Effect of Traffic Arrival Distributions on Routing Strategy in Multi-Hop Wireless Networks

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ABSTRACT

The basic problem of whether direct transmission or multi-hop routing increases goodput in multi-hop wireless networks still lacks investigation from many aspects. This article, approaches this problem by considering the effect of different traffic arrival distributions on the choice of routing strategy for enhancing goodput of IEEE 802.11 DCF based multi-hop wireless networks under hidden terminal existence. Different traffic arrival distributions; including Poisson, constant bit rate (CBR), Pareto and Exponential are considered, relaxing the generally adopted Poisson assumption, for various data rates over a wide range of traffic loads extending from unsaturated to saturated traffic loads.

The goodput performance for all traffic arrival distributions is found to be dependent on the traffic load in multi-hop networks. Of the four traffic models used, the network achieved the best goodput with Pareto and Exponential arrival distributions for light traffic loads, where CBR performs slightly better under heavy loads. The results suggest that a traffic load-aware pre-control mechanism on the traffic arrivals to the IEEE 802.11 MAC layer might provide significant goodput gains in multi-hop wireless networks.

Keywords

goodput; traffic arrival/source distribution; IEEE 802.11 DCF; multi-hop wireless networks; multi-hop routing; direct transmission

1. INTRODUCTION

The widespread use and variety of applications has begun a structural transformation from single-hop to multi-hop communications in the wireless networking world [10, 15, 11]. Moreover, the density of nodes are increasing in these multi-hop wireless networks, coming forth with a transmission choice of routing over a single long hop (i.e. direct transmission or single-hop routing) or multiple short hops (i.e. multi-hop routing) for enhancing network performance. Some example applications for these dense multi-hop wireless networks, where a simple routing choice among single-hop and multi-hop routing may increase performance, may be listed as follows: i) Wireless sensor networks (WSN) formed for agriculture monitoring and activation of an irrigation system, where the environmental humidity of a field is measured by hundreds/thousands of sensors monitored over the Internet; ii) Vehicular ad-hoc networks (VANET) for conveying instantaneous vehicular information (position, speed, destination, etc.) of a large number of vehicles to the Internet or among vehicles in order to solve the traffic jam by providing the optimal route for vehicles; iii) WSNs formed for industrial automation for monitoring hundreds/thousands of temperature sensors inside refrigerator chambers for detecting breaks in the cooling chain; iv) Wireless mesh networks (WMN) formed for smart metering of electricity consumption of several facilities/buildings in a city/campus area; v) Mobile ad-hoc networks (MANET) formed by hundreds of discovery robots, sent to a volcano/cavern/subsidence, which communicate with each other for position estimation while sustaining connectivity to the Internet through relays, vi) WMNs formed by hundreds of cubic satellites for measuring sunspot activity, etc.

The basic problem of whether direct transmission or multi-hop routing strategy increases the performance in multi-hop wireless networks is investigated in the literature from several aspects [12, 14, 28, 8, 21, 22, 2, 19], however none of these studies consider the effect of traffic arrival distributions. These studies assume either saturated traffic sources, where the nodes always have a packet waiting to be transmitted (due to capacity related concerns with optimal link scheduling and optimal routing assumptions), or assume the Poisson traffic arrival distribution only, omitting the effect of different traffic arrivals on the performance results. Furthermore, most of these studies neglect the hidden terminal effect, which is shown to have a significant effect on the choice of routing strategy in multi-hop wireless networks [4, 6, 5].

Goodput, defined as the number of useful end-to-end transmitted bits per second from source to destination, is a practical measure of efficiency of multi-hop communications in a multi-hop wireless network. The goodput performance, due to the existence of hidden terminals in multi-hop networks, is strongly related to the medium access control (MAC) dynamics at the data link layer and the routing protocol at the network layer. Hence, a thorough investigation of good-

DIVANet'16, November 13-17, 2016, Malta, Malta

DOI: http://dx.doi.org/10.1145/2989275.2989288

put performance in multi-hop wireless networks should take hidden terminals into account and conduct a cross-layer investigation, which includes the MAC dynamics (such as retransmissions, backoff, etc.) and the routing strategy.

Moreover, the goodput performance characteristic is shown to exhibit different behavior under changing traffic loads for both single-hop networks [25] and multi-hop wireless networks [5, 23], where traffic load is varied over a wide range from unsaturated to saturated traffic loads. The effect of this diverse range of traffic conditions is investigated focusing on the relation between power control and throughput of *single-hop* IEEE 802.11b ad-hoc wireless networks in [25], The relation between goodput and routing strategy in a IEEE 802.11b *multi-hop* wireless is shown to be significantly affected by the traffic load in [5], whereas the additional effect of data rate is investigated in [23] for IEEE 802.11g. Under light traffic, goodput is shown to increase with increasing traffic load achieving the same performance by different routing strategies. Additionally, multi-hop routing under moderate traffic load and single-hop routing at heavy traffic are shown to achieve higher goodput [5]. This goodput behavior with respect to traffic load is shown to remain under different data rates, whereas goodput is enhanced by higher data rate [23]. These results point out that the end-to-end goodput can be improved by adaptively switching between single-hopping and multi-hopping according to the traffic load. However, these studies rely on the assumption of a Poisson traffic arrival distribution, lacking the knowledge of validity of these results for different traffic arrival distributions.

The main contribution of this article is to investigate the effect of traffic arrival distribution on the routing strategy choice for enhancing the goodput performance in multi-hop wireless networks under hidden terminal existence. The impact of the following traffic arrival distributions is investigated for various data rates, short-hop and long-hop routing strategies and over a wide range of traffic loads in multi-hop wireless networks: Poisson, CBR, Pareto, Exponential and Poisson with mice-elephant users. The goal of this study is twofold: 1) Investigation of the generality of the results in [5, 23] for various traffic arrival distributions, 2) Laying out guidelines for data rate and route adaptation algorithms subject to different traffic arrival distributions for maximizing goodput in multi-hop wireless networks.

In this article, the widespread IEEE 802.11 Distributed Coordination Function (DCF) is chosen as the MAC protocol for goodput evaluation of multi-hop wireless networks. The IEEE 802.11g version is chosen due to the wide range of supported rates and inter-operability with former IEEE 802.11b and legacy standards. In this study, the discussion is focused on the investigation of the effect of traffic arrival distributions in perfect channel conditions in order to highlight the MAC and routing protocol dynamics, which become important in multi-hop wireless networks. Hence, the collisions stem from concurrent transmissions due to hidden terminals rather than channel errors due to wireless propagation in this study.

The results show that goodput performance for all traffic arrival distributions is dependent on the traffic load in multi-hop networks, contrary to the results for single-hop networks [24]. The goodput performance is affected by the traffic arrival distributions under light and heavy traffic loads, whereas the effect is negligible under moderate traffic loads. Higher goodput is achieved by bursty traffic sources, such as the on-off type exponential and pareto traffic sources, compared to the CBR and Poisson traffic sources under light traffic loads for all routing strategies and under heavy traffic loads for multi-hop routing. Despite the impact of the traffic arrival distributions on the goodput performance, there is no impact on the goodput-efficient *routing strategy*. In other words, multi-hop routing under moderate traffic loads and direct transmission under light and heavy traffic loads is the optimum choice for enhancing goodput performance in multi-hop wireless networks, independent from the traffic arrival distribution, generalizing the results in [5, 23] for the considered traffic arrival distributions.

The remainder of this article is organized as follows. A literature review is presented in Sec. 2 and the simulation settings and assumptions regarding the IEEE 802.11g DCF are described in Sec. 3. The simulation results presented in Sec. 4 are followed by some concluding remarks given in Sec. 5.

2. LITERATURE REVIEW

The investigation of the effect of traffic arrival distribution on the routing strategy for enhancing goodput performance of multi-hop IEEE 802.11 DCF based wireless networks under hidden terminal existence is related with three different lines of research investigating 1) goodput performance under presence of hidden terminals, 2) the effect of traffic arrival distribution on goodput performance and 3) optimal routing strategy for enhanced goodput. In this section, we review the literature of these three research lines.

Goodput and/or throughput of IEEE 802.11 DCF based *multi-hop* wireless networks are studied in [21, 32, 33, 1, 7, 29, 20, 16, 31, 34]. Owing to the comparable complexity increase when switching from single-hop to multi-hop network architecture, these studies are based on either simulations [21, 33] or on analytical models with simplified assumptions. For example, the hidden terminal effect is not considered in [1, 7, 34, 22], whereas [16] considers only a small portion of hidden terminals that are on the intended path. The hidden terminal problem is included in the throughput analysis of IEEE 802.11 in [29] and [20], where only 3-node and string topologies are considered, respectively. Moreover, these studies calculate the goodput or throughput under either saturated [7, 29, 20, 34, 16, 22] or unsaturated traffic loads [1, 31].

The first analytical model for the calculation of goodput and throughput in multi-hop wireless networks is introduced in [5], which is developed on top of the analytical IEEE 802.11 DCF model introduced in [4]. This goodput model, which provides fairly accurate results for a large range of traffic loads considering hidden terminals, provides an understanding for the following goodput dynamics in multi-hop wireless networks: Goodput is dependent on the traffic arrival rate under unsaturated traffic loads, whereas interface queue dynamics and MAC dynamics such as carrier sensing, collisions, retransmissions, exponential backoff, hidden terminal effect, etc., govern the goodput under saturated traffic loads. These goodput analyzes are generally based on the Poisson arrivals due to its analytical tractability it provides in multi-hop wireless networks.

The effect of traffic arrival distribution of multi-hop wireless networks under the joint effect of data rate and routing strategy on energy performance is investigated in [6], where goodput performance is not mentioned. This study extends this study by investigating the effect of traffic arrival distribution on the goodput performance.

The effect of traffic arrival distributions on wireless network performance is investigated for single-hop wireless networks in [24]. The effect of four diverse traffic models (Exponential, Pareto, Poisson, and CBR) on the performance of a typical IEEE 802.11 ad hoc network for TCP and UDP are investigated in [24], where the goodput performance for all traffic arrival distributions is found to be independent of the traffic load for single-hop networks. The effect of CBR, FTP and Telnet traffic sources on packet delivery ratio, throughput, average end to end delay and routing message overhead performances are compared for the AODV, DSR, Wireless Routing Protocols routing protocols in [3]. A similar study [18] investigates the packet delivery fraction, average end-to-end delay and number of dropped data packets for TCP and CBR traffic for the AODV, DSR and DSDV routing protocols in an ad-hoc network. Both studies based on the IEEE 802.11 DCF, where the mobility of the nodes are considered, conclude that reactive protocols (especially AODV) perform better.

However, these studies focus on performance of specific routing protocols over the limited range of traffic loads in sparse networks, where multi-hop routing is a necessity rather than an option for enhancing performance. The focus of this article, on the other hand, is the effect of traffic arrival distributions on long-hop versus short-hop *routing strategy* performance, rather than specific routing protocols, which is not investigated in the literature before.

Another line of related research is on the optimal routing strategy for enhanced goodput, where the routing strategy is focused on long-hop versus short-hop routing. In a IEEE 802.11 based wireless network where nodes have identical and omni-directional ranges, going from single-hopping to multi-hop routing increases the end-to-end delay, which decreases the goodput because only one of the multiple hops can be active at any time due to half-duplex operation. From a network point of view, the goodput tends to increase due to spatial reuse of the spectrum when multi-hopping is employed together with transmit power control.

Moreover, the goodput performance is affected by MAC related issues such as carrier sensing, collisions, retransmissions, etc. [9] and this effect is traffic load dependent [5]. Going from single-hopping to multi-hop routing, goodput increases under moderate traffic loads (due to the lower contention with multi-hop transmissions), whereas goodput decreases under heavy traffic loads (due to the decreased probability of success over all links over a multi-hop route) [5]. The reason behind these different behaviors under different traffic loads is that goodput is the end-to-end data transfer rate, where only successfully received packets at the final destinations are counted. Although successful link transmissions occur under heavy traffic, end-to-end goodput substantially suffers from congestion losses due to increased traffic with multi-hop routing. This goodput behavior with respect to traffic load is shown to remain under different data rates [23]. These studies rely on the assumption of a Poisson traffic distribution, lacking the knowledge of validity of these results for different traffic models. The contribution of this article is the investigation of the effect of various traffic arrival distributions on the routing strategy choice for enhancing the goodput performance in multi-hop wireless networks under hidden terminal existence, extending the study in [5].

3. MODELLING AND SIMULATION

The average node goodput metric, which is used in this study for investigation of the effect of traffic arrival distributions on the routing strategy in multi-hop wireless networks, is defined as the number of end-to-end delivered useful bits per second averaged over all nodes in the whole network. The useful bits are the bits containing valuable data, excluding header bits and any related control frames, in the packets received successfully by the destination nodes. Goodput is obtained by dividing the total number of useful bits delivered successfully in the network by the number of nodes and the simulation duration.

3.1 Modelling Assumptions and Simulation Settings

A simulation model was developed to study the effect of traffic arrival distributions on the goodput performance of a IEEE 802.11g multi-hop ad-hoc network. The simulations are conducted using Network Simulator 2, version ns-allinone-2.34 [26]. The parameters used in the simulations are listed in Table 1. The goodput performance of single-hop and multi-hop routing strategies with $h = \{1, 3\}$ are studied for a hexagonally placed 127-node regular topology shown in Fig. 1. The diameter of the network is selected to be four times the transmission range in order to let hidden terminals to exist.

An hexagonal topology is chosen for several reasons: 1) The traffic of each source is distributed regularly to six destinations to avoid conditions where a path is heavily loaded in a short time scale. 2) The hop length of direct transmission is an integer multiple of multi-hop transmission link length, which provides a fair comparison background for the effect of traffic models on routing strategies. 3) Additionally, this hexagonal topology provides a dense network, where all possible linear paths carry traffic so that hidden terminals are present for all the transmission pairs, except a small number of receivers on border of the topology. Different random topologies are planned to be investigated as part of the future work.

Some assumptions made by previous studies are adapted into the simulations [35], [17] and [36]. The assumptions are as follows: i) The unified disk radio model, ii) Stationary

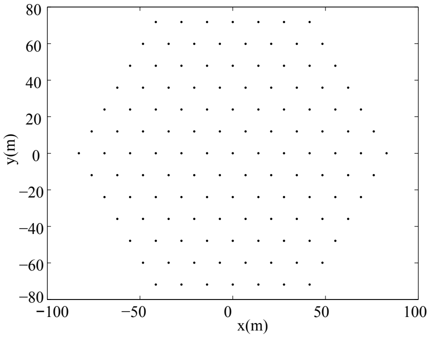


Figure 1: Node positions of the 127-node hexagonal topology

Table 1: Parameters used for simulation runs

Data rate (DR)	6 and 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

nodes. The unified disk radio model has been widely used by many researches in wireless networking due to its simplicity in mathematical characterization of physical layer [13] and is given by

$$P_{rx} = cP_{tx}d^{-\eta} \tag{1}$$

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

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 [30]. Thus, the RTS/CTS mechanism is used in this study.

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

The time durations of RTS, CTS, ACK and DATA frames are calculated according to ERP-OFDM specifications given by [6],

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

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

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

where DR is the transmission data rate.

The data rate, basic rate and corresponding receiver sensitivity values used in the study are $(6Mbps, 6Mbps, -112dB)$ and $(24Mbps, 54Mbps, -95dB)$, where the mandatory rate set when using the 20MHz channel spacing for an Independent Basic Service Set (IBSS)is used. Since the aim to to maximize goodput, the highest basic rate is preferred for the 54 Mbps data rate for a better performance comparison.

Nodes employ the maximum transmit power, $P_{txmax} = 0.25$, for direct transmission with data rate $54Mbps$. Power control is done to reduce the transmit power for lower data rates due to corresponding lower receiver-sensitivities. Also the transmit power is reduced so to reach the next hop for multi-hop routing.

3.2 Traffic Model

Simulations are done for unicast traffic and fixed routing scheme, where each generated packet traverses a path of h-hops, where h={1,3}. Hence, goodput under two different routing strategies, direct transmission versus multi-hop transmission is investigated for various data rates. The source-destination pairs are fixed during simulations for each data rate and h value for obtaining a fair comparison of the effect of traffic arrival rate. The source-destination pairs are determined so that one direct path and one h-hop multi-hop path are feasible. The error-free channel assumption is used in order to focus the discussion of the impact of joint traffic model, data rate and routing strategy on goodput under hidden terminal presence, so that collisions are due to hidden terminals instead of channel errors.

The traffic arrival distribution, i.e. traffic source distribution or the traffic model, describes the distribution of packet arrivals at source nodes in the network. Four models, which model real-life services adequately and have become generic models for a range of services in nature [24], and additionally traffic with mice-elephant users are used in this study:

- Poisson: The packets are generated at each station following an independent process with independent increments. The packet inter-arrival times are exponentially distributed. The Poisson trafic assumption is used in the literature to model various telecommunication traffic.

- Constant bit rate (CBR): Packets are generated at a constant rate and is generally used to model voice telephony and video-on demand.

- Exponential: The packets are generated at each station at a fixed rate during the ON periods, and no packets are generated during the OFF periods, where these periods are derived from an exponential distribution. The mean of ON and OFF periods selected to be 100 and 900 msec in this study.

- Pareto: The packet arrival process at nodes is similar to the Exponential arrivals, except that both ON and OFF periods are derived from a Pareto distribution. The LAN, TELNET and FTP traffic follow Pareto distribution. In the simulations, the shape parameter of the Pareto distribution is set as 1.5.

- Poisson with mice and elephant users: The packets are generated with Poisson distribution with extremely different packet arrival rates modelling different user behavior. In this study, half of the nodes generate Poisson traffic with an average rate of 100-times that of other nodes.

Each node is assumed to generate traffic with rate λ_o packets per second for all traffic arrival distributions considered in this study.

Traffic load generated by each source node is distributed regularly in the hexagonal topology to several destinations over multiple paths to avoid conditions where a path is heavily loaded in a short time scale. The simulations are performed from unsaturated up to saturated traffic loads. Under the saturated traffic load, there is always at least one packet waiting in the queue upon finishing processing of the last packet. The traffic load is classified as light, moderate and heavy in this study based on the average number of times a frame is retransmitted, n_{rtx}, over a link as follows:

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

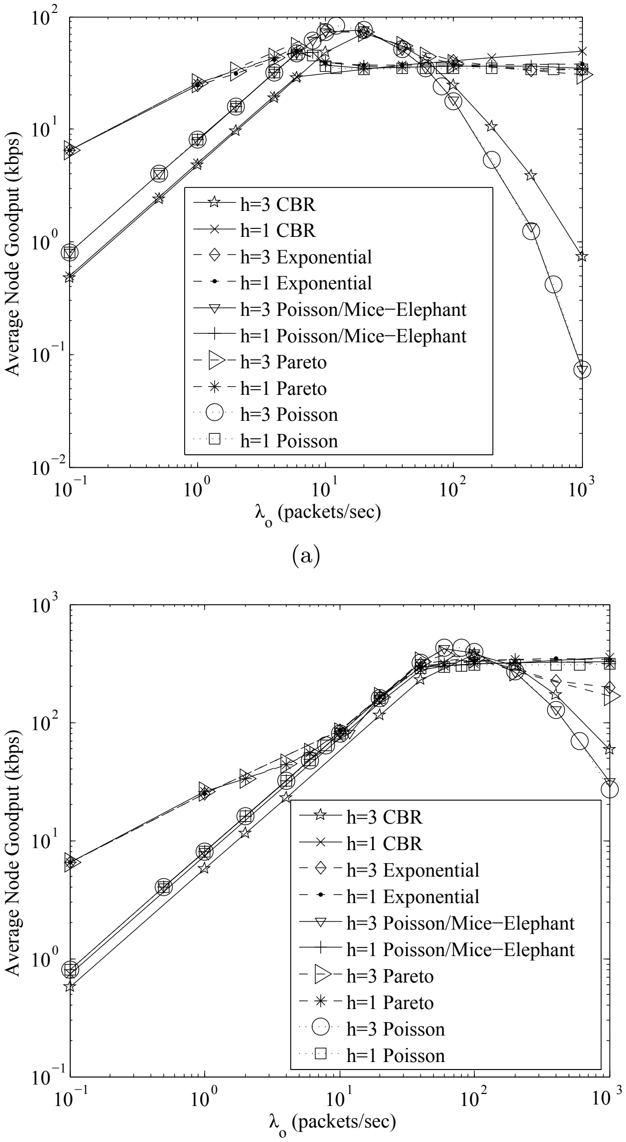
UDP streams are used as network traffic content where the source and destination pairs for each UDP flow are chosen so that each route has both single-hop and multi-hop alternative in order to provide a comparison for the routing strategy.

4. RESULTS

Simulation results for the effect of traffic arrival distributions on goodput performance of IEEE 802.11g based multi-hop wireless networks for different data rates and routing strategies over various traffic loads are given in Fig. 2. Average node goodput versus traffic load is illustrated for DR=6 Mbps in Fig. 2(a) and for DR=54 Mbps in Fig. 2(b). The average node goodput performance for each of the considered traffic arrival distributions are given Fig. 3 compared to the Poisson distribution for both data rates.

The behavior of the goodput curves under Poisson traffic arrivals, where multi-hop routing under moderate traffic load and single-hop routing at heavy traffic achieve higher goodput [5], is observed to also remain for the Exponential, Pareto, CBR and Poisson with mice-elephant users in Fig. 2. This result, different than the results for single-hop networks [24], demonstrates that the goodput performance for all traffic arrival distributions is *dependent* on the traffic load in single-hop networks. Additionally, all these traffic arrival distributions are observed to achieve higher goodput in Fig. 3 for higher data rates as the Poisson distribution shown in [23]. Hence, the goodput versus traffic load curve behavior in multi-hop networks for Poisson arrivals [5, 23] is found out to be valid for all the considered traffic arrival distributions.

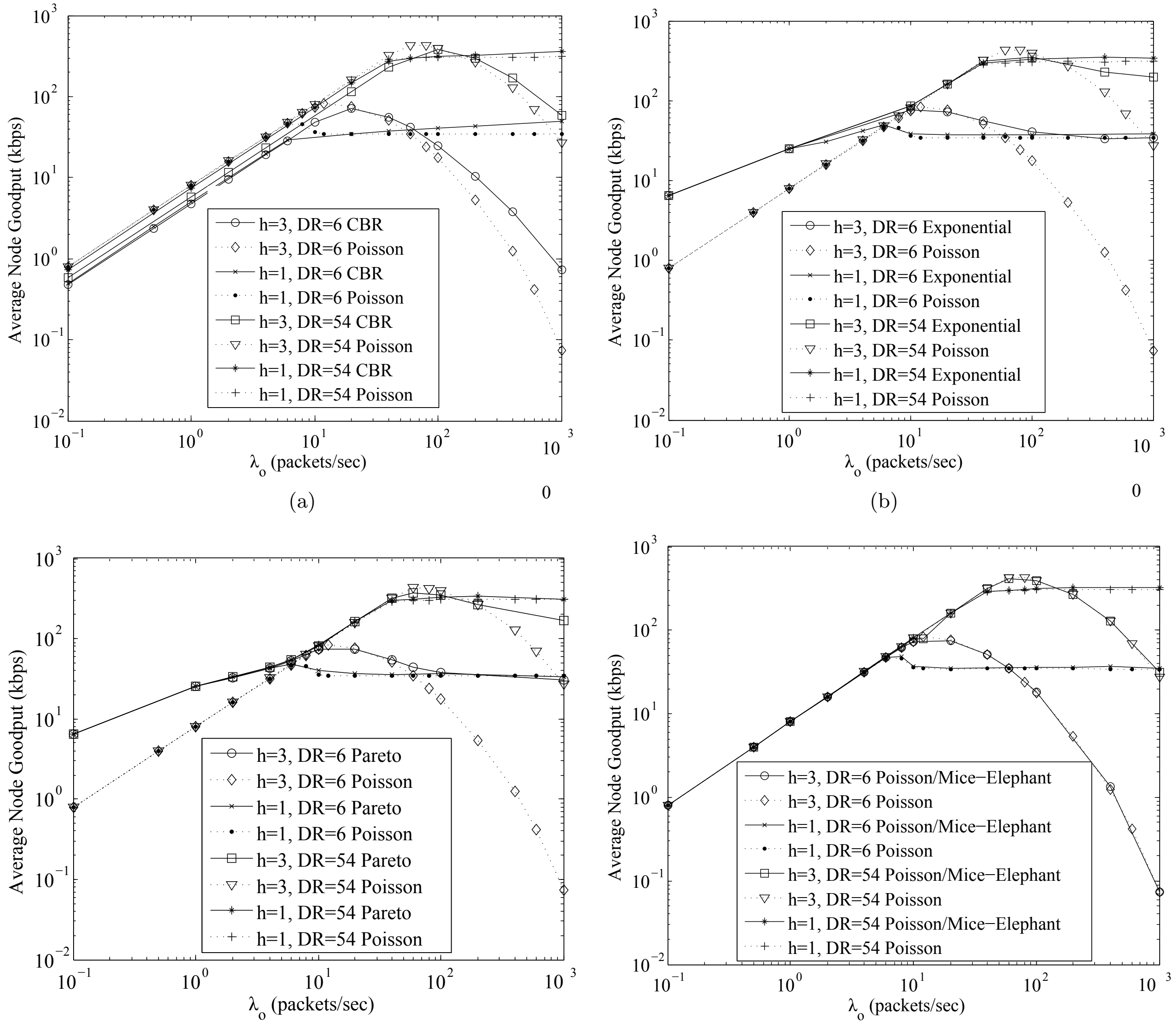
Under light traffic loads, CBR performs the worst goodput (Fig. 3(a)), whereas Exponential or Pareto traffic perform the best goodput (Fig. 3(b), Fig. 3(c)). The retransmission mechanism of IEEE 802.11 DCF generally results with repetitive hidden terminal collisions in multi-hop networks and the fixed packet inter-arrivals of the CBR traffic is observed to degrade the goodput performance by increasing the collision probability under light traffic loads. Additionally, the ON/OFF periods of the Exponential and Pareto traffic models are observed to introduce a control on the injected packets into the channel, providing a level of collision control and hence, the goodput of these traffic types with both routing strategies (direct transmission and multi-hop transmissions) becomes most advantageous. Under heavy traffic loads, Poisson traffic arrivals with multi-hop routing perform the worst, whereas CBR direct transmissions perform the best for all data rates. Under heavy traffic loads, the congestion losses due to increased traffic with multi-hop routing dominates and single-hop routing becomes better [5]. Hence, under heavy traffic loads, the interface queue saturates for multi-hop routing for all traffic arrival distributions. However, most of the multi-hop traffic arrivals during the ON period are dropped at the node interface queues for the



(a)

(b)

Figure 2: A comparison of impact of different traffic arrival distributions on goodput for data rates a) DR=6 Mbps and b) DR=54 Mbps



(a) (b)

(c) (d)

Figure 3: Goodput for the 127-node hexagonal topology for DR={6,54} and h={1,3} for traffic types: a) CBR, b) Exponential, c) Pareto, d) Poisson with mice and elephant users

bursty traffic models, such as Exponential and Pareto, resulting with a multi-hop routing goodput performance close to the single-hop routing case. It is observed that under moderate traffic loads, the joint effect of data rate and routing strategy on goodput is almost independent of the traffic type. The mice and elephant user behavior is observed to have a negligible impact on goodput performance, which shows that the IFQ already provides a control on the packets injected into the channel.

Although the traffic arrival distributions have an impact on the goodput performance in multi-hop networks, they have no effect on the selection of the routing strategy for maximizing goodput under perfect channel conditions, where collisions stem from concurrent transmissions due to hidden terminals rather than channel errors.

5. CONCLUSION

The primary contribution of this study is to show the effects of traffic arrival distributions on the decision of routing strategy (whether to directly transmit or multi-hop) for enhancing the goodput performance of multi-hop wireless networks under hidden terminal existence. Exponential, Pareto, Poisson, and CBR traffic models were used in the investigation. The behavior of IEEE 802.11g based multi-hop networks in an error-free, non-fading channel is observed by considering MAC contention and hidden terminals over a large range of traffic loads ranging from unsaturated to saturated by Network Simulator-2.

The goodput performance for all traffic arrival distributions is found to be dependent on the traffic load in multi-

Table 2: The best joint data rate and routing strategies for minimizing EPB for different topologies and traffic loads

Goodput		Traffic load		
		Low	Moderate	High
Traffic Model	Poisson	any h,any DR	h=3,DR=54	h=1,DR=54
	CBR	any h,any DR	h=3,DR=54	h=1,DR=54
	Exponential	h=1,DR=54	h=1,DR=54	h=1,DR=54
	Pareto	h=1,DR=54	h=3,DR=54	h=1,DR=54

hop networks, contrary to the results for single-hop networks [24]. Of the four traffic models used, the network achieved the best goodput with Pareto and Exponential arrival distributions for light traffic loads, where CBR performs slightly better under heavy loads. The CBR traffic results with the worst goodput performance under light traffic loads and Poisson results with the worst performance under heavy traffic loads.

Another important observation of this study is that the goodput behavior of the four traffic models are close to each other with a difference stemming from the burstiness of traffic. For example, the Exponential and Pareto models of on-off type perform almost the same goodput, whereas the Poisson and CBR have almost the same behavior. This is an outcome of the pacing of traffic induced bu the IEEE 802.11 DCF protocol shown in [27], which is different in case of an on-off type traffic model compared to a regular traffic.

The main conclusion of this study is that under perfect channel conditions, where collisions stem from concurrent transmissions due to hidden terminals rather than channel errors due to wireless propagation, the best strategy for maximizing goodput is to send data with Exponential or Pareto traffic under light traffic loads and with CBR traffic under heavy traffic loads, while jointly increasing the data rate and decreasing the hop-count of the routing strategy under moderate-to-heavy traffic loads. The best traffic arrival distributions, routing strategy and data rate for maximizing goodput are summarized in Table 2 over a wide range of traffic loads for the considered hexagonal topology.

In real life, traffic arrival distribution is generally determined by the application. However, for some applications, where delay is not critical, a traffic load-adaptive pre-control on the traffic arrivals into the IEEE 802.11 MAC layer in multi-hop networks will increase the goodput performance significantly. Such a pre-control provides early-elimination of packets and provides efficient use of network resources decreasing congestion losses due to hidden terminals. Shaping the arrival distributions as Pareto and Exponential under light traffic loads; as CBR traffic under heavy traffic loads and jointly using single-hop routing strategy increases goodput performance in multi-hop wireless networks.

As a conclusion, the results of this study provides guidelines on how traffic arrival distributions and routing strategy jointly affect goodput performance in IEEE 802.11 DCF based multi-hop wireless networks. As a future work, we suggest that a traffic load-aware pre-control mechanism on the traffic arrivals into the IEEE 802.11 MAC layer might provide significant goodput gains in multi-hop wireless networks.

An investigation of the impact of traffic arrival distribution for various network topologies and in error channels are planned as extensions of the study reported here.

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