

Effect of carrier sensing range on the throughput of multi-hop wireless Ad-Hoc network

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Abstract

Carrier sensing is a fundamental mechanism in Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocols and it has been used as an effective way to reduce collisions and exploit spatial reuse in wireless networks. The size of the carrier sensing range has a great effect on the network performance. This paper investigates the effect of sensing range on the throughput of multi-hop wireless ad hoc network by considering two fundamental issues in Medium Access Control (MAC), i.e., collisions and spatial reuse, in terms of persistent probability, transmission range and Exponential Increase Exponential Decrease (EIED) back-off time. Markov chain models were used to derive the duration time, transmission probabilities, transition probabilities and steady-state probabilities of the states of node as well as the throughput. Simulation results show that throughput increases along with increase in sensing range R_s , but when it reach its maximum value, its start decreasing with increase in the sensing range. This means that the larger the sensing range, the smaller the possibility that a new transmission attempt to interferes with some ongoing transmissions. Furthermore, smaller sensing range with a larger transmission range means more nodes have to defer their transmissions when one node is transmitting, which leads to lower spatial reuse and consequently decreases throughput. Similarly, smaller sensing range means more transmission hops which leads to more collisions. In the other hand, throughput decreases with increase in transmission range, number of nodes and back-off time.

Keywords: Carrier Sense; Spatial Reuse; Mobile Ad-hoc Networks; Medium Access Control; Back-off Mechanism; RTS/CTS Mechanism; Markov Chain.

Introduction

The Past few years have seen enormous development in wireless technologies, which significantly boost the growth of diverse wireless networks, from single-hop wireless networks to multi-hop wireless networks. In single-hop wireless networks such as cellular networks and Wireless Local Area Networks (WLANs), every node is within one hop of a central controlled entity (e.g., base stations, access points, etc.), and only communicates with the entity through single hop transmission. Such networks require much infrastructure support, hence are expensive to deploy. In the other hand, multi-hop wireless networks such as Mobile Ad Hoc Networks (MANETs) are usually collection of nodes equipped with radio transmitters, which not only have the capability to communicate with each other

in a multi-hop fashion, but also be able to route data packets as a relay from the source to the destination. Due to their inherently distributed nature, MANETs are more robust than their cellular counterparts against single-point failures, and have the flexibility to reroute around congested nodes. Furthermore, MANETs can conserve battery energy by delivering a packet over a multi-hop path that consists of short hop-by-hop links. Applications of MANETs include the battlefield applications, rescue work, as well as civilian applications like an outdoor meeting, or an ad-hoc classroom. In wireless ad hoc network, Medium Access Control (MAC) protocol is the main element that determines the efficiency in sharing the limited communication bandwidth of the wireless channel.

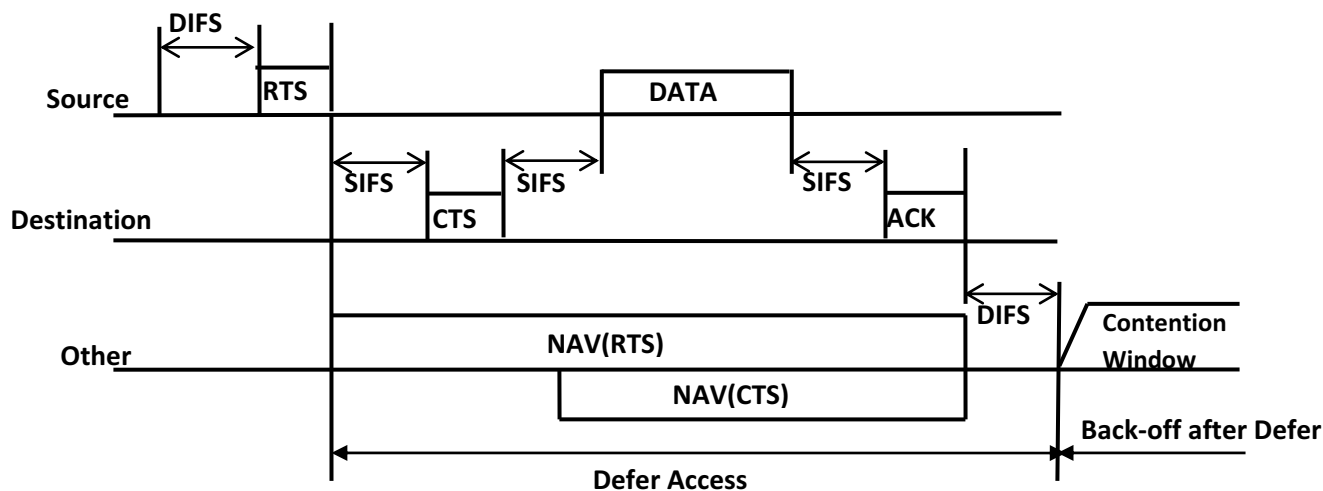


Fig. 1. The RTS/CTS Access Method

The IEEE 802.11 (IEEE Computer Society, 1999) protocol is a kind of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocols and it has been the standard for WLAN both in infrastructure and in ad hoc mode, although originally it was developed for a single access point scenario. The 802.11 specification supports two fundamentally different MAC schemes, namely the Distributed Coordination Function (DCF), and the Point Coordination Function (PCF). The DCF protocol can be described as CSMA/CA and it has been widely studied in wireless multi-hop ad hoc networks due to its simple implementation and distributed nature. There are two access methods that are used under DCF, namely the basic access method and the (Request To Send (RTS)/Clear To Send (CTS) access method. The RTS/CTS access method uses a four-phase RTS-CTS-DATA-ACK handshake as shown in Fig.1. There are five timing intervals for the protocol. Two of them are considered basic ones that are determined by the physical layer: the Short Inter-frame Space (SIFS) and the slot time. The other three intervals are defined based on the two basic intervals: the Priority Inter-frame Space (PIFS), the Distributed Inter-frame Space (DIFS), and the Extended Inter-frame Space (EIFS).

Carrier Sensing Range

Carrier sensing is a fundamental mechanism in CSMA/CA protocols. It is usually determined by

the antenna sensitivity. In this mechanism, a node senses the channel before transmission and defers the transmission if it senses a busy channel to reduce collision. This mechanism consists of physical carrier sensing and virtual carrier sensing. In the physical carrier sensing, the channel is determined busy if the sensed signal power exceeds a certain threshold, referred to as Carrier Sense Threshold (CST). Otherwise, the channel is determined idle. It is clear that the value of CST decides the sensing range and affects both the collision possibility and spatial reuse in MANETs, since a smaller CST means the node can sense the signal in a larger sensing range, and vice versa. Physical carrier sensing range, in which a transmission is heard but may not be decoded correctly, can be much larger than the transmission range and hence it can be more effective than the virtual carrier sensing in avoiding the interference especially in the multi-hop networks. Sensing range is the range within which a transmitter triggers carrier sense while transmission range represents the range within which a packet is successfully received if there is no interference from other radios. Fig. 2 shows both transmission and sensing ranges of a node. However, large carrier sensing range reduces the number of concurrent transmissions, which is referred to as “spatial reuse” and affects the aggregate throughput because any potential transmitters, which sense a busy channel, are required to keep silent. The size

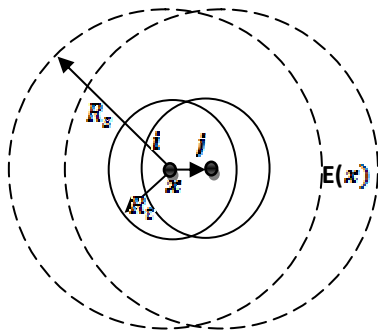


Fig. 2. Transmission and Sensing Ranges of a Node. (The small and larger circle denote the transmission and sensing range, respectively)

of the carrier sensing range has a great impact on the system performance. Although a smaller carrier sensing range allows more transmissions to happen concurrently, it introduces more interference that may lead failure to more transmissions.

Back-off Mechanisms

To reduce collision possibility, the DCF mechanism uses a back-off mechanism in which every node has a back-off counter and a back-off stage. The back-off counter value is initially chosen as described below. The back-off procedure selects a random number of time slots between 0 and the contention window CW, according to the following equation:

$$\text{Back-off Counter} = \text{Int}(\text{CW} * \text{Random}(\)) * \text{Slot Time} \quad (1)$$

Where CW is an integer between CW_{\min} and CW_{\max} , typical values being 31 and 1023, respectively. Random () is a random number between 0 and 1. Slot time is fixed for a given physical transmission scheme (IEEE Computer Society, 1999). Although Binary Exponential Back-off (BEB) mechanism is widely used in many contention-based MAC protocols for its simplicity and good performance, it is not a perfect back-off mechanism in fairness and efficiency especially in multi-hop ad hoc networks. Because of the drawbacks of BEB, some new back-off mechanisms were proposed (Bharghavan *et al.*, 1994; Song *et al.*, 2003). A Multiplicative Increase and Linear Decrease (MILD) mechanism is adopted in the MACAW protocol (Bharghavan *et al.*, 1994) to address the large variation of the contention window size and the unfairness problem

of BEB. MILD performs well when the traffic load is steadily heavy. However, the “linear decrease” sometimes is too conservative, and it degrades the performance when the traffic load is light or the number of active nodes changes sharply (Song *et al.*, 2003). To overcome these problems, the Exponential Increase Exponential Decrease (EIED) back-off algorithm has been studied in (Song *et al.*, 2003). In the EIED algorithm, the contention window size is increased and decreased exponentially on every collision and successful transmission, respectively. As a result, EIED is not as conservative as the “linear decrease” of MILD and not as radical as the “reset” of BEB.

Persistent Probability

Persistent probability reduces the collisions caused by the propagation delay, because there is a small chance that just after a node begins sending, another node will become ready and sense the channel; if the first node’s signal has not yet reached the second one, the latter will sense an idle channel and will also begin sending, resulting in a collision. The longer the propagation delay the larger the possibility of the collision. Even if the propagation delay is zero, there will still be collisions. If two nodes become ready in the middle of a third node’s transmission, both will wait politely until the transmission ends. If they happen to have the same back-off timer, then both will begin transmitting exactly simultaneously, resulting in a collision. To address this problem, some MAC protocols introduce a persistent probability p (Ivan *et al.*, 2007). When a node becomes ready to send, it senses the channel. If it is idle, it transmits with a persistent probability p. With a probability $1 - p$, it defers until the next slot. If that slot is also idle, it either transmits or defers again, with probability p and $1 - p$.

This paper investigates the effect of sensing range on the throughput of multi-hop wireless ad hoc network by considering two fundamental issues in Medium Access Control (MAC), i.e., collisions and spatial reuse, in terms of persistent probability, transmission range and Exponential

Increase Exponential Decrease (EIED) back-off time.

Related work

MANETs have particular features and complexity compared to conventional wireless networks. Several mechanisms have been proposed to improve network performance and to avoid collisions in MAC protocol for multi-hop wireless ad hoc networks, namely carrier sense, handshake, and back-off mechanism (Saikat *et al.*, 2005; Jing *et al.*, 2004). Many papers (Zhai & Fang, 2006; Kim *et al.*, 2006; Chongqing, 2010) have already attempted to optimize the system throughput by tuning carrier sensing range and transmit power. (Yang & Vaidya, 2005) shows that the MAC overhead, bandwidth-independent and bandwidth-dependent, has a significant effect on the choice of carrier sensing range. (Zhai & Fang, 2006) identify the optimum carrier sensing range for different data rates. (Chongqing, 2010) proposed a framework to determine the optimum carrier sensing range of a network using transmission relation graph (TRG), they used the framework to compute a precise optimum carrier sensing range for the given network they also investigated the changing rules of the optimum carrier sensing range of several types of wireless networks. (Shunyuan & Shivendra, 2009) derived an analytical model to calculate the successful transmission probability and throughput of routing protocols using different link metrics. They also investigate the impact of some other important factors, such as node density, average contention window size and packet length. It is shown in (Deng, 2004; Guo, 2003) that the spatial reuse efficiency could be improved significantly by tuning the carrier sensing threshold. Based on a simplified interference model, an analytical model is presented in (Zhu, 2004) to demonstrate how to derive the optimal sensing threshold given reception power, data rate and network topology. In (Kim *et al.*, 2006), similar model is adopted to study how to improve spatial reuse through tuning transmit power, carrier sensing threshold and data rate.

Throughput Analysis of a MANET

Throughput of a MANET is defined as the fraction of time the channel is used to successfully transmit payload bits (Bianchi, 2000). Since four-way RTS/CTS/DATA/ACK handshake is widely adopted in MANETs, such a handshake mechanism is assumed in this paper. In MANETs, it is assumed that all the nodes use the same sensing range of radius R_s and the same persistent probability p . The average back-off time of each node during a transmission is denoted by T_b . During the transmission, it is assumed that each node has three states: a successful transmission state *success*, a wait state *wait*, and a failed transmission state *failure*. We use $s_i = (i = s, w, f, \text{respectively})$ to denote these states.

Let Q_{s_i} be the steady-state probability for state s_i of the node (Q_{s_j} equals the long run proportion of transitions which are into state s_j), T_{DATA} be the data transmission time, T_{s_i} be the time which the node spends on state s_i , the throughput of MANETs is equal to the limiting probability that the node is transmitting data and thus can be denoted by

$$Th = \frac{Q_s T_{DATA}}{\sum_{s_i} Q_{s_i} T_{s_i}} \tag{2}$$

A three-state Markov chain is used to model a channel around node i that is Idle, Busy-success and Busy-failure and their durations are denoted as T_i , T_{bs} and T_{bf} respectively (Mustapha *et al.*, 2011). $T_i = \tau$, $T_{bs} = T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + 4\tau$ and $T_{bf} = T_{RTS} + T_{CTS} + 2\tau$.

The transition probabilities from idle to idle, from idle to busy1-success, and from idle to busy2-failure are denoted as P_{ii} , P_{is} and P_{if} respectively. Thus,

$$P_{ii} + P_{is} + P_{if} = 1 \tag{3}$$

The idle channel around node i changes to the busy1-success state in three circumstances. First circumstance is that node i is exposed to at least one source node which performs a successful transmission. Here “expose” means that two nodes can sense each other. Second circumstance is that node i is not exposed to a source node but it is exposed to at least one destination node, which performs a successful reception. The third

circumstance is that node i itself transmits to a destination node successfully. Let P_{ts1} and P_{ts2} be the probability that there is at least one successful transmission in node i 's sensing area and probability that there is at least one successful reception in node i 's sensing area respectively. The probability that a node successfully transmits in a slot is P_s , and since on average \bar{N} nodes including node i itself participate in generating a busy slot,

$$P_{ts1} = 1 - \sum_{n=1}^{\infty} (1 - P_s)^n \frac{\bar{N}^n}{n!} e^{-\bar{N}} \quad (4)$$

The probability that at least one of the transmissions from nodes in an area A has a destination node in the sensing range of node i , is given by

$$P_{ts2} = 1 - \sum_{n=0}^{\infty} (1 - P_i)^n \frac{\bar{N}_A^n}{n!} e^{-\bar{N}_A} \quad (5)$$

Where P_i is the probability that any node in area A initiates a successful four-way handshake to a node in a sensing area of i . Therefore, the transition probability P_{is} is given by

$$P_{is} = P_{ts1} + P_{ts2} \quad (6)$$

The idle channel stays in idle state if none of the nodes in the sensing area of node i transmit in this slot. Thus P_{ii} is given by:

$$P_{ii} = \sum_{n=1}^{\infty} (1 - P_t)^n \frac{\bar{N}^n}{n!} \quad (7)$$

Therefore,

$$P_{if} = 1 - P_{ii} - P_{is} \quad (8)$$

Let π_{ii} , π_{is} and π_{if} denote the steady-state probabilities of states idle, busy1-success and busy2-failure, respectively. Thus, the following relationships exist: $\pi_i P_{is} = \pi_{bs}$; $\pi_i P_{if} = \pi_{bf}$

In collision avoidance MAC protocol, when the channel is sensed idle, in each time slot, a node intends to transmit a frame with the persistent probability p . Therefore, the probability that a node transmits in any time slot is called *transmission probability* P_t , which is given as: $P_t = p \cdot P_i$. P_i is the limiting probability that the channel is in idle state. Note that even a node transmits; it still may fail due to collisions with other transmissions at the same time. The limiting probability P_i , i.e., the long run probability that the channel around node i is sensed idle, can be obtained by:

$$P_t = \frac{p P_i}{P_i + P_{ts} T_{bs} + P_{if} T_{bf}} \quad (9)$$

A three-state Markov chain is used to model the states of node i (Mustapha *et al.*, 2011). The three states of this Markov chain are *Wait*, *Success* and *Failure* and their durations are T_w , T_s and T_f respectively. $T_s = T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + 4 \tau$, $T_f = T_{RTS} + T_{CTS} + 2 \tau$ and $T_w = \bar{T}_b + \bar{T}_d$. \bar{T}_b is the average back-off time and \bar{T}_d is the average deferring time. The transition probabilities from wait to wait, from wait to success and from wait to failure are denoted as P_{ww} , P_{ws} and P_{wf} , respectively. Thus,

$$P_{ww} + P_{ws} + P_{wf} = 1 \quad (10)$$

A parameter \bar{M} is defined to be the average number of nodes within the transmission range of node i . Since when the node density does not change, the number of nodes is proportional to the area size,

$$\bar{M} = \frac{N \pi R_c^2}{\pi R_s^2} \quad (11)$$

The transition probability P_{ww} that node i continues to stay in *wait* state in a given slot, is the probability that node i does not initiate any transmission and there is no node within the transmission range of node i initiating a transmission.

$$P_{ww} = (1 - P_t) \sum_{n=1}^{\infty} (1 - P_t)^{n-1} \frac{\bar{M}^n}{n!} e^{-\bar{M}} \quad (12)$$

Given that each sending node chooses any one of its neighbors as the receiver with equal probability, x can be considered as a uniform random variable in the range $0 < x < R_c$. Then, the probability density function of the distance x between node i and j is

$$f(x) = \frac{1}{R_c} \quad (13)$$

From the total probability theorem (Ross, 1970) P_{ws} can be written as follows:

$$P_{ws} = \int_0^{R_c} f(x) P_{ws}(x) dx \quad (14)$$

$$P_{wf} = 1 - P_{ww} - P_{ws} \quad (15)$$

Let π_w , π_s and π_f denote the steady-state probability of state wait, success, and failure, respectively. Then

$$\pi_w + \pi_s + \pi_f = 1 \quad (16)$$

The steady-state probability of wait state is given by $\pi_s = \pi_w P_{ws}$, $\pi_f = \pi_w P_{wf}$, $\pi_w = \frac{1}{2 - P_{ww}}$.

For EIED back-off mechanism the contention window size is decreased by a factor r_D upon a successful transmission, and increased by a factor r_L upon a collision. Simulation results in (Bharghavan *et al*, 1994) show that EIED with relatively smaller value of r_D compared to the value of r_L has higher performance gain. For example, let $r_L = 2$, and $r_D = 2^{1/8}$, Then the back-off time can be written as

$$\bar{T}_b = \frac{\frac{1}{2} \cdot \frac{r_L}{r_D} m \tau}{p \tau}, \quad \bar{T}_d \text{ is given by } \bar{T}_d = \frac{\tau}{2p\tau} \quad \text{and}$$

$$T_w = \bar{T}_b + \frac{\tau}{2p\tau}$$

Therefore,

$$Th = \frac{\pi_s T_{DATA}}{\pi_w T_w + \pi_s T_s + \pi_f T_f} \quad (17)$$

Simulation Results and Discussions

The simulation was carried out using MATLAB 7.1 release 14. The results show that sensing range has significant effect on the throughput of MANETs.

Fig.3 illustrates the effect of sensing range on the throughput of MANETs by varying persistence probability p . The result show that for $R_s = 250m, 550m$ and $750m$, the throughput always achieve a maximum value at some point of persistent probability p . It is observed that the throughput increases when R_s increases, for example, in Fig 3 if R_s increases from $250m$ to $750m$, the throughput increase by 45%. This means that the larger the sensing range, the smaller the possibility that a new transmission attempt interferes with some ongoing transmissions.

Fig.4 illustrates the effect of sensing range on the throughput of MANETs by varying transmission range. It is observed that the throughput of MANETs increases with increase in sensing range R_s . For example, in Fig 4 when R_s increases from $250m$ to $750m$ at a transmission range of $R_t = 250m$, the throughput increases by 26.4%. In the other hand, the throughput decreases with increase in the transmission range. This

indicate that smaller sensing range with a larger transmission range means more nodes have to defer their transmissions when one node is transmitting, which leads to lower spatial reuse and consequently decreases throughput. It is also observed that for the same R_s , the smaller transmission range has a higher throughput. Also a smaller sensing range means more transmission hops which leads to more collisions.

Fig.5 illustrates the effect of sensing range R_s on the throughput of MANETs by varying number of nodes, The maximum throughput decreases with increase in number of nodes, because the more number of nodes, the more collisions may happen, and the more time is needed for a successful transmission. For instance, in Fig 5 when N is increase from 5 to 20 at a sensing range of $R_s = 750m$, the maximum throughput dropped by 42.2%. This illustrates that number of nodes has to increase along with the gain of the sensing range to obtain the maximum throughput.

Fig.6 shows the effect of sensing range on throughput by varying back-off time. It is observed that the throughput increases along with increase in the sensing range linearly. In the other hand, throughput decreases with increase in back-off time linearly. For example, when $R_s = 750m$, the throughput is around 0.051 Mbps, while for $R_s = 250m$ the throughput is about 0.028 Mbps, which is 45% lower than the former. Similarly, the back-time decreases with increase in sensing range.

Fig.7 revealed the relationship between the throughput and the sensing range. The result shows that throughput increases along with the increase of R_s , but when it reach its maximum value, it start decreasing with increase in sensing range.

Conclusions

MANETs have particular features and complexity compared to conventional wireless networks. One of the fundamental challenges in MANETs research is how to increase the overall network throughput while maintaining low energy consumption for packet processing and communications. Effect of sensing range on the throughput of multi-hop wireless ad hoc network

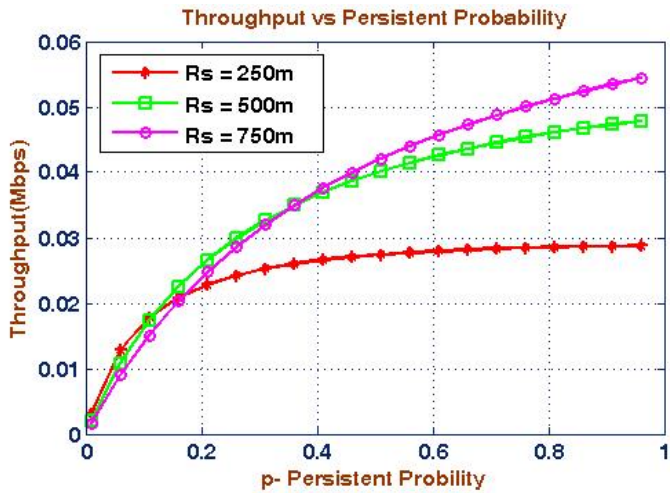


Fig. 3. Throughput vs Persistent Probability

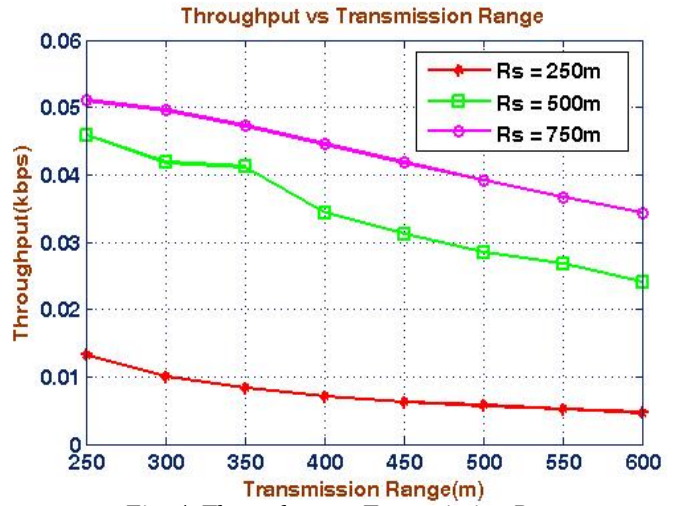


Fig. 4. Throughput vs Transmission Range

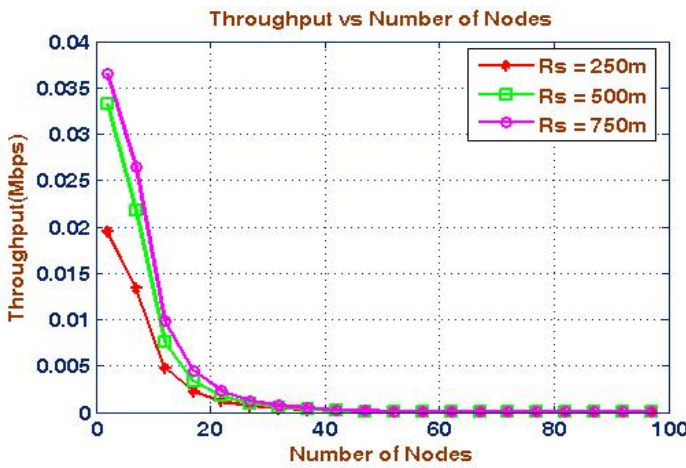


Fig. 5. Throughput vs Number of Nodes

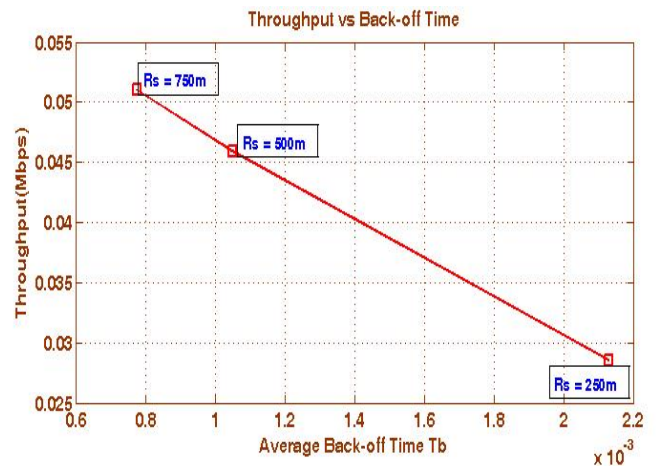


Fig. 6. Throughput vs Average Back-off Time

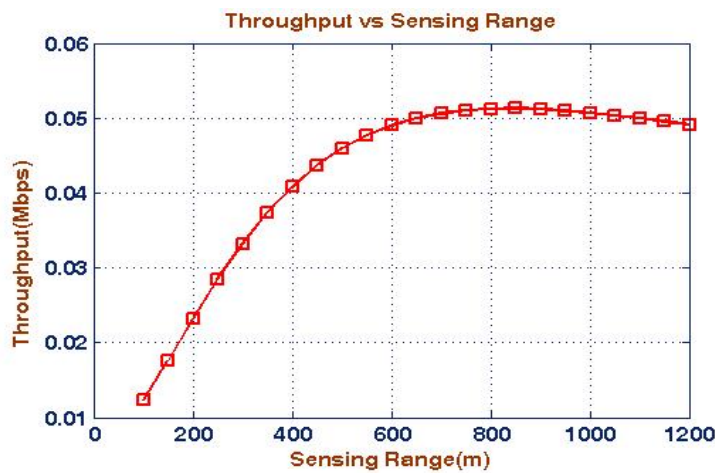


Fig. 7. Throughput vs Average Back-off Time

was investigated by considering two fundamental issues in MAC, i.e., collisions and spatial reuse, in terms of persistent probability, transmission range and back-off time

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