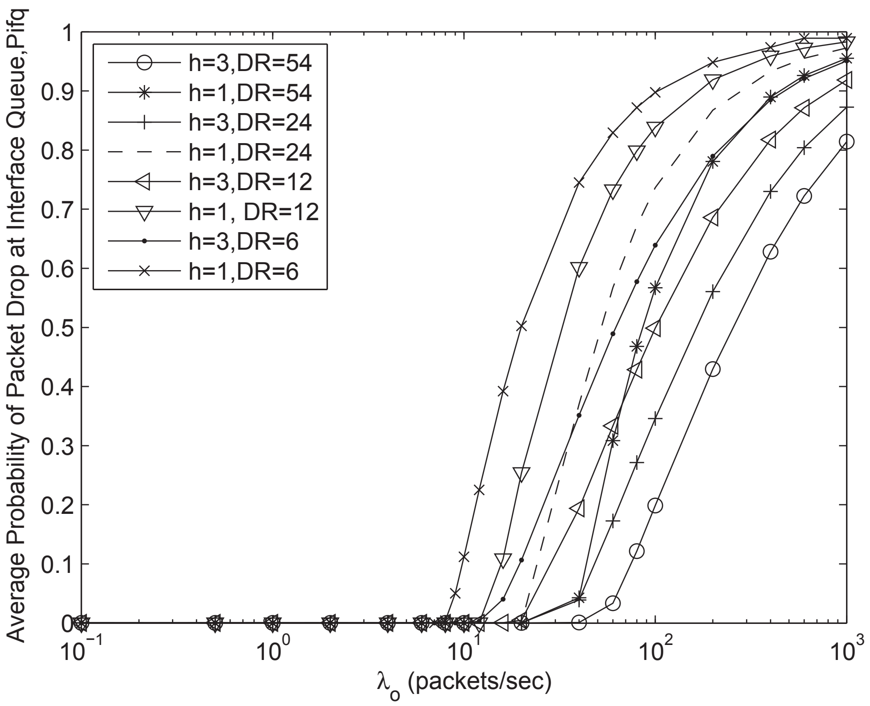
Although rate reduction is a necessity when packet drops occur due to channel impairments, this suggests that reducing the rate in case of packet drops because of hidden terminals/concurrent transmissions/IFQ blocking may result in under utilization of goodput in multi-hop networks.

Many rate adaptation algorithms decrease the transmission rate only by considering the improper channel conditions, so that there occurs performance reduction due to insensitivity to collision reason. Table 4.4 shows goodput, throughput and energy reduction which are obtained by decreasing the transmission rate from 54Mbps to 24Mbps for each topology and routing strategy.

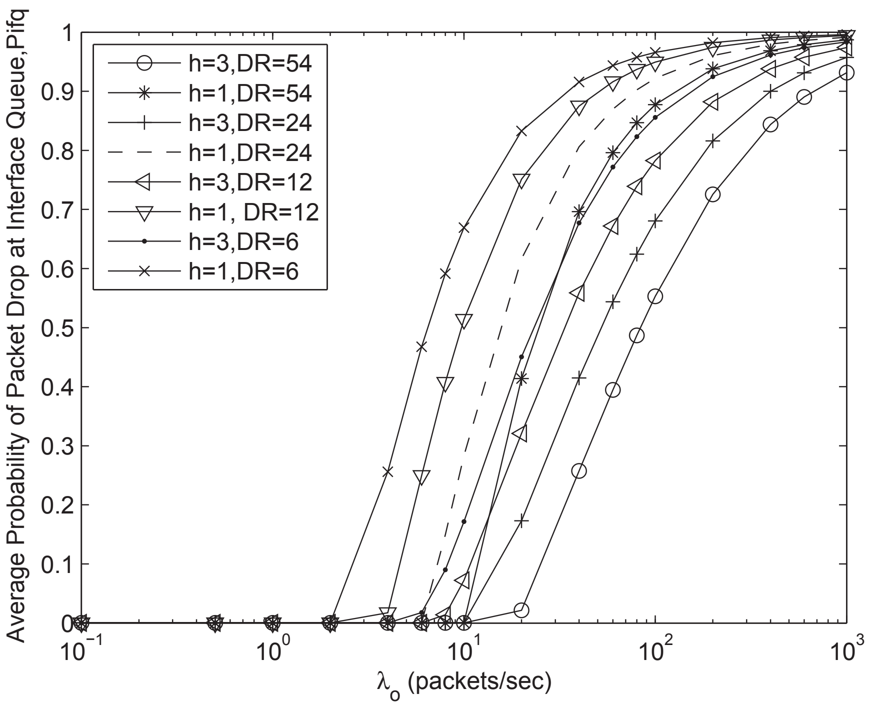
Table 4.4. Performance reduction of RAAs due to insensitivity to collision reason

		Goodput	Throughput	EPB
127-Node Regular Topology	h=1	85%	125%	87%
	h=3	95%	82%	96%
127-Node Random Topology	h=1	75%	65%	82%
	h=3	95%	72%	108%
469-Node Regular Topology	h=1	112%	102%	95%
	h=3	240%	68%	105%
469-Node Random Topology	h=1	125%	96%	78%
	h=3	240%	78%	108%

The average goodput for random topologies is also shown in Fig 4.10. According to these figures, the goodput is almost same for each data rate and routing strategy under the light traffic loads whereas it depends on the network density under the moderate-to-saturated traffic loads. Among the networks considered in this dissertation, the highest goodput is obtained at data rate of 54Mbps with multi-hopping routing for 469-node random network whereas it goodput is maximized by direct transmission for 127-node random topology under the moderate-to-saturated traffic loads. For the 469-node random network, goodput increases up to 15%-25% by multi-hopping compared with direct transmission strategy for moderate traffic rates.

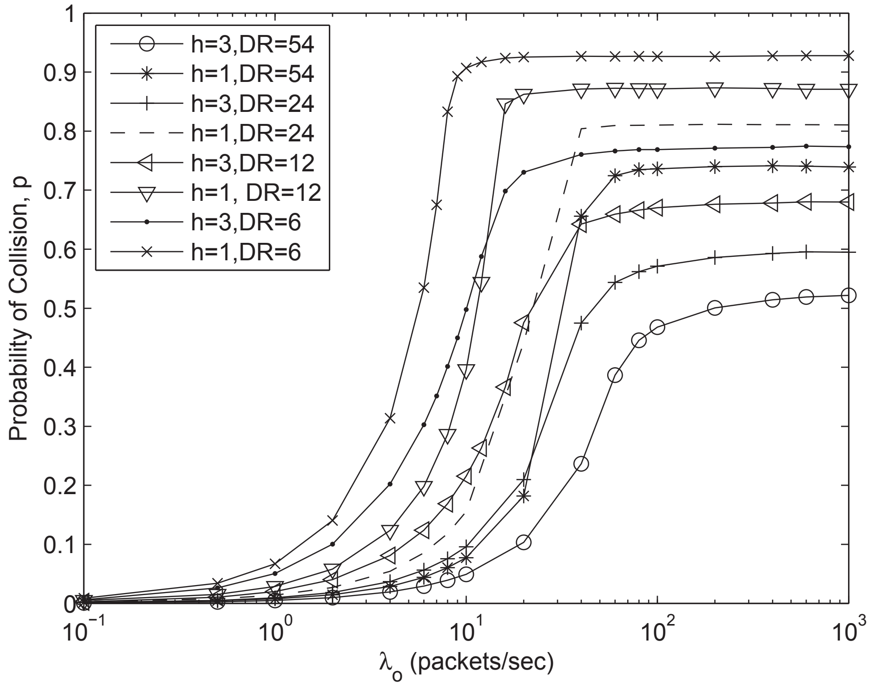


(a)

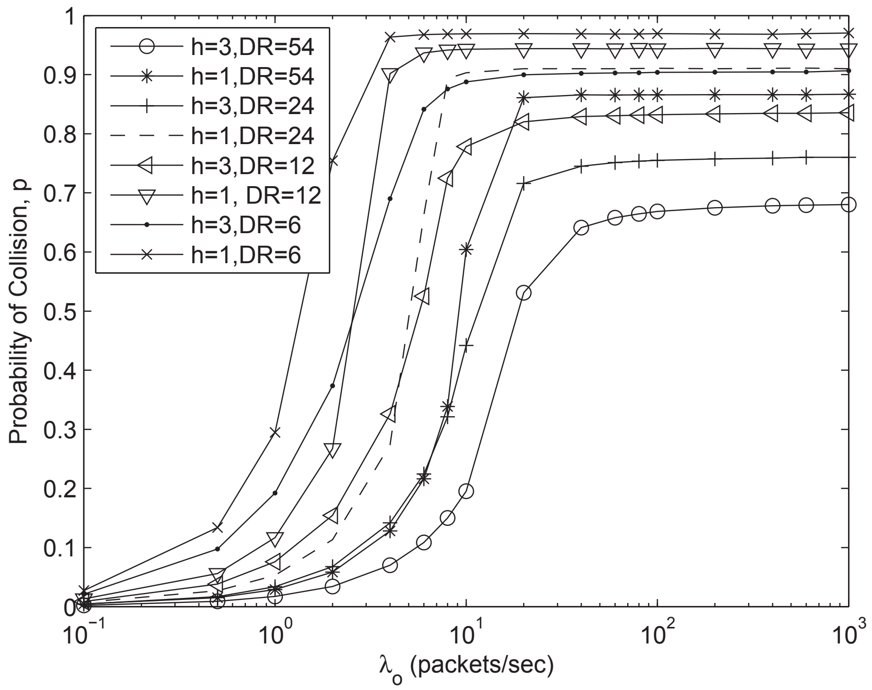


(b)

Figure 4.8. Average interface queue blocking probability, p_{ifq} for the a) 127-node and b) 469-node hexagonal topologies (hop count h={1,3}, data rate DR={54,24,12,6})

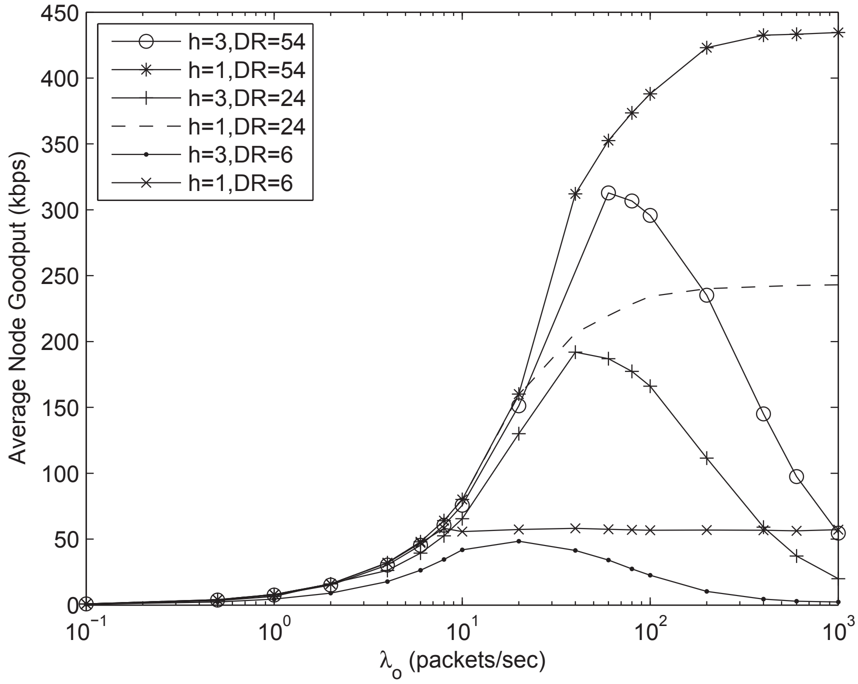


(a)

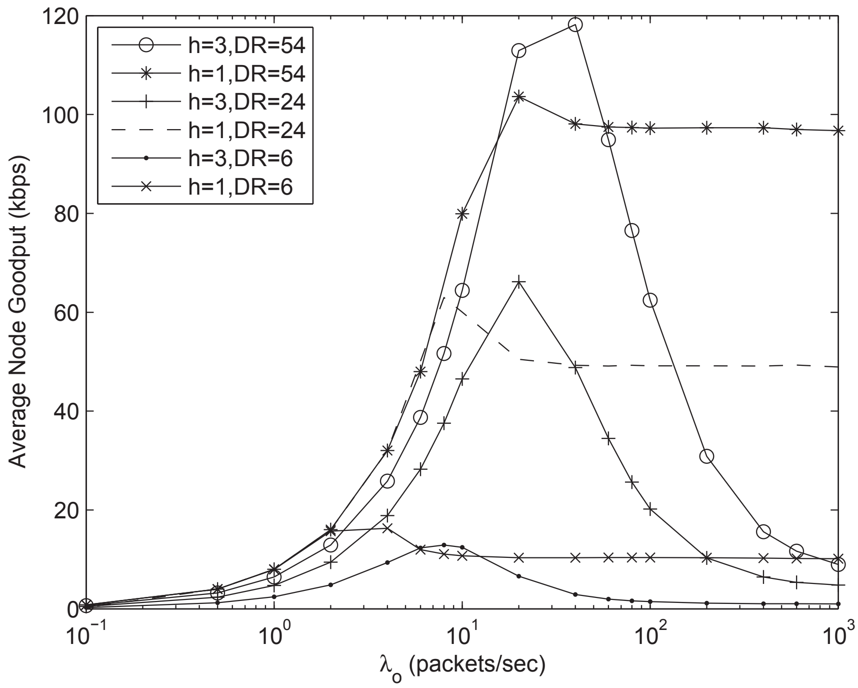


(b)

Figure 4.9. Probability of collision, p, for the a) 127-node b) 469-node hexagonal topologies (hop count h={1,3}, data rate DR={54,24,12,6})



(a)



(b)

Figure 4.10. Average node goodput for the 127-node and 469-node random topologies (hop count h={1,3}, data rate DR={54,24,6}Mbps)

Taking into consideration Fig 4.7 and Fig 4.10, it is observed that the average goodput, obtained by using multi-hop routing substantially decreases while the offered load increases due to excessive congestion losses in the network. Under the heavy traffic loads, direct transmission strategy yields significantly higher goodput than multi-hop routing. This is because direct transmission is less affected by increasing offered load. For all the topologies considered, goodput is maximized by either direct transmission or multi-hopping with the highest data rate.

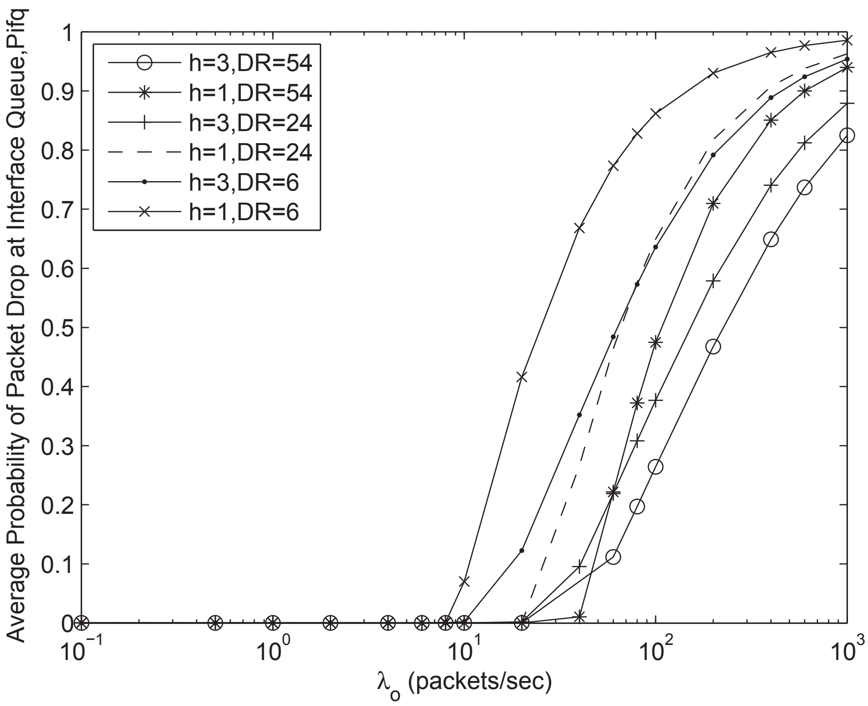
The probability of collision, p, is plotted for random topologies in Fig 4.12. By considering all data rates and direct transmission, the probability of collision is not zero while it is too small under the light traffic loads. It increases sharply moderate-to-saturated traffic loads until it becomes constant after saturation. On the other hand, p increases smoothly in moderate-to-saturated traffic loads and has a considerable big value under the light traffic loads, especially at 6Mpbs data rate, with multi-hopping.

Under the heavy traffic load, each data rate p for direct transmission is greater than multi-hop transmission. Having considered data rate, it can be seen that p is more for multi-hopping at the rate of 54Mbps than for direct transmission at data rate of 6Mbps under the moderate-to-saturated traffic loads. Additionally, p increases by enhancing the size of network for all routing strategies and data rates.

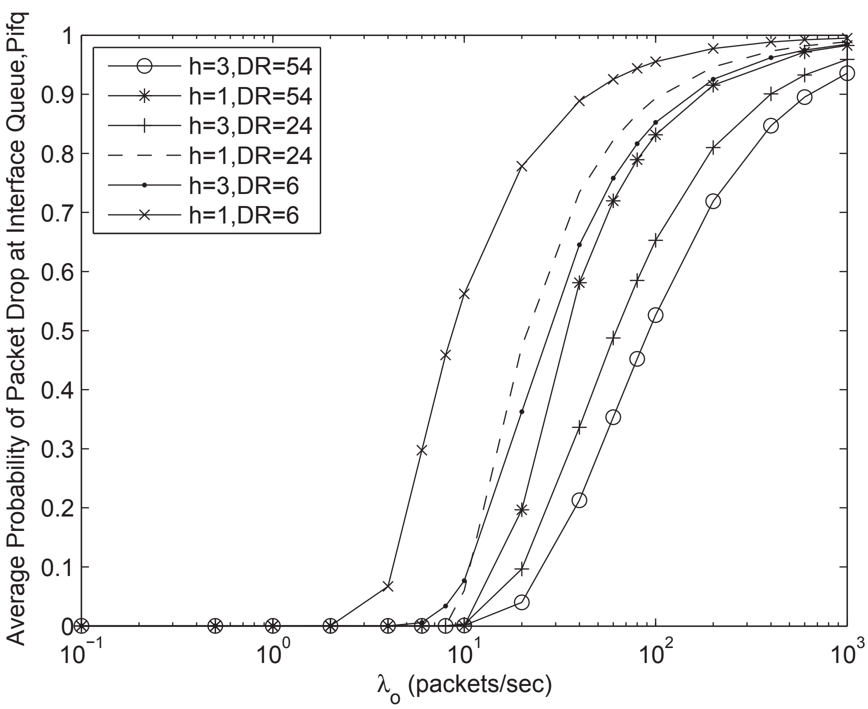
Fig. 4.13(a) compares the average goodput results of 127-node hexagonal topology with 127-node random topology. Fig. 4.13(b) compares the average goodput results of 469-node hexagonal topology with 469-node random topology.

The maximum goodput value is obtained for hexagonal topologies if multi-hop routing is used and for random topologies if direct transmission is used. Homogeneous networks achieve more goodput than non-homogeneous networks (Aydogdu and Karasan 2011). But, the larger goodput is obtained using multi-hopping for random topologies while it is less achieved in case of direct transmission for regular topologies. The shorter range and fewer number of routes of the random topology causes goodput to increase.

Considering Fig. 4.14 and Fig 4.15, the average interface queue blocking probability, p_{ifq}, is zero for light traffic loads whereas it increases under moderate-to-heavy traffic loads. For the larger topology this increase occurs earlier at lower traffic loads and becomes close to one for λ_o= 1000 packets/sec. Thus, the same routing strategy is used for all topologies, p depends on network density, traffic loads and routing strategy.

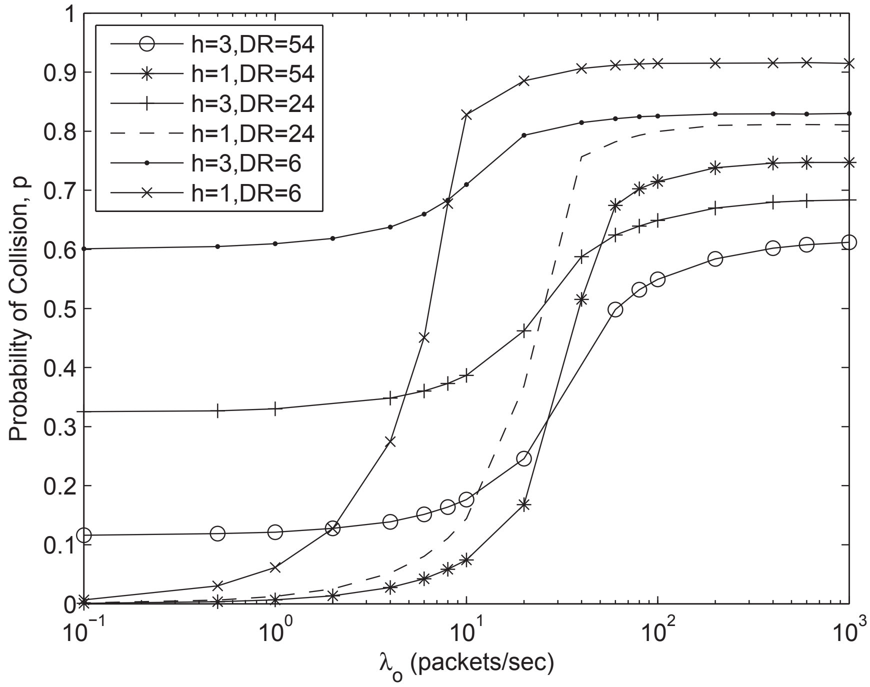


(a)

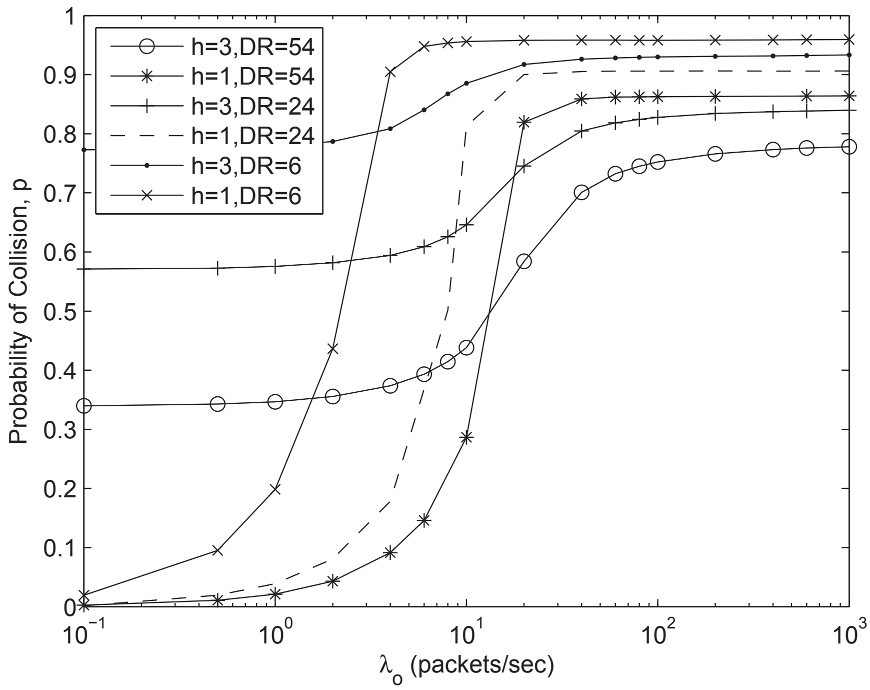


(b)

Figure 4.11. Average interface queue blocking probability, p_{ifq} for the a) 127-node and b) 469-node random topologies (hop count h={1,3}, data rate DR={54,24,6}Mbps)

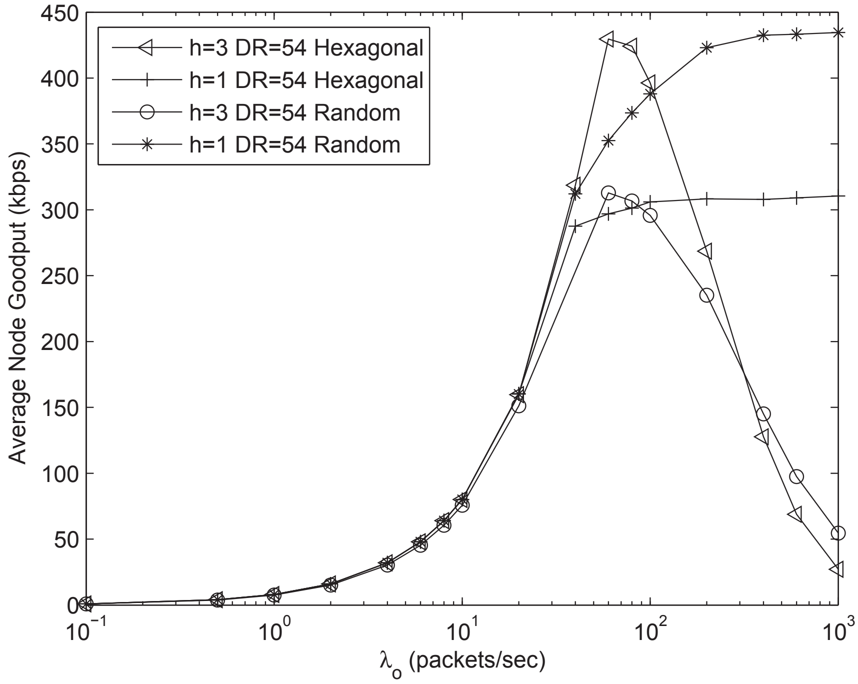


(a)

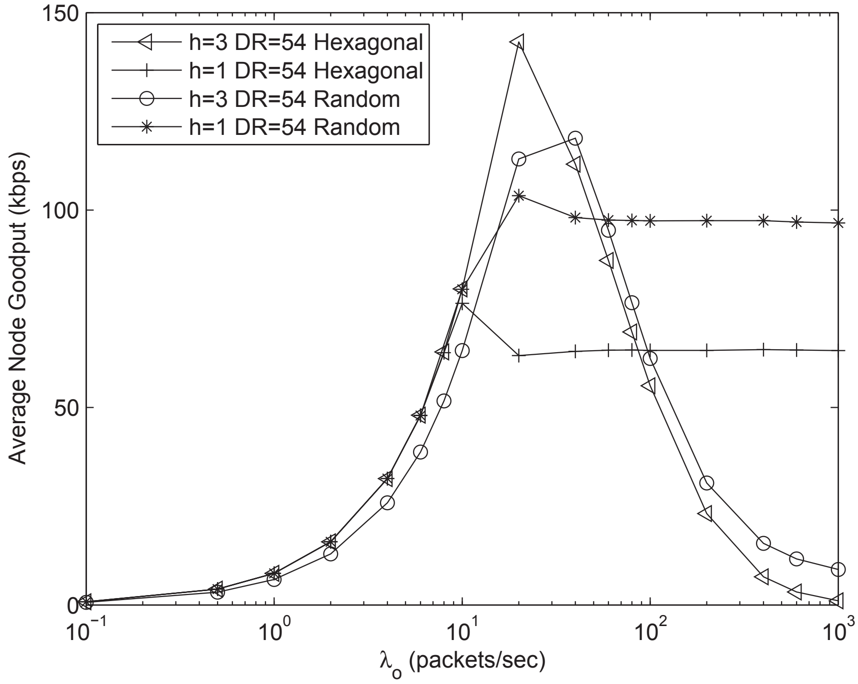


(b)

Figure 4.12. Probability of collision, *p*, for the a) 127-node b) 469-node random topologies (hop count h={1,3}, data rate DR={54,24,6}Mbps)

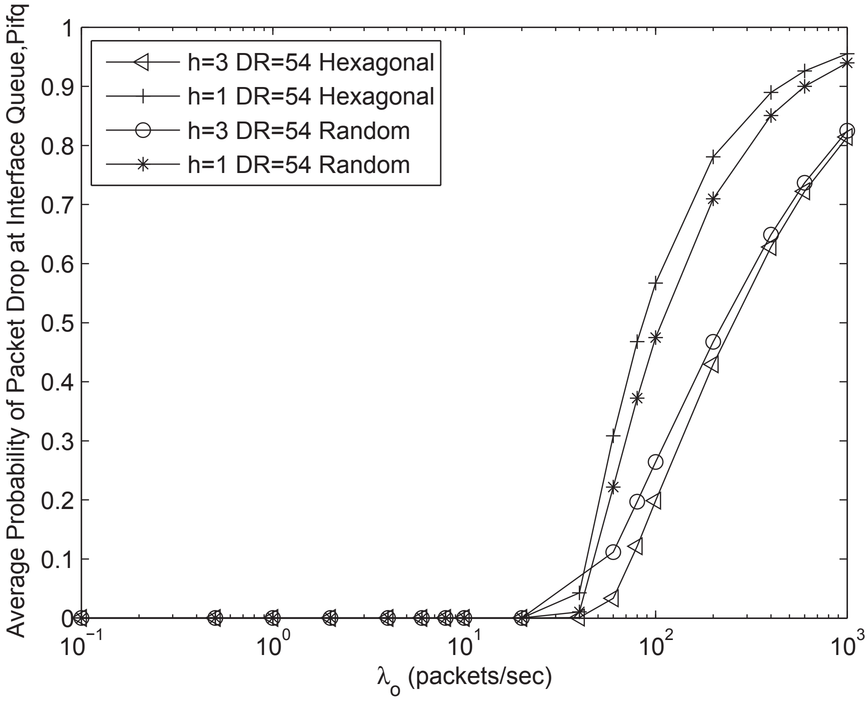


(a)

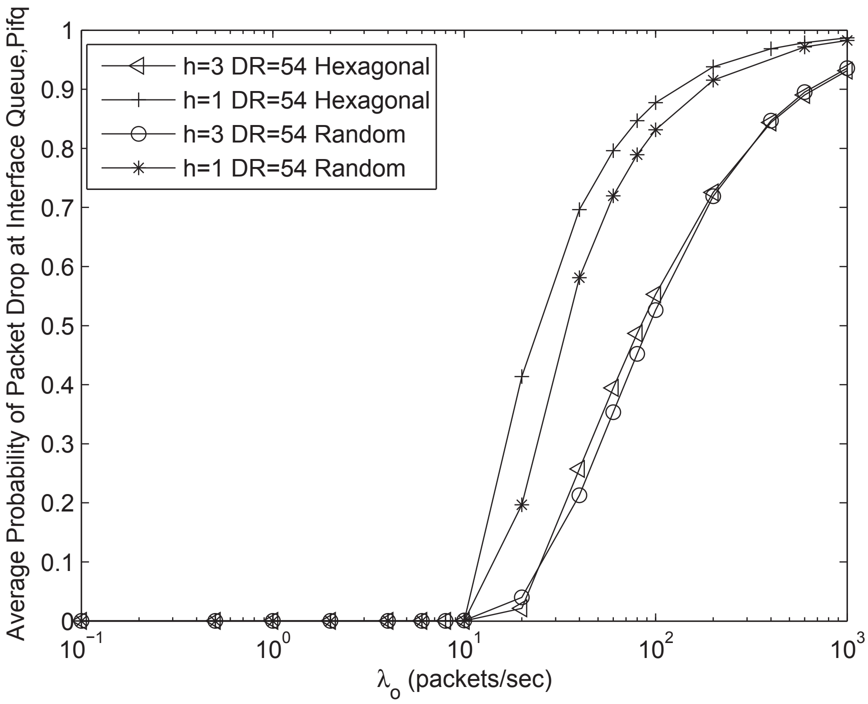


(b)

Figure 4.13. Average node goodput for the a) 127-node and b) 469-node hexagonal and random topologies, data rate DR=54Mbps (hop count h={1,3})

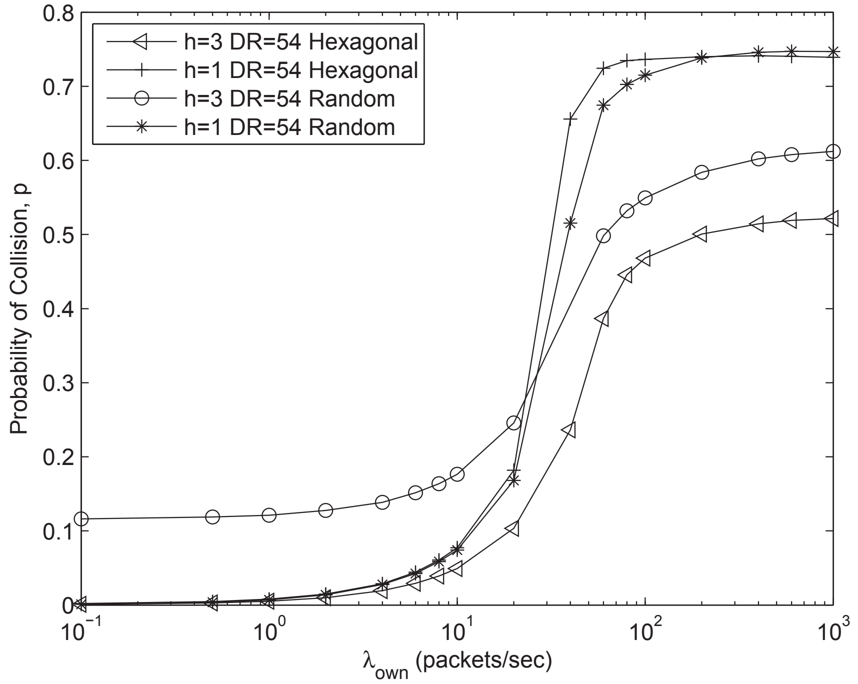


(a)

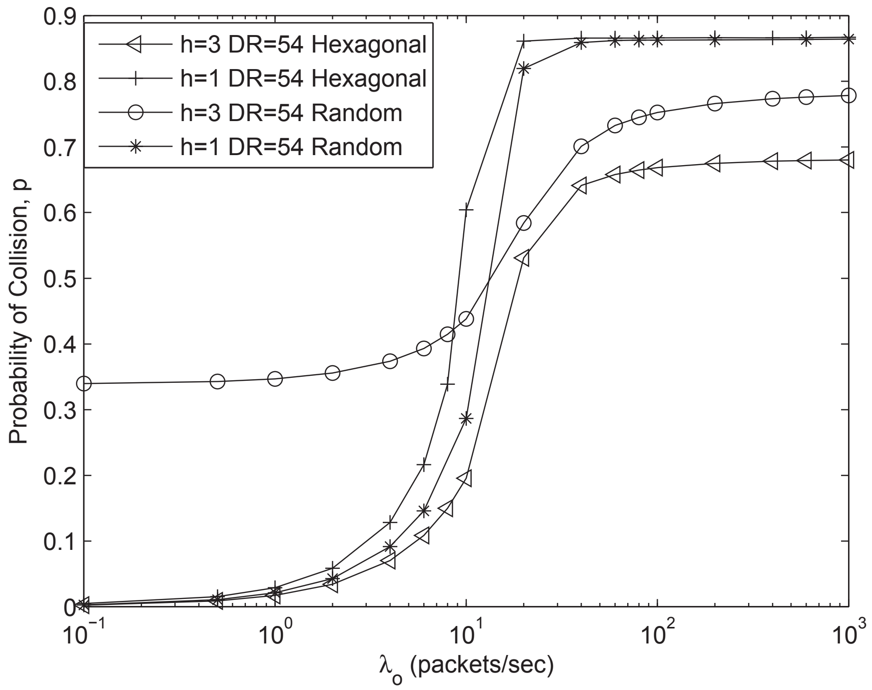


(b)

Figure 4.14. Average interface queue blocking probability, p_{ifq} for the a) 127-node and b) 469-node hexagonal and random topologies, data rate DR=54Mbps (hop count h={1,3})



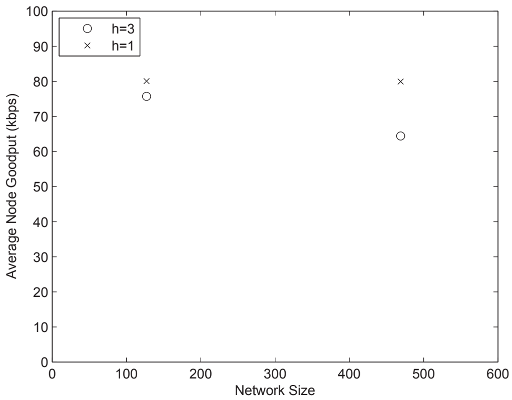
(a)



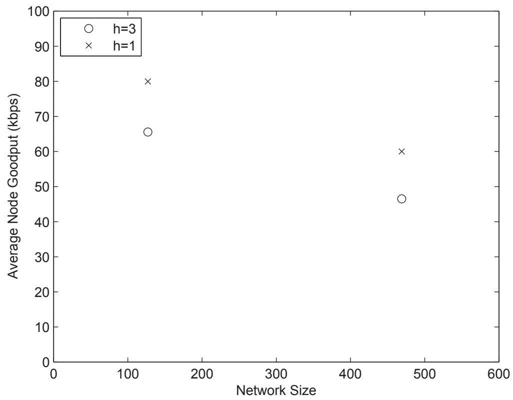
(b)

Figure 4.15. Probability of collision, p, for the a) 127-node and b) 469-node hexagonal and random topologies data rate DR=54Mbps (hop count h={1,3})

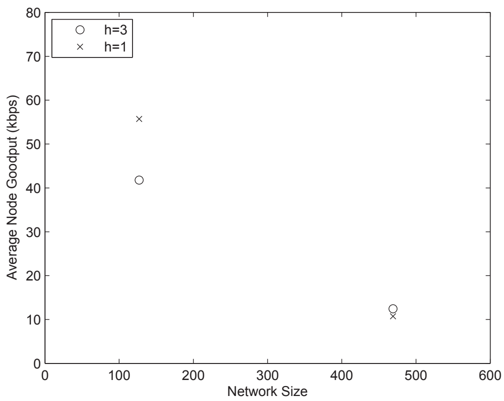
Fig. 4.16 illustrates the average node goodput versus network size for the 127-node and 469-node random topologies under moderate traffic load which is taken as λ_o=10 packets per second. The average goodput performance for each topology is nearly the same when data rate is 54Mbps whereas it decreases for denser topologies at the rate of 6Mbps.



(a) DR=54Mbps, λ_o=10 packets/sec



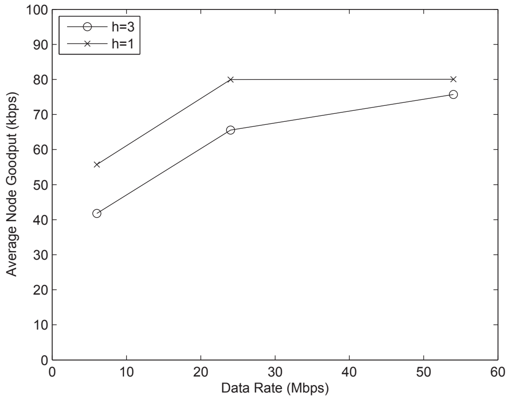
(b) DR=24Mbps, λ_o=10 packets/sec



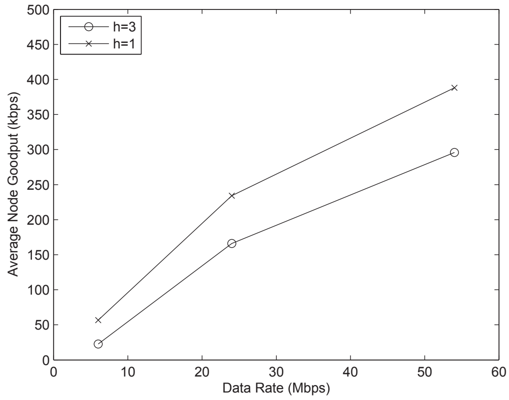
(c) DR=6Mbps, λ_o=10 packets/sec

Figure 4.16. The average node goodput for the 127-node and 469-node random topologies under a constant traffic load, λ_o=10 packets/sec and at various data rates a) DR=54Mbps b) DR=24Mbps c)DR=6Mbps (hop count h={1,3})

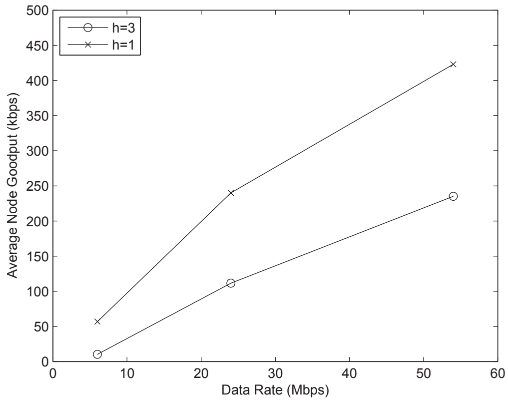
Fig. 4.17 displays that average node goodput versus data rate for the 127-node random topology varies for each data rate and routing strategies under various traffic loads. The gap between the goodput, obtained by multi-hopping and direct transmission, increases while the traffic load enlarges.



(a) λ_o=10 packets/sec



(b) λ_o=100 packets/sec



(c) λ_o=200 packets/sec

Figure 4.17. The average node goodput for the 127-random topology under various traffic loads a) λ_o=10 packets/sec, b) λ_o=100 packets/sec , c) λ_o=200 packets/sec (hop count h={1,3})

The simulation results show that the goodput performs differently under various traffic loads in multi-hop networks, as summarized in Table 4.5 and Table 4.6.

Table 4.5. Routing strategy and data rate which maximize goodput performance under different size regular topologies and traffic conditions

Goodput		Traffic load		
		Low	Moderate	High
Network Size	Small	any h, DR	h=3, DR=54	h=1, DR=54
	Large	any h, DR	h=3, DR=54	h=1, DR=54

Table 4.6. Routing strategy and data rate which maximize goodput performance under different size random topologies and traffic conditions

Goodput		Traffic load		
		Low	Moderate	High
Network Size	Small	any h, DR	h=1, DR=54	h=1, DR=54
	Large	any h, DR	h=3, DR=54	h=1, DR=54

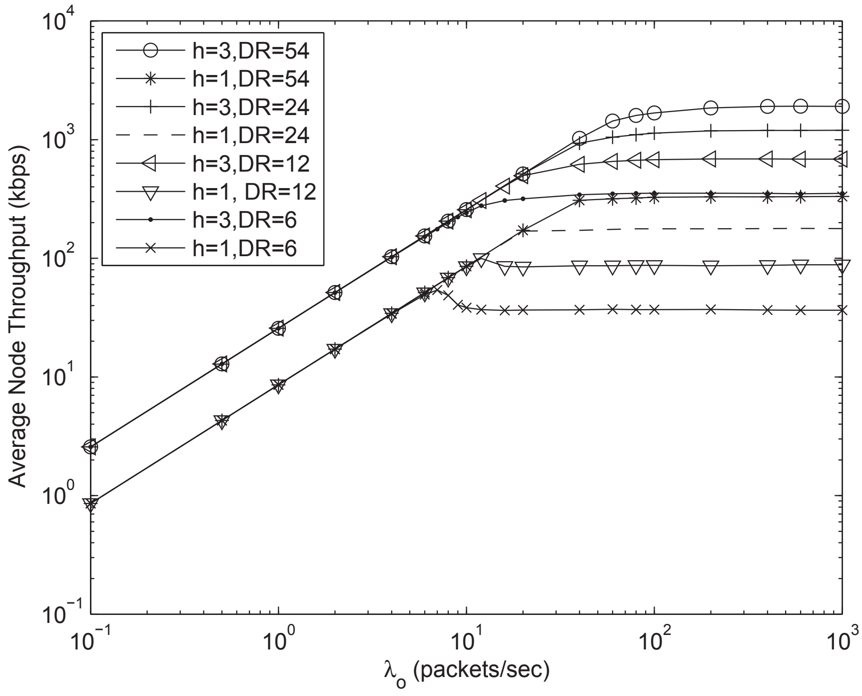
4.3.2. Average Node Throughput Performances

The average throughput is illustrated for hexagonal topologies in Fig. 4.18 and for random topologies in Fig 4.19. Fig. 4.18 shows that average throughput increases with increasing traffic load until it becomes constant at heavy traffic loads, where packets are retransmited/dropped because of the increased congestion. Under the light loads, throughput with multi-hopping is nearly more than twice of the throughput of direct transmission whereas the gap is bigger under the moderate-to-heavy traffic loads. It is also observed that throughput is the same for each data rate for light traffic loads.

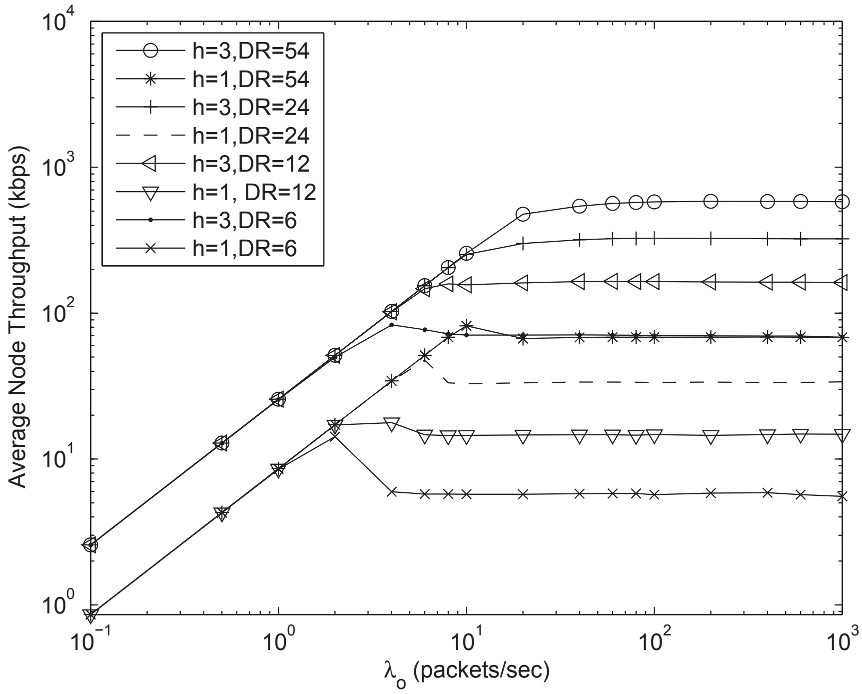
The throughput performances, obtained at 6Mbps data rate with multi-hopping and 54Mbps data rate in direct transmission, are almost the same for these two topologies. This points put that the same throughput performance can be obtained only by changing the routing strategy for different data rates.

Figure 4.20 demonstrates that throughput is nearly the same for each topology if the routing strategy is the same, either multi-hopping or direct transmission. However, it increases with multi-hopping, independent of network density.

Fig. 4.21 illustrates the average node throughput for the 127-node and 469-node random topologies under moderate traffic load where λ_o=10 packets per second and at various data rates. The throughput is nearly the same for each topology when data rate is 54Mbps; however it decreases according to network topology density when data rate is 6Mbps. The reduction is about 50%.

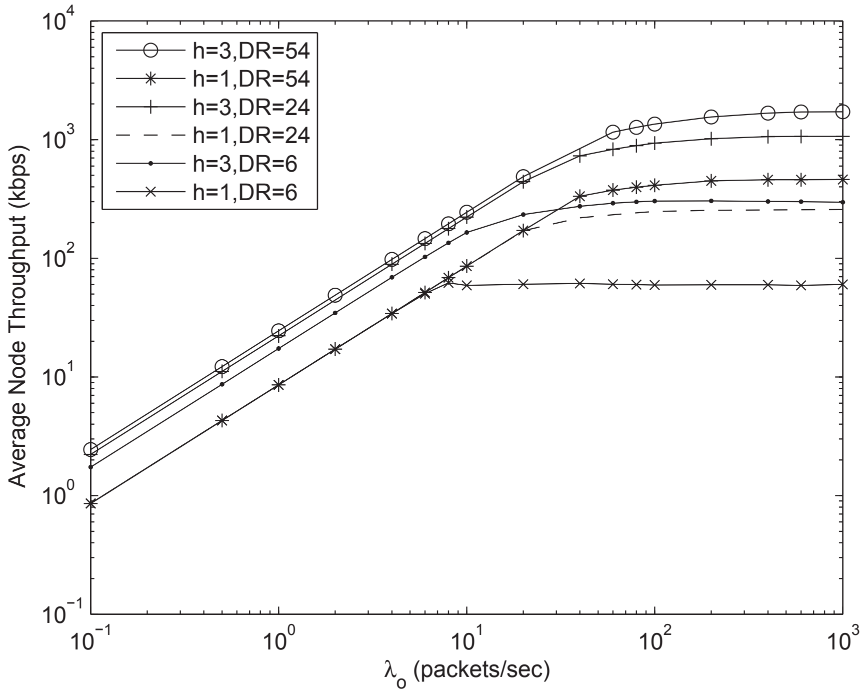


(a)

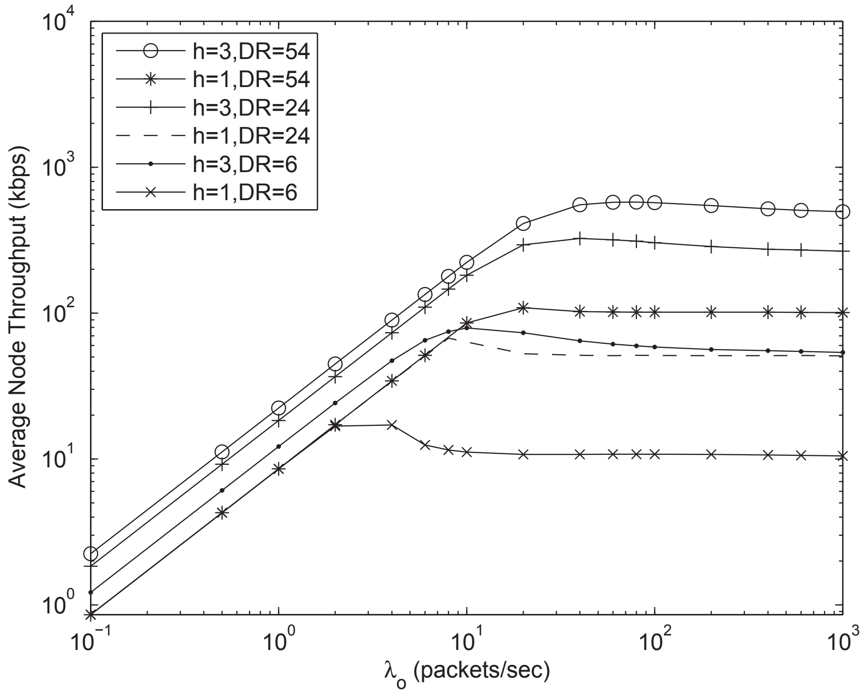


(b)

Figure 4.18. Average node throughput for the a) 127-node and b) 469-node hexagonal topologies (hop count h={1,3}, data rate DR={54,24,12,6})

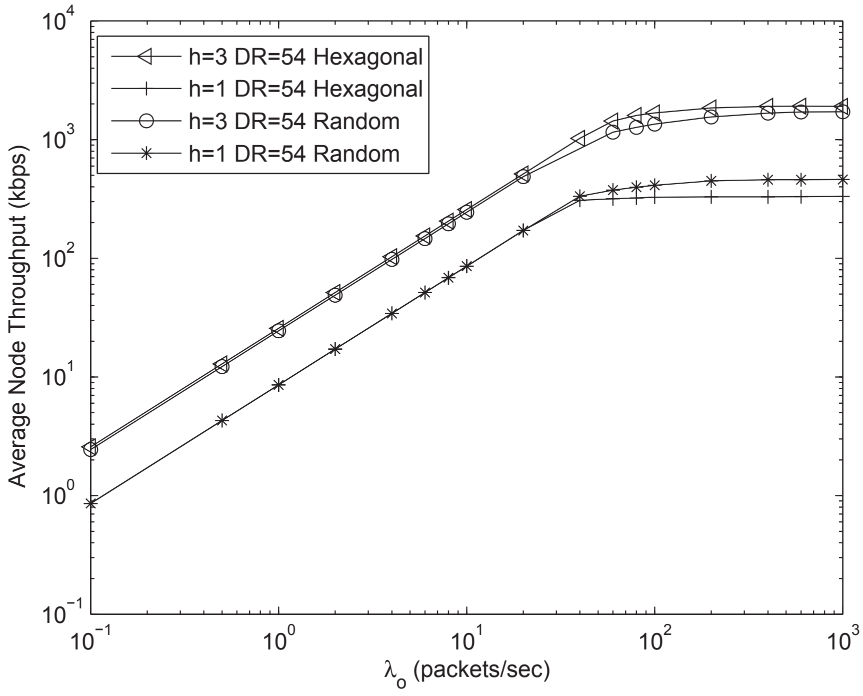


(a)

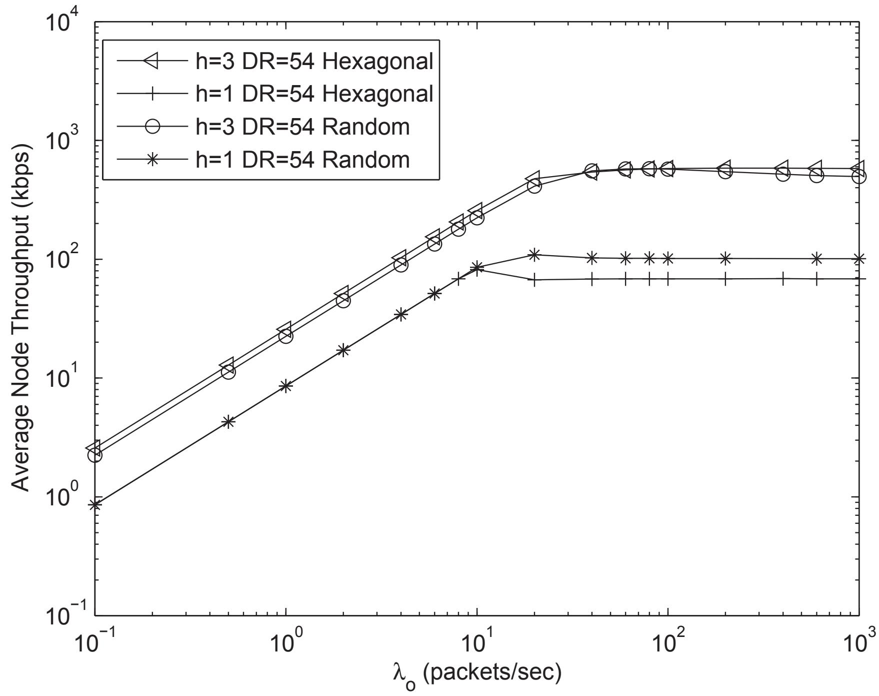


(b)

Figure 4.19. Average node throughput for the a) 127-node and b) 469-node random topologies (hop count h={1,3}, data rate DR={54,24,12,6})

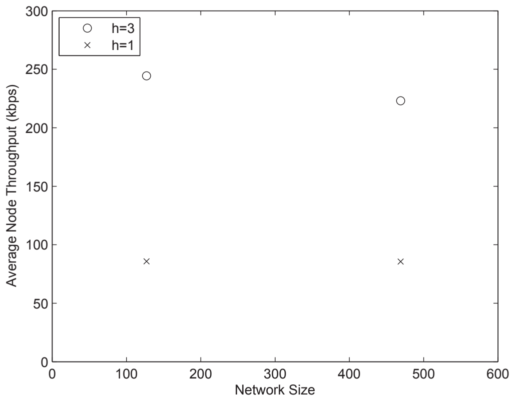


(a)

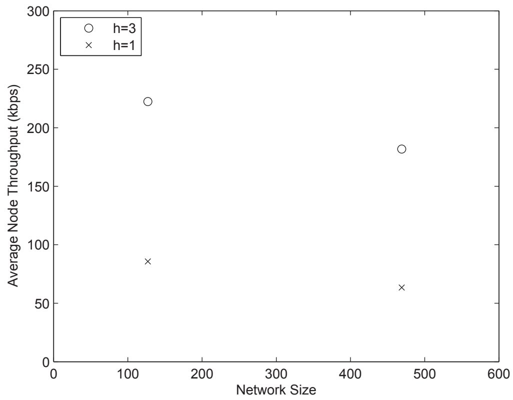


(b)

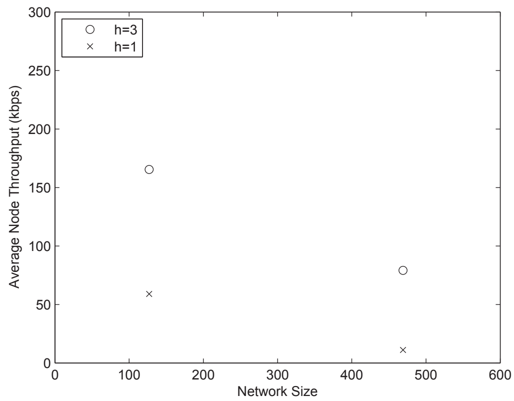
Figure 4.20. Average node throughput for ta) 127-node and b) 469-node hexagonal and random topologies, data rate DR=54Mbps (hop count h={1,3})



(a) DR=54Mbps, λ_o=10 packets/sec



(b) DR=24Mbps, λ_o=10 packets/sec



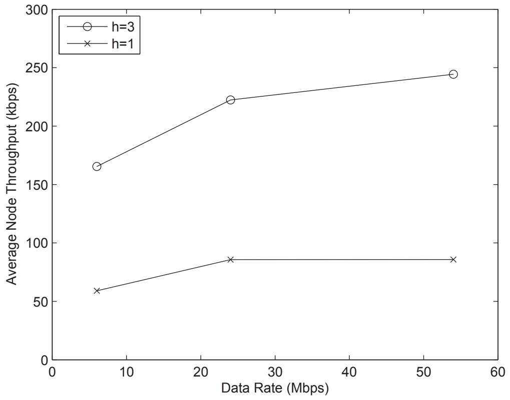
(c) DR=6Mbps, λ_o=10 packets/sec

Figure 4.21. The average node throughput for the 127-node and 469-node random topologies under a constant traffic load, λ_o=10 packets/sec and at various data rates a) DR=54Mbps b) DR=24Mbps c)DR=6Mbps (hop count h={1,3})

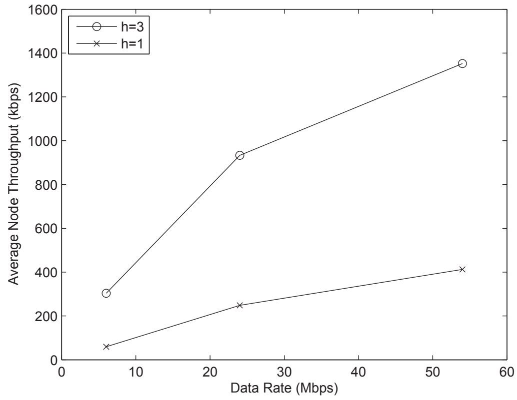
The average node throughput for the 127-node random topology is shown under moderate traffic loads in Fig. 4.22. In each traffic load, the throughput increases by multi-hoppping in all data rates while it is enhanced almost at the highest data rate.

Table 4.7. Routing strategy and data rate which maximize throughput performance under different traffic conditions for both regular and random topologies

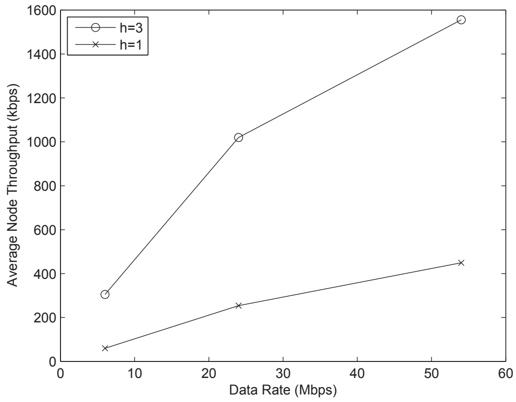
Throughput		Traffic load		
		Low	Moderate	High
Network Size	Small	any h, DR	h=3, DR=54	h=3, DR=54
	Large	any h, DR	h=3, DR=54	h=3, DR=54



(a) λ_o=10 packets/sec



(b) λ_o=100 packets/sec



(c) λ_o=200 packets/sec

Figure 4.22. The average node throughput for the 127-random topology under various traffic loads a) λ_o=10 packets/sec, b) λ_o=100 packets/sec , c) λ_o=200 packets/sec (hop count h={1,3})

Table 4.7 summarizes all the results on throughput. Throughput performance is different for various traffic loads.

4.3.3. Energy Per Bit (EPB) Performances

Fig. 4.23 displays the energy per bit in which the energy consumption in the idle mode is included, for 127-node and 469-node hexagonal topologies, respectively. In EPB calculations, it is considered that energy is consumed by a DATA packet, any related control packets, packet drops, collisions and retransmissions.

Fig 4.23 shows that energy-efficiency depends highly on traffic loads. Under the light traffic loads, it is observed that energy consumption is mainly due to the idle mode while it receives energy to make any routing strategy or data rate equivalently optimum. Under the moderate traffic loads, multi-hopping routing strategy is more effective than direct transmission. Moreover, the least energy consumption is obtained with multi-hopping at 54Mbps data rate for each network density. Under heavy traffic, direct transmission is more energy efficient and stable than multi-hopping since the packet collisions are increased and the traffic congestion is excessive.

To sum up, the results are summarized in Table 4.8 and Table 4.9 in which the behaviour of EPB performance metric varies traffic loads in regular and random topologies, respectively.

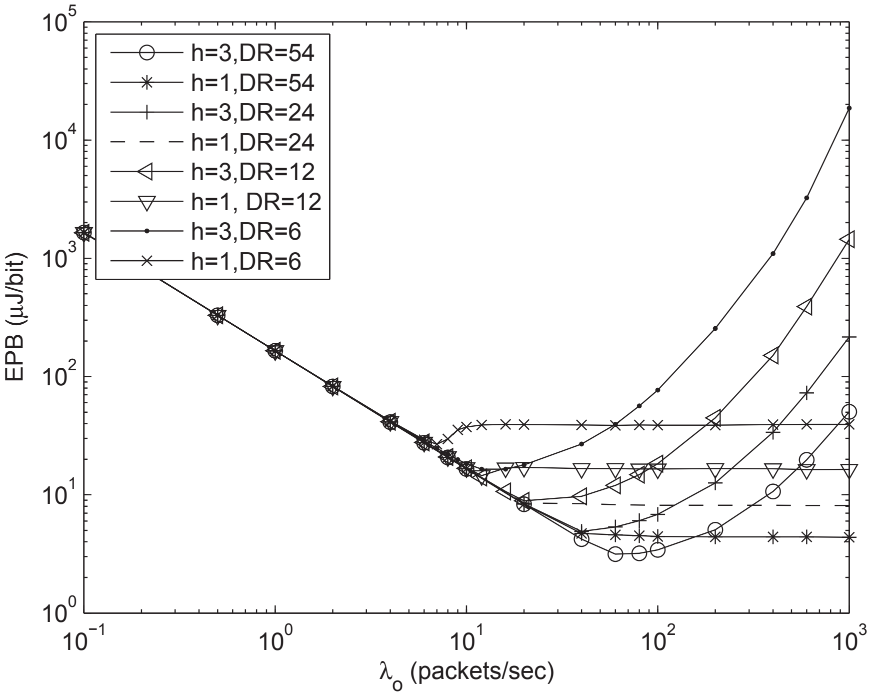
Table 4.8. Routing strategy and data rate which maximize EPB performance under different size regular topologies and traffic conditions

EPB		Traffic load		
		Low	Moderate	High
Network Size	Small	any h, DR	h=3, DR=54	h=1, DR=54
	Large	any h, DR	h=3, DR=54	h=1, DR=54

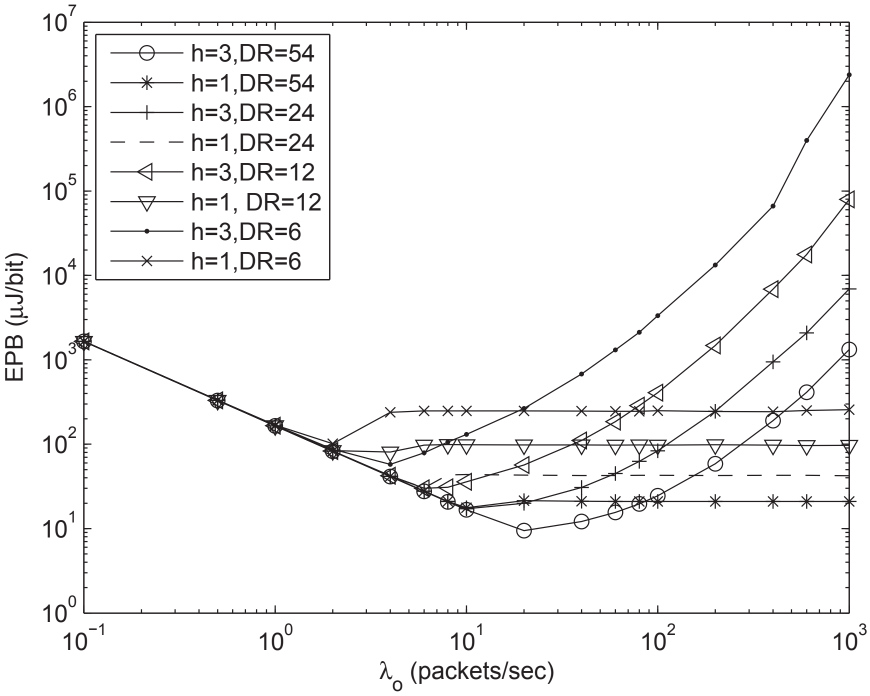
Table 4.9. Routing strategy and data rate which maximize EPB performance under different size random topologies and traffic conditions

EPB		Traffic load		
		Low	Moderate	High
Network Size	Small	any h, DR	h=1, DR=54	h=1, DR=54
	Large	any h, DR	h=3, DR=54	h=1, DR=54

The effect of network density on the energy performance is clearly illustrated in Fig. 4.26. As it is expected, the energy consumption increases at denser topology 469-node. EPB for the 127-node random topology is also obtained under various traffic load in Fig. 4.27. For each traffic load, the most energy consumption is obtained at the lowest data rate and the consumption decreases by increasing data rate. While the traffic load increases, the gap between the energy consumption at 6Mbps with the energy consumption at 54Mbps enlarges.

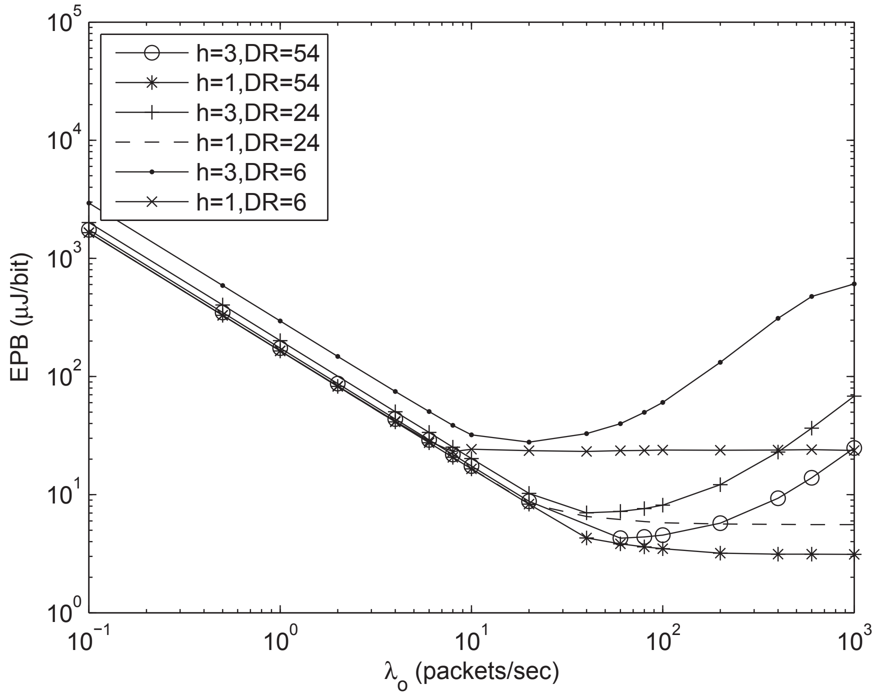


(a)

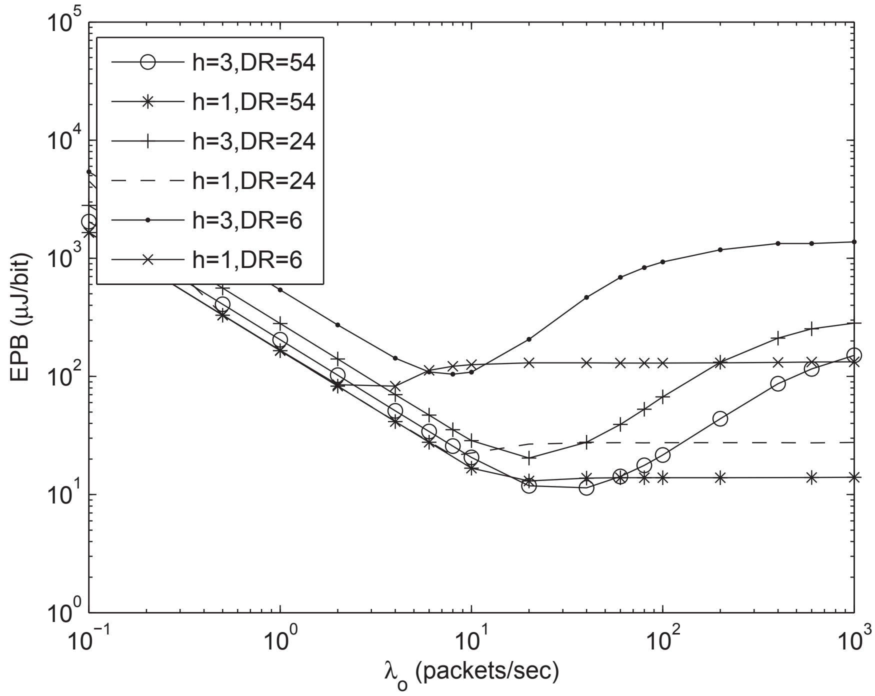


(b)

Figure 4.23. EPB with inclusion of energy consumed in the idle mode a) 127-node and b) 469-node hexagonal topologies (hop count h={1,3}, data rate DR={54,24,12,6})

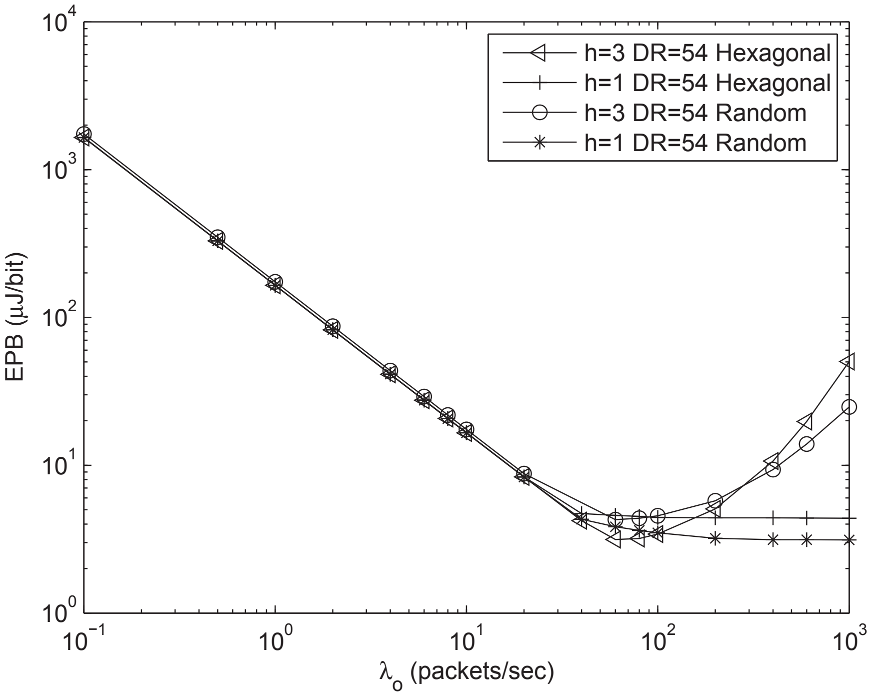


(a)

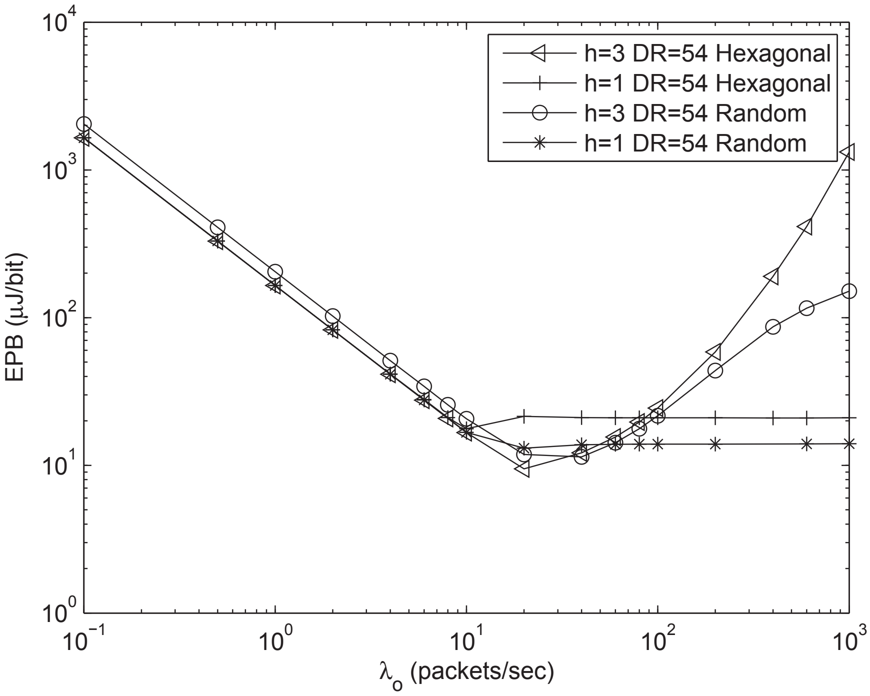


(b)

Figure 4.24. EPB with inclusion of energy consumed in the idle mode a) 127-node and b) 469-node random topologies (hop count h={1,3}, data rate DR={54,24,6})

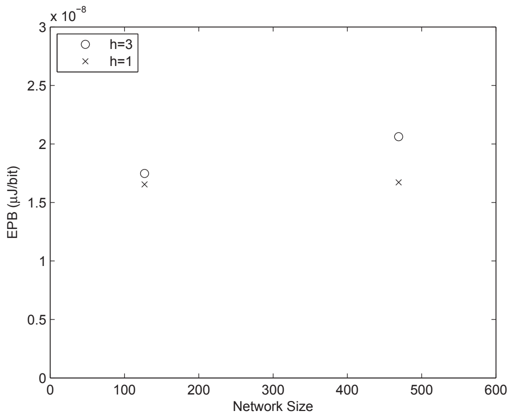


(a)

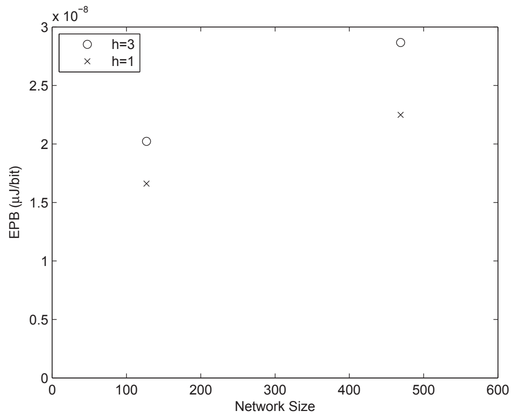


(b)

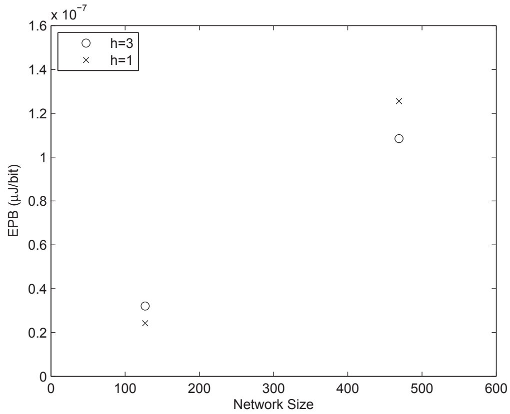
Figure 4.25. EPB with inclusion of energy consumed in the idle mode a) 127-node and b) 469-node hexagonal and random topologies, data rate DR=54Mbps (hop count h={1,3})



(a) DR=54Mbps, λ_o=10 packets/sec

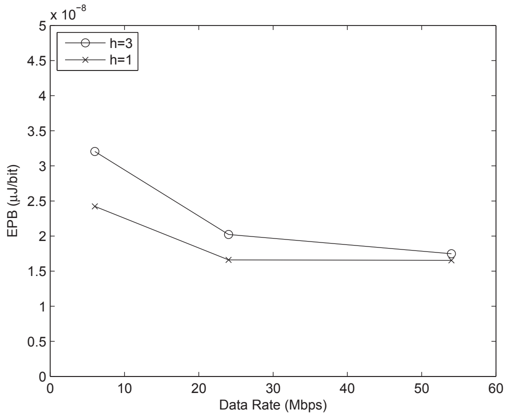


(b) DR=24Mbps, λ_o=10 packets/sec

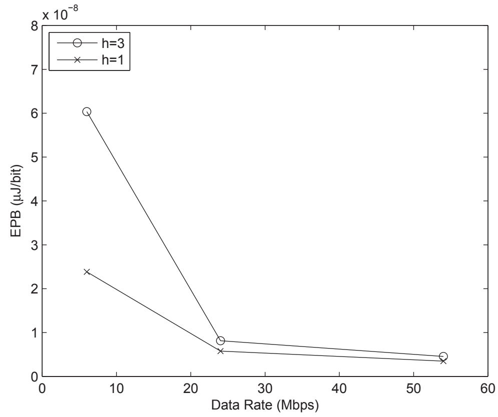


(c) DR=6Mbps, λ_o=10 packets/sec

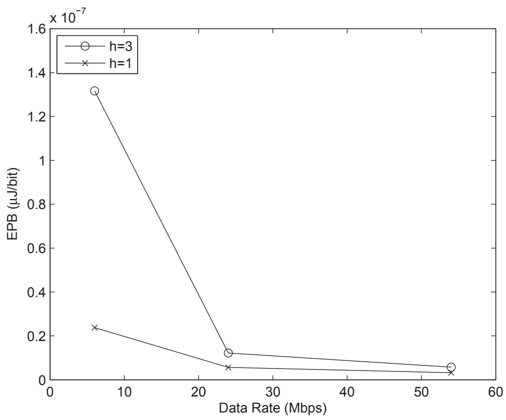
Figure 4.26. The EPB with inclusion of energy consumed in the idle mode for the 127-node and 469-node random topologies under a constant traffic load, λ_o=10 packets/sec and at various data rates a) DR=54Mbps b) DR=24Mbps c)DR=6Mbps (hop count h={1,3})



(a) λ_o=10 packets/sec



(b) λ_o=100 packets/sec



(c) λ_o=200 packets/sec

Figure 4.27. EPB for the 127-random topology under various traffic loads a) λ_o=10 packets/sec, b) λ_o=100 packets/sec , c) λ_o=200 packets/sec (hop count h={1,3})

CHAPTER 5

CONCLUSION

In this dissertation, the effects of transmission rate on goodput, throughput and energy performances of IEEE 802.11g DCF based multi-hop wireless networks are investigated. This study aims to state guidelines for goodput, throughput and energy efficient routing and transmission rate, considering MAC contention, BEB, retranmissions, overhearing of nodes and collisions.

In IEEE 802.11 WLANs, various transmission rates can be exploited in an adaptive manner which depends on channel conditions to maximize the system performance. In the literature, many studies propose rate adaptation schemes which decrease the transmission rate when there is a collision assuming that the collisions are caused by improper channel conditions. However, they do not consider the hidden terminal effect which emerges in multi-hop networks and causes transmission failures, so they can malfunction severely. As a result of this, it is not a proper solution to decrease the transmission rate only considering collisions without a classification of reason of collision.

This dissertation aims to investigate the effect of various transmission rates on goodput, throughput and energy performances. The behaviour of 802.11g is observed by considering MAC contention and hidden terminals in both single hop and multi-hop networks over a large range of traffic loads ranging from unsaturated to saturated. An error-free, non-fading channel model is used which neglects the noise. NS-2 simulations conducted on various size regular and random topologies, a 127-node and a denser 469-node regular topology, as well as a 127-node and a denser 469-node random topology.

This study shows that the system performance can be decreased due to MAC contention and hidden terminal effect even if channel conditions are perfect. The results reveal that goodput performance drops sharply under moderate-to-saturated traffic loads at each data rate with multi-hop transmission, whereas it becomes constant by direct transmission. The reason of this is that more packet drops occur due to hidden terminals and IFQ blocking in multi-hop transmission than single hop transmission under moderate-to-saturated traffic loads. Also, it is shown that the highest available transmission rate is optimum for moderate-to-saturated traffic loads.

Under unsaturated traffic loads, any routing strategy and data rate is equivalently optimum for goodput performance, which means that packet drops due to hidden terminals, concurrent transmissions and IFQ blocking may cause a load-unaware rate adaptation scheme to change data rate unnecessarily under unsaturated loads in wireless multi-hop networks whereas the throughput performance gets a higher value in multi-hop transmission than direct transmission for each data rate.

The goodput increases if and only if the packets are received successfully at the destination, whereas any successful transmission at a link layer enhances throughput. Under the heavy traffic loads, packet collisions and excessive traffic congestion increase; thus, many packets can not reach the destination and drop at intermediate node. As a results, it decreases goodput while throughput becomes constant. This shows that goodput has a different behaviour than throughput in multi-hop wireless networks, which is important to investigate the techniques by which goodput performance is optimized. Consequently, it is shown that throughput does not depend on traffic load even though goodput is traffic load dependent.

The energy per bit performance is also shown to depend on traffic load for changing transmission rate. Under the light traffic loads, energy is consumed mostly in the idle mode and receive modes; hence, any routing strategy or data rate becomes equivalently optimum. Moreover, multi-hopping routing strategy is more effective than single hop transmission and the least energy is consumed with multi-hopping at 54Mbps under the moderate traffic loads. At heavy traffic, single hop transmission is more energy efficient and stable than multi-hopping for each data rate due to the increased packet collisions and excessive traffic congestion.

As a conclusion, a load-aware rate adaptation scheme is suggested, which discriminates the reason of packet drops due to hidden terminals/concurrent transmissions/IFQ blocking from packet drops due to channel impairments provides significant goodput gains in multi-hop wireless networks.

The results of this study is important since it considers the hidden terminal effects and as a result, it enable designers to enhance the system performance of the multi-hop wireless communication system networks.

5.1. Future Work

Using the guidelines for maximum goodput and minimum EPB obtained in this study, a rate adaptation scheme will be proposed and tested under imperfect channel conditions where shadowing and multi-path fading are included. The performance gains obtained by sensitivity of reason of collisions and traffic load will be evaluated.

This dissertation includes a performance analysis based on ERP-OFDM IEEE 802.11g multi-hop networks. The guidelines obtained in this study are applicable to IEEE 802.11a , IEEE 802.11n for higher throughput improvement using MIMO and IEEE 802.11p for vehicular ad-hoc networks, which use ERP-OFDM. Furthermore, all of them have multi-hop characteristics and require improved goodput and energy performances.

As a future work, an analytical model will be proposed in order to provide an in-depth understanding of effect of transmission rate on performance of multi-hop networks. Afterwards, numerical results obtained will be compared by the simulation results obtained in this dissertation.

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