Analytical Evaluation of the 802.11 Wireless Broadcast under Saturated Conditions

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Abstract

The popular IEEE 802.11 wireless networking standard has been traditionally used for *unicast* communications. There is, however, a recent trend in harnessing the *broadcast* capability of the standard in a range of monitoring and safety related applications, e.g., transportation safety and vehicular traffic management. As this trend continues, models that accurately predict the performance of the 802.11 broadcast will be increasingly useful. Although unicast modelling received considerable attention, analytical evaluation of the broadcast protocol remained relatively unexplored. Using a simple one-dimensional discrete time Markov chain, we analyse the reliability and throughput performance of the IEEE 802.11 broadcast communications for saturated traffic conditions. The model is validated by means of an independent commercial simulator. Using the proposed model, we provide an extensive performance analysis of the 802.11 broadcast communications. The analysis allows us to study the tradeoff between the communication reliability and the system throughput of a local area wireless broadcast network. The throughput performance of broadcast is compared with that of the unicast under different network sizes and different combinations of 802.11 protocol parameters.

1 Introduction

The IEEE 802.11 standard [13] has fueled an unprecedented growth in the wireless industry. An exploding number of consumer electronic devices now have the 802.11 wireless communication capability (WiFi-enabled devices) making the standard one of the most pervasive protocols in the world. IEEE 802.11 supports both unicast and broadcast communications. With unicast, the sender has a specific destination in mind, whereas a broadcast is intended for every nodes within the wireless communication range of the sender. Most traditional applications, e.g., wireless access to the Internet using a portable device and making phone calls over a wireless local area network using a WiFi phone, use the unicast protocol.

Performance modelling of 802.11 unicast has received significant attention from the research community. Soon after IEEE released the specification for 802.11, Bianchi [3] proposed a Markov chain model of the unicast communication that subsequently became the main reference for many researchers who attempted to improve upon it [2, 5, 7, 14, 15]. On the contrary, analytical evaluation of the broadcast protocol received little or no attention, probably due to the lack of critical applications.

There is, however, a recent trend in utilising the broadcast capability of the 802.11 standard in a range of monitoring and safety related applications. For example, it is now believed that by allowing vehicles to broadcast status and warning messages to all other nearby vehicles can potentially prevent fatal accidents on the roads and improve the overall security and efficiency of the transportation systems [6, 9]. The interest from the car manufacturers to embed 802.11 radios in their future models, and the standardization of the Direct Short Range Communication (DSRC) [4] and the Wireless Access for Vehicular Environments (WAVE) [1] have prompted many researchers to study the performance of 802.11 broadcast [9, 11, 12]. However, these efforts were confined to simulation-based evaluation only. Analytical evaluation of the 802.11 broadcast remains largely unexplored.

In this report, we make an attempt to analytically evaluate the performance of 802.11 broadcast under saturated conditions (i.e., all network nodes always have a message waiting in the queue). In particular, we propose a simple Markov chain model that is mathematically tractable yet captures the important behaviours of the broadcast protocol. By means of an independent commercial simulator (*Qualnet* [10]), we demonstrate that the model is valid and capable of accurately predicting the performance of 802.11 broadcast communication under saturated condition. Using the proposed model, we carry out an extensive throughput and reliability performance analysis of wireless broadcast for different flavours of 802.11 (802.11a and 802.11b). Throughput performance of broadcast is compared with that of unicast in different networking scenarios.

The rest of the report is organised as follows. Section 2 provides an overview of the IEEE 802.11 standard highlighting the key differences between the unicast and broadcast protocols. The proposed Markov chain model of the 802.11 broadcast is presented in Section 3 followed by its validation in Section 4. Using a series of numerical experiments, the 802.11 broadcast performance is evaluated in Section 5. A comparative study between unicast and broadcast performance is carried out in Section 6. We draw our conclusions in Section 7.

2 Overview of IEEE 802.11

The IEEE 802.11 Distributed Coordination Function (DCF) Medium Access Control (MAC) protocol [13] is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The medium is shared by multiple nodes cooperating in a so called *random backoff scheme*. According to the protocol, if a node detects the medium being busy when it has a packet to send, this node will set its backoff counter to a random value between 0 and the *contention window size*. The backoff counter is then starts decrementing once per *backoff slot time* after the medium becomes idle. The decrement will stop if the medium is detected busy again and then continue after the medium remain idle for a DCF Inter Frame Space (DIFS) time. Upon finishing a transmission, the node will enter the random backoff process again whether or not it has additional packets currently queued for transmission.

The phenomenon where transmissions from two or more nodes overlap in time, is called a *collision*. Usually, unless there is some sort of *capture* [1], all packets involved in a collision are destroyed beyond repair. To improve network reliability in the face of collisions, a two-way handshake (*Ack*) scheme is adopted by the 802.11 standard for *unicast* communications. Upon receiving a packet, the receiver sends a *Ack* message to the sender. If no *Ack* is received within a specified timeout interval (because the packet is destroyed in a collision), the sender doubles its contention window and queues the packet for retransmission. The sender keeps doubling the window at each successive retransmission until an *Ack* is received or the window size reaches its maximum value. By forcing the nodes to wait longer before a transmission, the exponential increase of the contention window improves the performance of unicast communication, especially in highly congested network. The two-way handshake scheme described above is called the *basic access* mechanism (basic unicast). DCF also defines an additional four-way handshaking technique, called *request to send* and *clear to send*(RTS/CTS) to shorten the collision detection time and bypass the hidden terminal problem[2] (RTS/CTS unicast).

However, the handshaking schemes can only be applied to the packets that have a unique receiving node. In broadcast, all nodes within the wireless communication range of the sender are expected to receive the transmitted packet. Clearly, handshaking is not applicable to broadcast communications. As a result, there is no retransmission and no exponential increase of the window for broadcast. The lack of handshaking between the sender and the receiver is a major source of reliability problem for 802.11-based broadcast communications.

3 Markov Chain Model

The discrete time Markov chain model we propose for the IEEE 802.11 broadcast is based on the assumption that every node is always ready to transmit and all communication happens in ideal channel conditions. Specifically, we assume the following :

- Each node always have a packet in the queue ready for transmission (saturated condition)

[1] Capture (or power capture) refers to the phenomenon in wireless communications where a packet is still captured successfully despite being involved in a collision because of its high received power compared to the other colliding packets.

[2] A node is considered *hidden* if it remains outside the wireless communication range of the sender, but within the range of the receiver.

Table 1: Parameter Definition for the Markov Chain

Parameter	Definition
n	Number of nodes in the network (network size)
W	The contention window size
p	The probability that the channel is busy when the node is trying to decrease the backoff counter

- Any transmitted packet is always successfully received by all nodes in the network unless it collides with another transmission (no hidden terminal)
- All packets involved in a collision are destroyed beyond repair (no capture effect)

3.1 Model Description

Previously, researchers [2, 3, 5, 7, 14, 15] proposed a *two dimensional* Markov chain model to study the random backoff process of each node with saturated unicast traffic load. The second dimension was needed to accommodate the exponential increase in the contention window during retransmissions. Since there is no retransmission (window never increases) with broadcast, we do not need the second dimension in our model. The broadcast backoff process of a saturated node is modeled as a one dimensional Markov chain as shown in Figure 1 with the model parameters defined in Table 1.

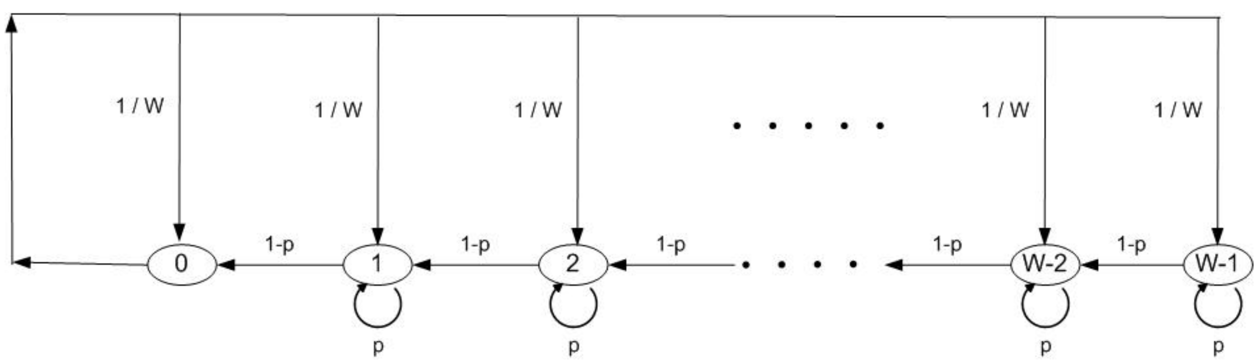


Figure 1: Markov chain model for 802.11 broadcast

When a node has a packet to transmit, it starts the backoff process by randomly selecting a backoff counter value from 0 to $(W-1)$ and then starting to decrement the counter all the way to 0. The state (k) represents the current backoff counter value. The transition from state (k) to $(k-1)$ happens with probability $(1-p)$ after a *backoff slot time*, while with probability p the backoff process remains at the current state. The packet is finally transmitted when the backoff process reaches the state (0). After the transmission finishes, the transition probabilities from state (0) to all the other states are the same $(1/W)$, i.e., the backoff counter value selection is uniformly distributed from 0 to $(W-1)$.

3.2 Transmission Probability

Let b_k denotes the stationary distribution of the corresponding states in Figure 1. We are particularly interested to find the value of b_0, which is the *transmission probability*, i.e., the probability that a node is in transmission state in a randomly chosen time slot. From the chain regularities, and by computing recursively through the chain from right to left, we get:

$$b_k = \frac{(W-k)b_0}{W}, k = 1, 2, ..., W-1 \tag{1}$$

By replacing b_k with equation (1), the normalization condition:

$$\sum_{k=0}^{W-1} (b_k) = 1 \tag{2}$$

turns out to be a formula with b_0 being the only unknown variable, from which the value of b_0 is derived as:

$$b_0 = \frac{1}{\frac{W-1}{2(1-p)} + 1} \tag{3}$$

In (3), b_0 depends on the probability p, which is still unknown. For an *ideal channel*, the probability that the channel being busy when a node is trying to decrement its backoff counter is the probability that among the rest of the nodes, at least one is in transmission state. Therefore,

$$p = 1 - (1 - b_0)^{(n-1)} \tag{4}$$

The transmission probability b_0 can be obtained by solving (3) and (4) simultaneously. In the remainder of this section, we will derive closed form expressions for broadcast reliability and saturation throughput in terms of the b_0.

3.3 Reliability

The reliability R is defined as the probability that the transmitted packet does not collide with other packets. R can be calculated as the probability that only one node is transmitting over the average number of packets transmitted in a randomly selected time slot:

$$R = \frac{nb_0(1-b_0)^{n-1}}{nb_0} \tag{5}$$

It is interesting to observe that the packet size has no bearing on the reliability of broadcast communication. R depends only on the network size (n) and the size of the contention window (note that b_0 depends on W).

3.4 Throughput

The following two probabilities are needed to calculate the throughput: P_t and P_s. P_t is defined as the probability that at least one node is transmitting in a randomly selected time slot

$$P_t = 1 - (1 - b_0)^n \tag{6}$$

P_s is the probability that only one node is in the transmission state, conditioned on that at least one node is transmitting. So the conditional probability can be derived as:

$$P_s = \frac{nb_0(1-b_0)^{n-1}}{P_t} = \frac{nb_0(1-b_0)^{n-1}}{1-(1-b_0)^n} \tag{7}$$

The normalized throughput S is defined as:

$$S = \frac{E[time\_spent\_on\_successfully\_transmitting\_payload\_information\_in\_a\_slottime]}{E[length\_of\_a\_slot\_time]} \tag{8}$$

Since a successful transmission occurs in a slot with probability $P_t P_s$, the average time spent on the successful transmission is $P_t P_s T_{PL}$, where T_{PL} is the time spent to transmit the payload information of each packet. The average length of a slot time can be obtained by considering the following three possible cases:

- With probability $1 - P_t$, no node is transmitting in the slot. The duration is σ, which is the empty *backoff-slot-time*.
- With probability $P_t P_s$, only one node is transmitting in the slot. The duration is T_s, which is the transmission time of each packet, including the time spent to transmit the physical header, MAC header and the payload, plus DIFS and propagation delay.
- With probability $P_t(1 - P_s)$, there are two or more nodes transmitting in a slot time, which means collision happens. The duration of this slot is also T_s since the collision of broadcast packets does not have effect on the backoff process.

Hence Equation (8) becomes:

$$S = \frac{P_t P_s T_{PL}}{(1 - P_t)\sigma + P_t P_s T_s + P_t(1 - P_s)T_s} \tag{9}$$

Note that Equation (9) is slightly different from the equation presented in [3]. The reason for this is that the duration of a collision-free slot and a collision slot are the same for broadcast, but they are different for unicast (the collision-free slot for unicast contains a SIFS and transmission delay of *Ack* message while the collision slot does not).

For negligible propagation delay, T_{PL} and T_s are calculated as:

$$T_{PL} = \frac{Packet\_Size \times 8}{Bit\_Rate} \tag{10}$$

$$T_s = T_{PHY} + T_{MAC} + T_{PL} + DIFS = T_{PHY} + T_{MAC} + T_{PL} + 2\sigma + SIFS \tag{11}$$

4 Model Validation

In order to validate the proposed model, we use an independent commercial simulator (*Qualnet* [10]) to simulate a 802.11 broadcast network. We then compare the reliability and the throughput performance of the network obtained from the simulations with those predicted by our model. It should be emphasized that *Qualnet* is not only an independent simulator, it is also known for its detailed implementation of the physical and medium access control (MAC) layers of the 802.11 standard (see [8] for example).

The parameters used for the analytical and the simulation experiments are summarized in Table 2. All broadcast packets have the same size. Considering DSRC as a typical application of broadcast communication, we choose 128-byte packets, which is the same size as the Forward Collision Warning (FCW) message studied in [9]. Unless otherwise specified, the numerical results derived in this report are based on 802.11a parameters.

Table 2: 802.11 Parameters

	802.11a	802.11b
Data Rate	6Mbps	1Mbps
Backoff Window Size (W)	16	32
Backoff Slot Time (σ)	9μs	20μs
Physical Header	20μs	192μs
MAC Header	28Bytes	28Bytes
SIFS	16μs	16μs
Retry Limit	7	7

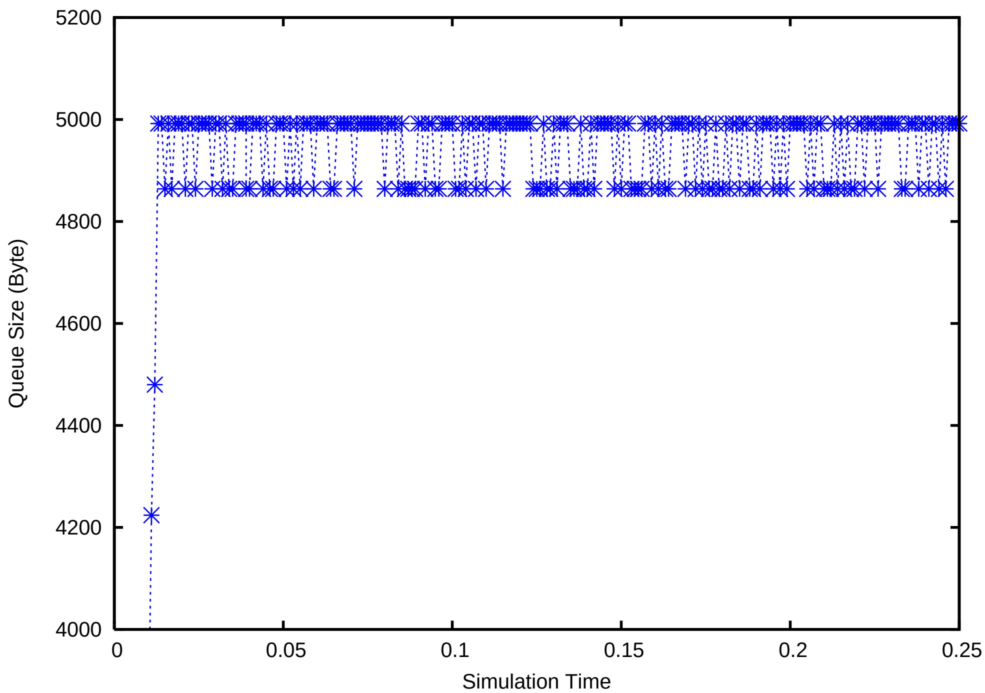


Figure 2: Queue size versus simulation time

To simulate the ideal channel condition, we have reprogrammed the bit error rate (BER) property of *Qualnet* as follows. If there is no other nodes transmitting at the same time, the probability of bit error of the receiving signal is set to 0. On the other hand, if there is any other node transmitting when receiving the signal, the probability of bit error is set to 1.

Saturated traffic condition is simulated by selecting a Poisson packet arrival process for each node with a mean arrival rate large enough to keep the MAC queue non-empty all the time. In particular, we have selected a mean packet arrival rate of 5000 packets per second yielding a mean inter-packet interval of 200 microsecond. According to the parameters listed in Table 2 and the calculation in Equation (11), the transmission delay is more than 200 microseconds guaranteeing a non-empty queue for our simulations (Figure 2 shows the queue occupancy as a function of time during one of the simulation experiments with a 5000-byte MAC queue).

In our simulation, we calculate the reliability and throughput of the network as follows. If a packet is transmitted successfully without collision, each node will receive a copy of this packet except the sender. Therefore, for every $(n-1)$ packets received in the network, there is one

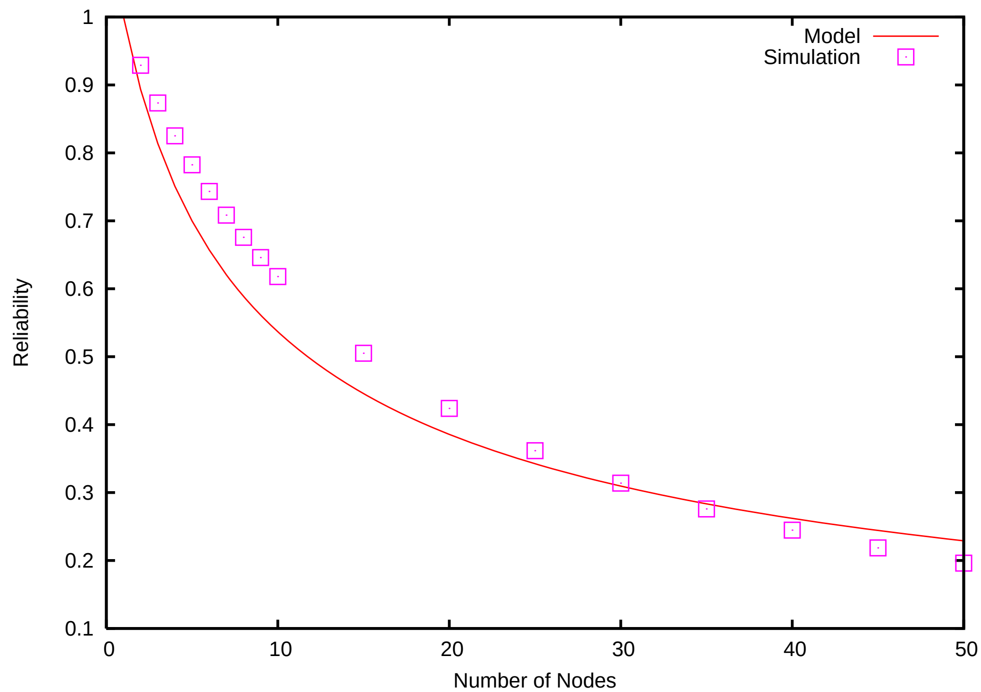


Figure 3: Comparison of numerical and simulation results for broadcast reliability

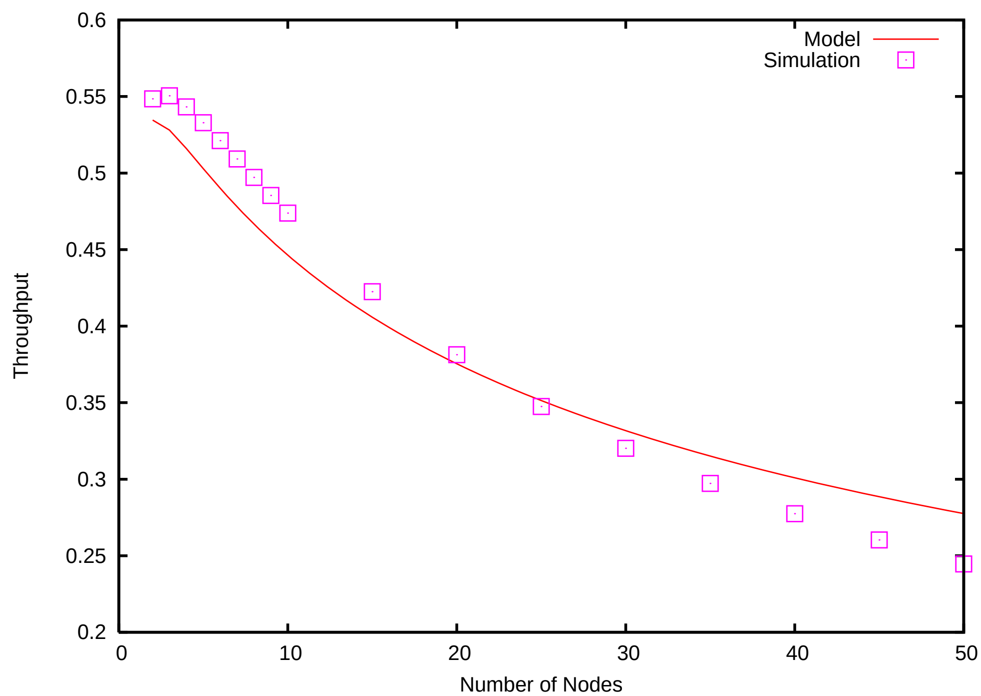


Figure 4: Comparison of numerical and simulation results for broadcast throughput

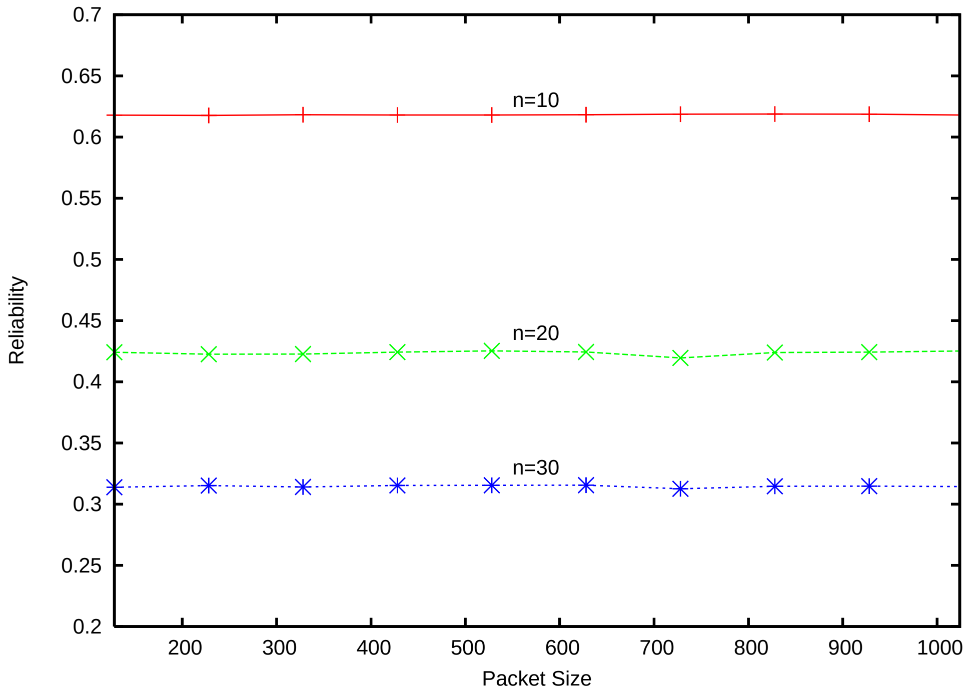


Figure 5: Simulation results for broadcast reliability as a function of packet size

successful transmission. Let t_i and r_i denote the number of broadcast packets transmitted and received by node i. The reliability is calculated as:

$$R = \frac{\sum_{i=1}^{n} r_i}{(n-1)\sum_{i=1}^{n} t_i} \tag{12}$$

The throughput is calculated as

$$S = \frac{8 \times L \times \sum_{i=1}^{n} r_i}{(n-1) \times T_{sim} \times BitRate} \tag{13}$$

where L is the packet size and T_{sim} is the simulation time.

We have run many simulations with different network and packet sizes. Each simulation experiment is repeated 10 times (we report the mean value) with different seeds for the random number generator. As a consequence of these repetitions, all reported simulation results have a 95% confidence interval with a relative precision lower than 1%.

The reliability and throughput results are shown in Figures 3 and 4. We can see that the simulation results match the numerical results fairly closely, validating the accuracy of the proposed Markov chain model. Finally, Figure 5 validates the analytical prediction (see Section 3.3) that the reliability does not depend on the packet size.

5 Numerical Experiments

In this section, we analyse the performance of IEEE 802.11 broadcast by conducting a series of numerical experiments. Communication reliability and the system throughput are the two key performance metrics studied in this analysis.

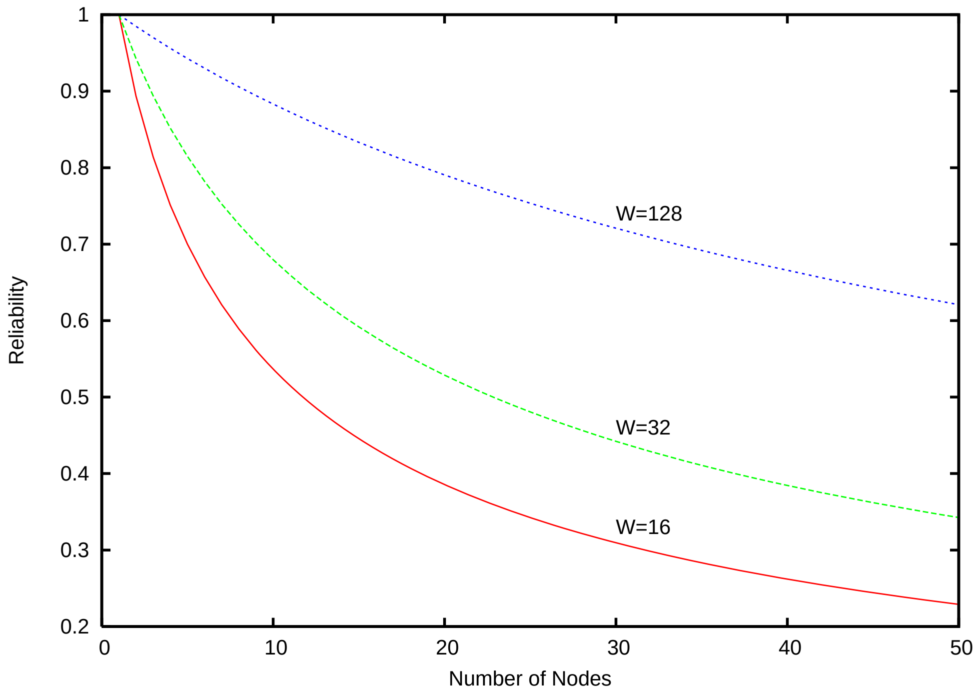


Figure 6: Broadcast reliability as a function of network size

5.1 Reliability

Figure 6 shows that the number of nodes in the broadcast area (network size) directly affects the broadcast reliability of 802.11. With the scaling of the network, reliability decreases quadratically indicating that the 802.11 standard does not scale well for saturated broadcast communications. We also notice that the reliability decreases faster with a smaller contention window. For example, with a window of 16, the reliability drops below 25% when 50 nodes join the broadcast network. This observation can be explained as follows. As the contention window shrinks, the nodes contend for the wireless channel more aggressively by waiting a shorter duration between each transmission, resulting in a higher probability of collision with other nodes.

By displaying the reliability as a function of W, the effect of contention window is further analysed in Figure 7. In this set of experiments, we used contention window values that are standardized for both 802.11a and 802.11b (see Table 2) as well as values that are not (for practical reasons, we only consider values that are powers of 2). It is interesting to note that none of the 802.11 standard window values (16 and 32) can provide a 90% reliability even for a network as small as 5 nodes. To achieve a 90% broadcast reliability, 802.11 would need to operate under contention windows that are much larger than the ones currently specified. For example, to deliver a broadcast reliability of 90% or higher for networks up to 10 nodes, a window of 256 would be required. Similarly, for a 20-node network, we need a window of 512.

From the above observations, it may appear that, for a given broadcast network, any arbitrarily high broadcast reliability can be achieved by simply selecting a large enough contention window. However, as we shall see in the next section, scaling up the contention window may negatively impact the system throughput, leading to the so called *reliability-throughput tradeoff*.

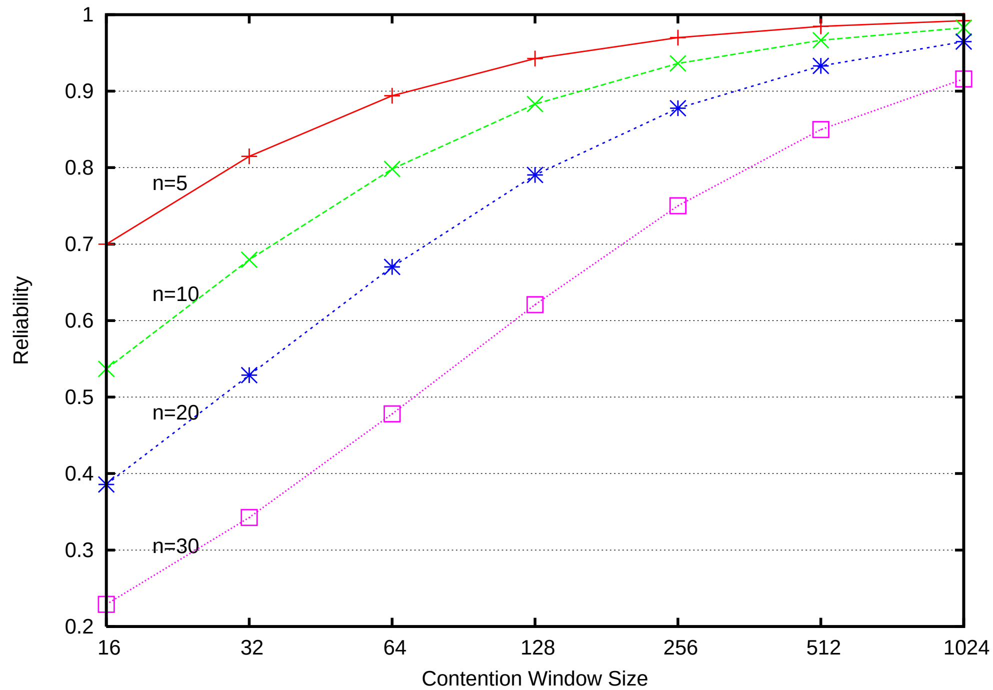


Figure 7: Broadcast reliability as a function W

Table 3: Throughput achieved for 90+% reliability

n	W	Reliability	Throughput
5	128	94%	0.43
10	256	94%	0.43
20	512	93%	0.43
50	1024	92%	0.45

5.2 Throughput

Unlike reliability, throughput depends on the packet size. For the initial set of experiments, we study the effect of network size and the contention window on the achieved throughput by fixing the packet size to 128 bytes which is being considered for vehicular safety applications [9]. The initial experiments are followed by another experiment where we study the effect of packet size on the throughput.

Figure 8 shows the throughput achieved for different network sizes as a function of the contention window size. We observe the following interesting broadcast behaviour (the basic unicast exhibits this behaviour [3] as well). For a given network size, there exists an optimum W for which the broadcast throughput is maximised. The optimum W is a function of the network size; it grows proportionally with the network size. The maximum throughput achievable, however, is practically independent of the network size. In the case of 128-byte packets, the maximum throughput for broadcast is 0.5, i.e., broadcast communication can utilise only 50% of the total network bandwidth irrespective of the number of nodes in the network.

The existence of the optimal window raises an important reliability-throughput tradeoff issue for broadcast communications. We have seen in the previous section that the broadcast would need to operate under window sizes much larger than the values currently specified in the 802.11

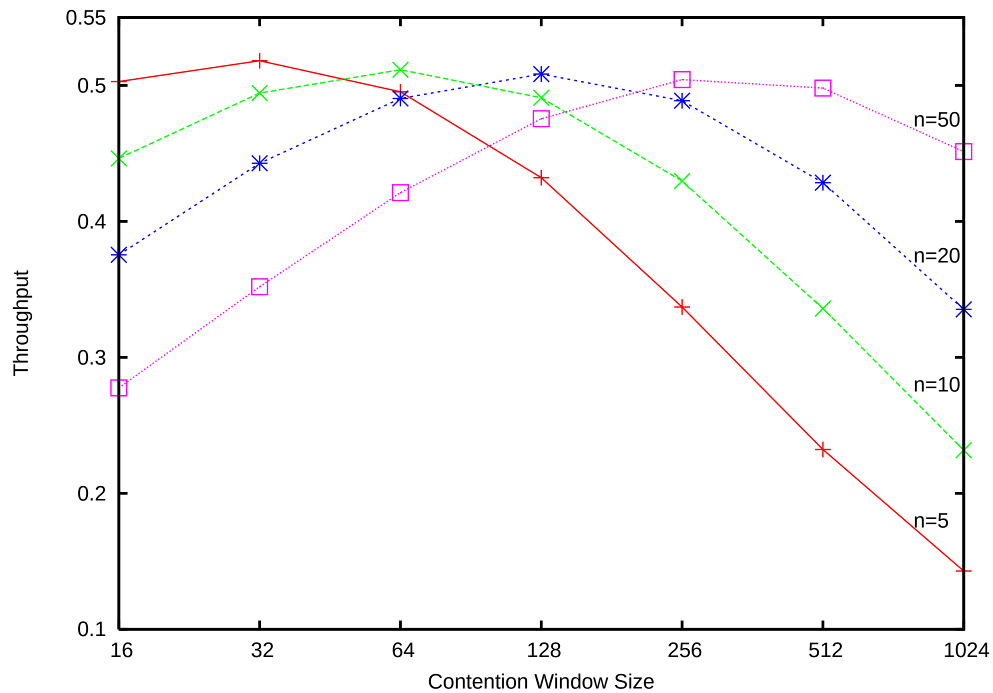


Figure 8: Broadcast throughput as a function of W

Table 4: Reliability achieved for maximum throughput

n	W	Throughput	Reliability
5	32	0.52	81%
10	64	0.51	80%
20	128	0.51	80%
50	256	0.50	75%

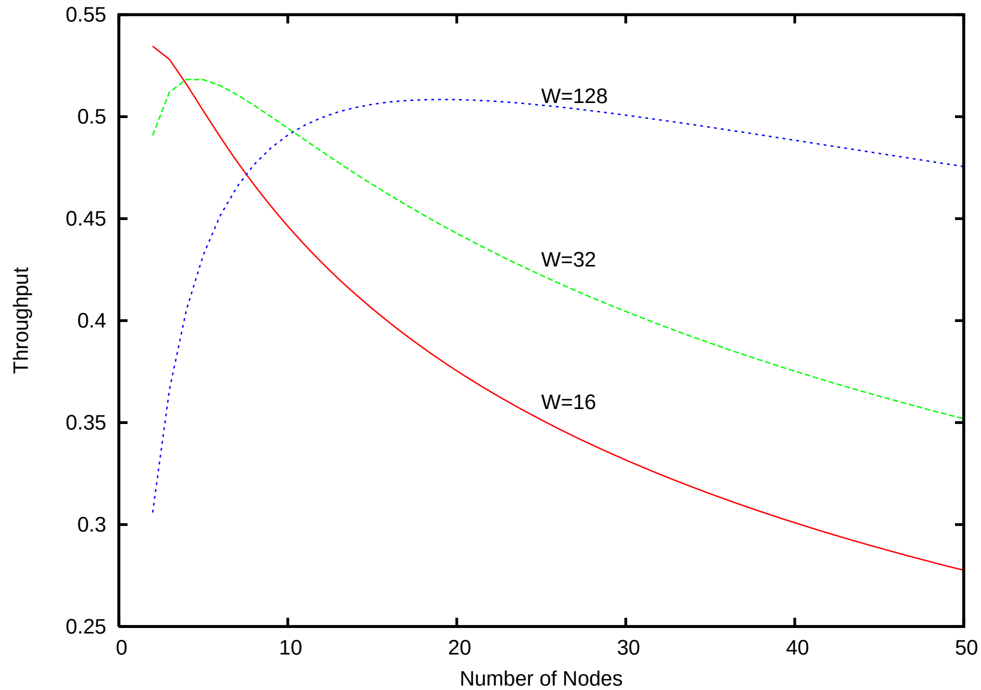


Figure 9: Throughput versus number of nodes

standard if we are to expect high reliability. However, as revealed by Figure 8, selecting a window larger than the optimal value would prevent the network from achieving the maximum throughput. For various network sizes, Table 3 lists the throughput achieved when operating the broadcast network above 90% reliability (for practical reasons, we only consider window sizes that are powers of 2). We see that, to maintain a 90% reliability, only a reduced throughput (around 0.4) can be achieved. Conversely, the reliability achieved is given in Table 4 when the networks are operated for maximum throughput (0.5). We find that for maximum throughput, reliability is reduced to only around 80%.

5.3 Derivation of Optimum Window

The procedure proposed in [3] for obtaining the optimum window for unicast communication can be used to derive an approximate solution for the broadcast communication as well.

By replacing P_t and P_s in Equation (9) with Equations (6) and (7), since T_{PL}, T_s and σ are constants, the normalized throughout becomes a function of the transmission probability b_0. Figure 10 shows the curves of the throughput versus transmission probability. The figure clearly shows that for a given network size, there exist an optimized transmission probability that can maximize the throughput.

Rearranging Equation (9), we obtain:

$$S = \frac{T_{PL}}{\frac{\sigma(1-P_t)/P_t+T_s}{P_s}} \tag{14}$$

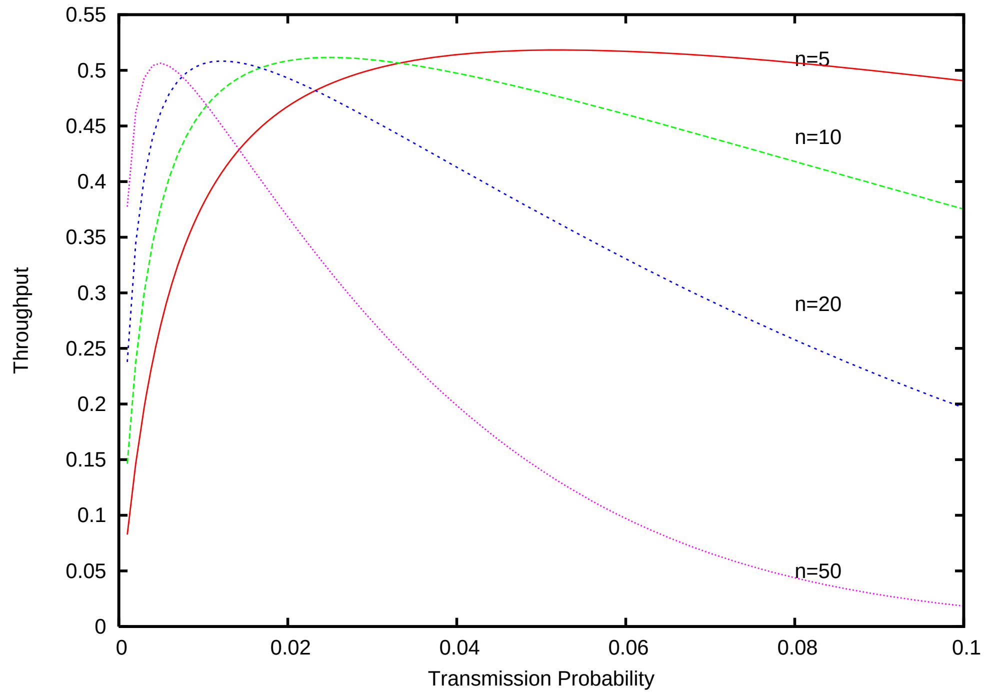


Figure 10: Throughput versus transmission probability

The maximum throughput is achieved when the following quantity is maximized:

$$\frac{P_s}{(1-P_t)/P_t + T_s/\sigma} = \frac{nb_0(1-b_0)^{n-1}}{T_s^* - (1-b_0)^n(T_s^*-1)} \tag{15}$$

where $T_s^* = T_s/\sigma$. Taking the derivative of (15) with respect to b_0, and equaling it to 0, we can find the optimized transmission probability b_0. The approximate optimized transmission probability is given in [3]:

$$b_0^{opt} \approx \frac{1}{n\sqrt{T_s^*/2}} \tag{16}$$

We can readily find

$$W^{opt} \approx n\sqrt{2T_s^*} \tag{17}$$

Figure 11 shows the maximum throughput achievable for 802.11a and 802.11b standards (the parameters used to calculate the throughput are listed in Table 2) as a function of the packet size. We see that by using an increasing packet size, the network utilisation can be increased quadratically. Although this result may seem satisfying at first, for many practical broadcast applications, the user may not have any control over the packet size. In fact, for broadcast applications, packet sizes are expected to be small. For example, a packet size of only 128 bytes is being considered for the vehicular safety applications [9].

6 Comparison with Unicast

Figure 12 compares the maximum throughput that can be theoretically achieved by broadcast and unicast communications. It is interesting to see that when operating under optimum contention window, broadcast is capable of achieving higher throughput than unicast. This difference in

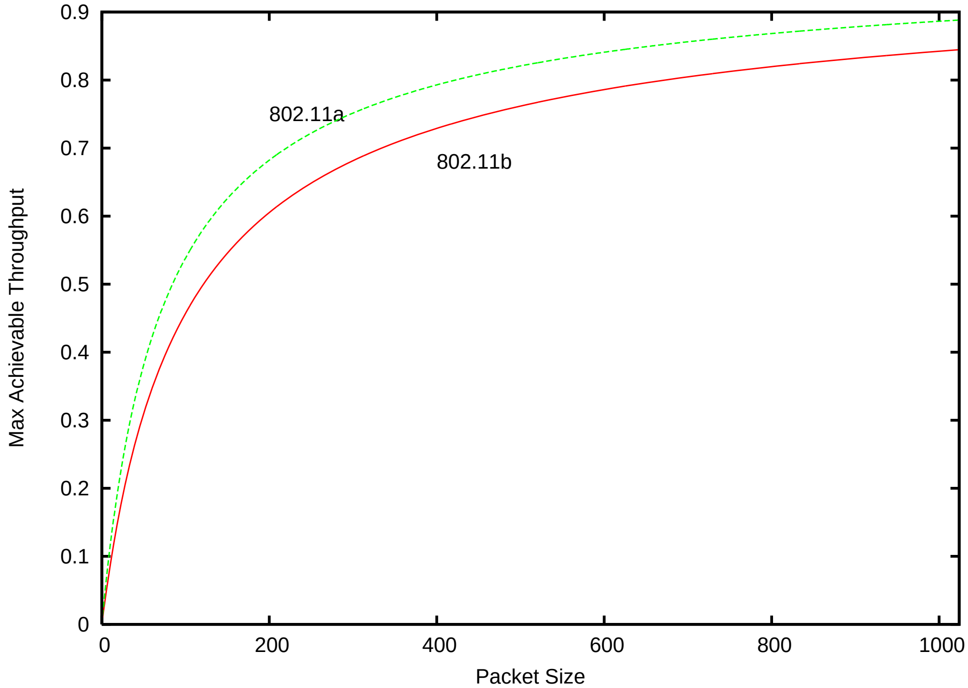


Figure 11: Max achievable throughput versus packet size (n=10)

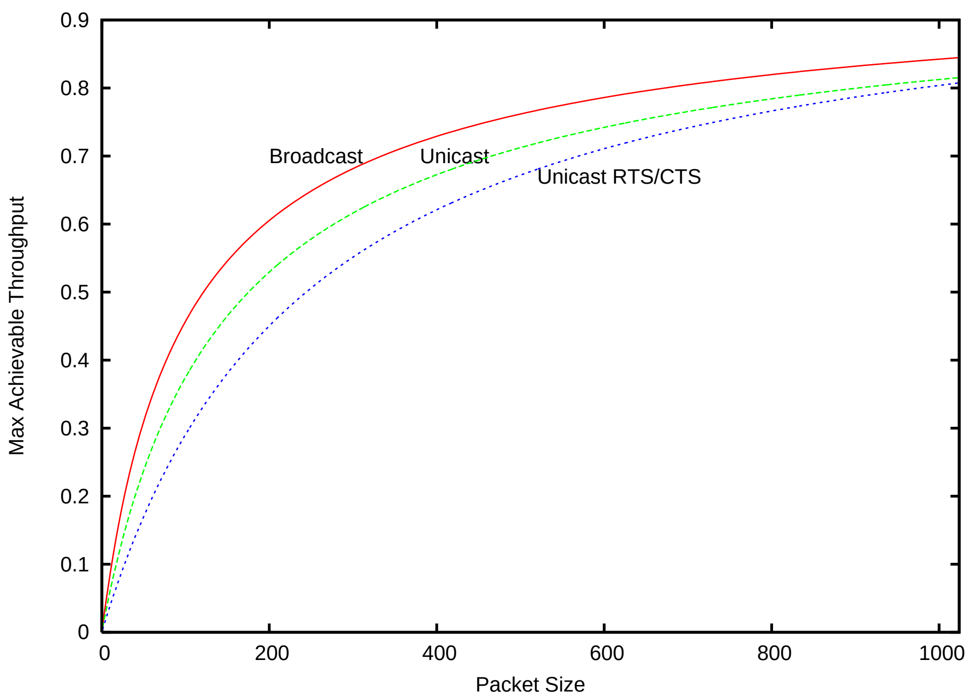
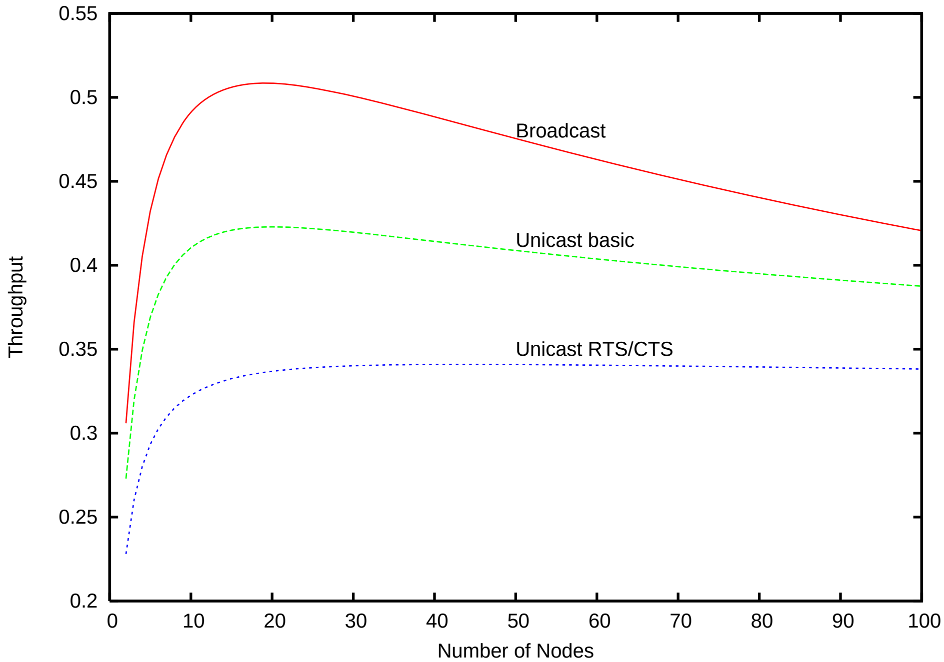


Figure 12: Max achievable throughput versus packet size (n=10)



(a) Large contention window (128) and small packets (128 bytes)

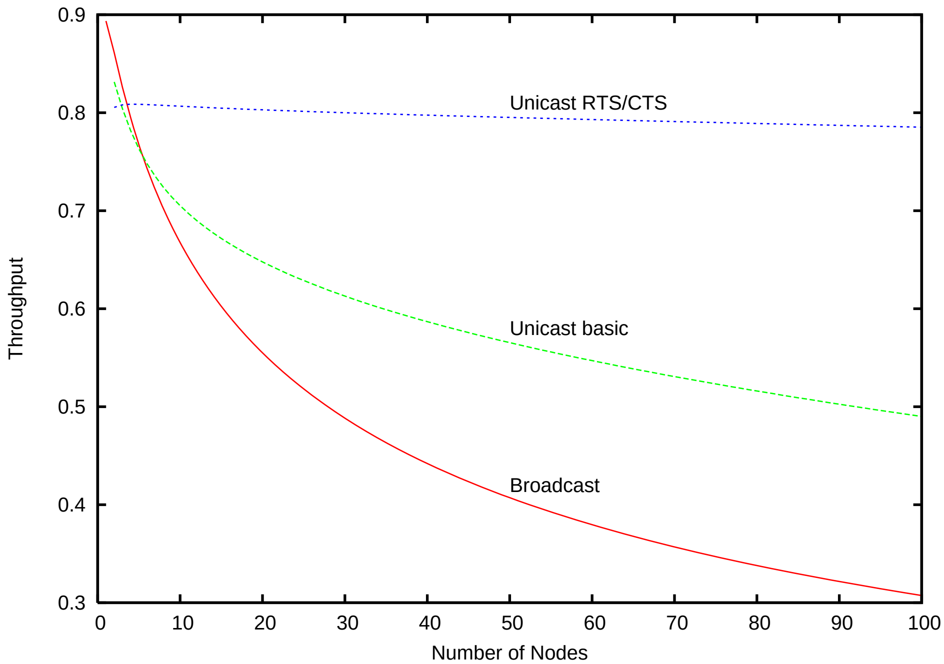
Figure 13: Throughput comparison for broadcast and unicast

throughput can be attributed to the ACK/RTS/CTS overhead of the unicast communication. For the same reason, the maximum throughput of unicast basic access is higher than the RTS/CTS access.

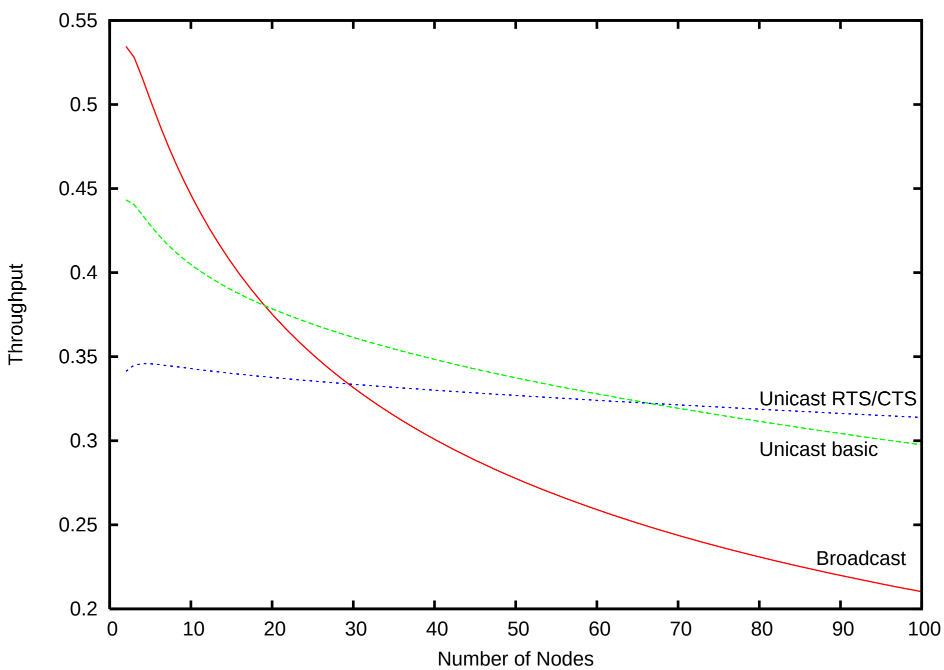
Figure 13 compares the throughput performance of broadcast and unicast for different combinations of the contention window and packet size. The comparison shows that when contention window is large and packet size is small (Figure 13a), broadcast always outperforms unicast because very little collision happens and the overhead communication of unicast is the dominant factor affecting the throughput. In contrast, when contention window is small while the packet size is large (Figure 13b), broadcast throughput drops sharply due to the effect of collision, while the RTS/CTS scheme of unicast shows clearly its advantage of avoiding collision. For the combination of small contention window and small packet size (Figure 13c), and large contention window and large packet size (Figure 13d), the differences of throughput performance mainly depends on the network size (the broadcast achieves higher throughput in small networks, whereas the unicast does so in large networks).

7 Conclusion

Using a simple one-dimensional discrete time Markov chain, we have analysed the reliability and throughput performance of the popular IEEE 802.11 broadcast communications for saturated traffic conditions. The validity of the Markov chain model has been confirmed by comparing the numerical results with those obtained from the simulation experiments. Using the model, we have also conducted a detailed study comparing the throughput performance of unicast and broadcast under different network sizes and different combinations of 802.11 protocol parameters. Our findings are

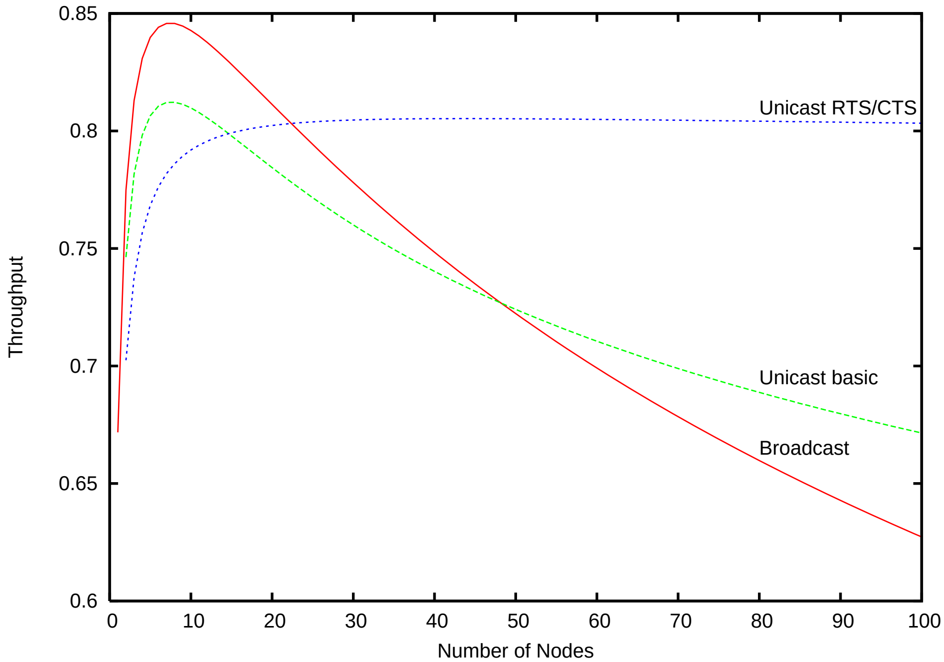


(b) Small contention window (16) and large packets (1024 bytes)



(c) Small contention window (16) and small packets (128 bytes)

Figure 13: Throughput comparison for broadcast and unicast (continued)



(d) Large contention window (128) and large packets (1024 bytes)

Figure 13: Throughput comparison for broadcast and unicast (continued)

summarised as follows:

- Broadcast reliability does not depend on the packet size. Rather, it is the size of the contention window that influences the reliability in 802.11 broadcast communications. The larger the contention window, the better the reliability, and vice versa.
- Contention window sizes specified by the current 802.11 standards are too small to achieve high reliability for broadcast communications
- 802.11 broadcast faces a reliability-throughput tradeoff which dictates that *high reliability* and *maximum throughput* cannot be realised at the same time
- There exists an optimum contention window size that maximises broadcast throughput (the same observation was made previously by other researchers for the unicast communication with basic handshake)
- The maximum broadcast throughput increases quadratically with the increase in packet size. For the vehicular safety applications (128-byte broadcast packets), maximum throughput is only 0.5
- The maximum broadcast throughput is higher than the maximum unicast (for both the basic and the RTS/CTS handshakes) throughput
- The combination of the contention window and the packet size is a major factor influencing the difference in throughput performance for broadcast and unicast. For the combination of large contention window and small packet, broadcast achieves higher throughput than unicast. For the combination of small contention window and large packet, broadcast achieves lower

throughput than unicast. For all other combinations, the difference of throughput depends on the network size (the broadcast achieves higher throughput in small networks, whereas the unicast does the same in large networks)

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