Numerical Analysis of IEEE 802.11 Broadcast Scheme in Multihop Wireless Ad Hoc Networks*

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Abstract. In this paper, we study the performance of IEEE 802.11 broadcast scheme in multihop wireless networks using an analytical model. Previous works have evaluated the performance of IEEE 802.11 protocol assuming unicast communication, but there has not been an analysis considering broadcast communication. Analyzing performance of broadcast communication is important because multicast communication is gaining attention in wireless networks with numerous potential applications. Broadcast in IEEE 802.11 does not use virtual carrier sensing and thus only relies on physical carrier sensing to reduce collision. For this study, we define a successful broadcast transmission to be the case when all of the sender's neighbors receive the broadcast frame correctly, and calculate the achievable throughput.

1 Introduction

The IEEE 802.11 standard [3] is widely deployed and used in wireless systems today. Its de facto medium access control (MAC) protocol, called Distributed Coordination Function (DCF) allows multiple nodes to share the wireless medium without any central coordinator. Although IEEE 802.11 DCF was designed for a wireless LAN, it is also used in multihop wireless networks because of its distributed nature.

The major goal of a MAC protocol is to have only a single node in a broadcast domain transmit at a given time. If two nodes that are nearby each other transmit frames at the same time, the frames collide and the channel bandwidth is wasted. To achieve this goal, IEEE 802.11 DCF uses a technology called Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). In CSMA/CA, whenever a node has a data frame to transmit, it listens on the channel for a duration of time. This duration of time is called *slot time*. If the channel is sensed

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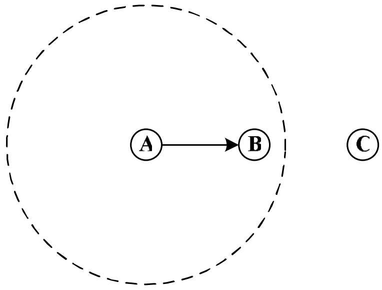


Fig. 1. Illustration of the hidden terminal problem in a multihop wireless network

to be idle during a predefined slot time, the node transmits the data frame. If the channel is busy, then the node defers its transmission and waits for a random delay (called *random backoff interval*) before retrying. Sensing the channel to determine if it is busy or idle is called *physical carrier sensing*.

When a node receives a frame, the node is able to decode the frame correctly only if the received signal power is higher than a threshold called *receiver sensitivity*, which is also called *receive threshold*. Also, when a node senses the channel to see whether it is busy or not, it determines the channel to be busy if the sensed power is greater than the *carrier sense threshold*. The carrier sense threshold is a tunable parameter.

Let us assume for now that the carrier sense threshold is equal to the receive threshold. It means while node A is transmitting a data frame, all nodes in A's transmission range senses the channel to be busy, and the nodes outside of A's transmission ranges senses the channel to be idle. Under this assumption, the scenario in Fig. 1 illustrates a situation where physical carrier sensing cannot prevent collision.

Suppose node A starts transmitting a frame to node B. Since node C is outside of A's transmission range, it senses the channel as idle. So node C can start transmitting its frame, which collides at node B. In this scenario, node C is said to be *hidden* from node A, and C is a *hidden terminal* from A's view [4]. When node A transmits a data frame to B, there is a period of time in which if node C starts transmitting, it will collide with node A's transmission. This period is called a *vulnerable period*[1].[3]

To prevent collisions caused by hidden terminals, a mechanism called *virtual carrier sensing* is used in addition to CSMA/CA. When a node S wants to transmit a frame, it first transmits a Request-To-Send (RTS) frame which is much smaller in size than a data frame. On receiving RTS, the receiver replies with Clear-To-Send (CTS) frame also very small in size. Any node other then the sender and the receiver that receives RTS or CTS defers its transmission while S transmits the data frame. So the RTS/CTS exchange has the effect

[3] The vulnerable period for IEEE 802.11 broadcast scheme is calculated in section II.

of reserving the space around the sender and receiver for the duration of the data transmission. This is called *Virtual Carrier Sensing*, because it provides information on the channel but not by physically sensing the channel.

In IEEE 802.11 DCF, the virtual carrier sensing mechanism is only used in unicast transmissions, and it is an optional feature that can be turned on or off. For a broadcast transmission, only physical carrier sensing is used. Virtual carrier sensing is not directly applicable to broadcast transmissions because CTS messages sent by multiple receivers will result in a collision.

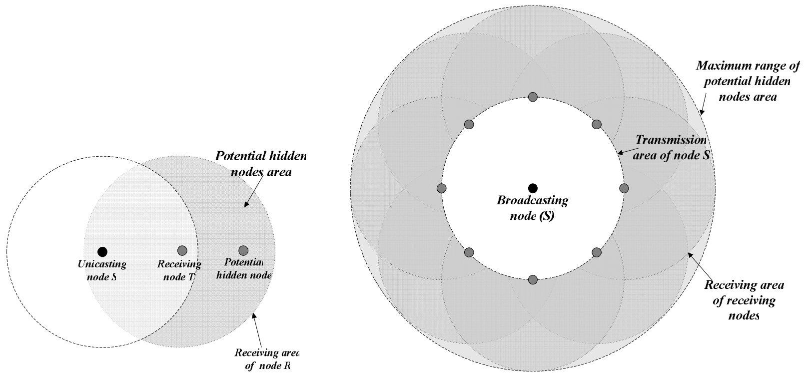
The performance of IEEE 802.11 DCF for unicast transmissions has been studied using mathematical analysis. Cali et al. [5] calculates the throughput of IEEE 802.11 DCF when the basic CSMA/CA scheme is used without RTS/CTS mechanism. Bianchi [6] calculates the throughput of DCF with and without RTS/CTS mechanism, and also a combination of the two. These two studies are for wireless LANs, and so they do not consider hidden terminals. Wu et al. [1] studies the throughput the CSMA protocol in multihop wireless networks, considering hidden terminals.

All of these studies are for unicast communication, and do not consider broadcast communications. We are interested in the performance analysis of broadcast scheme in IEEE 802.11 DCF, operated in a multihop network. Also, we are interested in reliable broadcast, where a broadcast transmission is considered successful only if all of the sender's neighbors receive the broadcast message correctly. Reliable broadcast can be used for numerous applications, such as code distribution, database replication, and a basis for supporting distributed protocols.

The rest of paper is organized as follows: In section 2, we present the analysis of the IEEE 802.11 broadcast scheme. To our knowledge, this is the first analytical study of IEEE 802.11 broadcast scheme in multihop wireless networks. In section 3, we present numerical results from our analysis. Finally, we conclude in Section 4.

2 Numerical Analysis Model

Before analyzing performance of IEEE 802.11 broadcast scheme, we examine the hidden node problem in a broadcast scenario. As you see in the Fig. 2(a), nodes in the receiving region of node T but not in the receiving region of node S, may cause hidden terminal problem. We call this area as a *potential hidden node area*. For unicast communications, the size of the *potential hidden node area* can be calculated using the distance between the sender and receiver. However, in case of broadcast communication (see Fig. 2(b)), the *potential hidden node area* needs to include the receiving range of all the neighbors of the senders. So it is difficult to exactly compute the size of this area. Moreover, as explained earlier, varying the carrier sensing area also change the form of this area. The worst case, where the size of the *potential hidden node area* is maximized, is when there are infinite number of node at the edge of the sender's transmission range. Let R denote the transmission range of a node. As you see in the Fig. 2, maximum size of *potential*



(a) Unicast (b) Broadcast

Fig. 2. Potential hidden node area

hidden node area can be $\pi(2R)^2 - \pi R^2 = 3\pi R^2$. Thus, in case of broadcast, the potential hidden node area can be dramatically larger than that of unicast.

We use the similar approximate approaches used in [1] to achieve the average throughput for multihop wireless networks.

To make our numerical model tractable, we assume followings for the multihop wireless network model.

1. All nodes in the network are two-dimensionally Poisson distributed with density λ, i.e., the probability $p(i, A)$ of finding i nodes in an area of size A is given by
$$p(i, A) = \frac{(\lambda A)^i e^{-\lambda A}}{i!}$$
2. All nodes have the same transmission and receiving range, which is denoted as R. N is the average number of neighbor nodes within a circular region of radius R. Therefore, we have $N = \lambda \pi R^2$
3. A node transmits a frame only at the beginning of each slot time. The size of a slot time, τ , is the duration including transmit-to-receive turn-around time, carrier sensing delay and processing time.
4. The transmission time or the frame length is the same for all nodes.
5. When a node is transmitting, it cannot receive simultaneously.
6. A node is ready to transmit with probability p. Let p' denote probability that a node transmits in a time slot. If p' is independent at any time slot, it can be defined to be
$$p' = p \cdot \text{Prob}\{\text{Channel is sensed idle in a slot}\} \approx p \cdot P_I$$
where P_I is the limiting probability that the channel is sensed to be idle.
7. The carrier sensing range is assumed to vary between the range $[R, 2R]$.

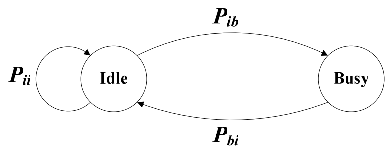


Fig. 3. Markov chain model for the channel

With above assumptions, the channel process can be modeled as a two-state Markov chain shown in Fig. 3. The description of the states of this Markov chain is the following:

Idle is the state when the channel around node x is sensed idle, and its duration T_{idle}, is τ.

Busy is the state when a successful DATA transfer is done. The channel is in effect busy for the duration of the DATA transfer, thus the busy time, T_{busy}, is equal to the data transmission time δ_{data}. ($T_{busy} = \delta_{data}$)

In IEEE 802.11 scheme, all nodes should not transmit immediately after the channel becomes idle. Instead, nodes should stay idle for at least one slot time. Thus the transition probability P_{bi} is 1.

The transition probability P_{ii} is that probability of the neighbor nodes transmits is given by,

$$P_{ii} = \sum_{i=0}^{\infty}(1-p')^i \frac{(\lambda\pi R^2)^i}{i!} e^{-\lambda\pi R^2} = \sum_{i=0}^{\infty} \frac{((1-p')\lambda\pi R^2)^i}{i!} e^{-\lambda\pi R^2(1-p')} e^{-p'N} = e^{-p'N}$$

Let, Φ_i and Φ_b denote the steady-state probabilities of state idle and busy, respectively. From Fig. 3, we have

$$\Phi_i = \Phi_i P_{ii} + \Phi_b P_{bi} = \Phi_i P_{ii} + \Phi_b$$

Since $\Phi_b = 1 - \Phi_i$, we have

$$\Phi_i = \frac{1}{2 - P_{ii}} = \frac{1}{2 - e^{-p'N}}$$

Now the limiting probability P_I can be obtained by

$$P_I = \frac{T_{idle}\Phi_i}{T_{busy}(1-\Phi_i) + T_{idle}\Phi_i} = \frac{\tau}{\delta_{data}(1 - e^{-p'N}) + \tau}$$

According to the relationship between p' and p, p' can be

$$p' = \frac{\tau p}{(\delta_{data})(1 - e^{-p'N}) + \tau}$$

To obtain the throughput, we need to calculate the probability of a successful transmission. The transmission state of a node x can also be modeled by a three-state Markov chain, as shown in Fig. 4. In the figure, *wait* is the state when the

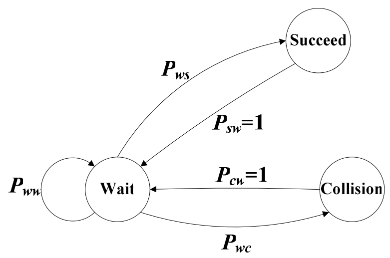


Fig. 4. Markov chain model for the transmission states of node

node in deferring its transmission, *succeed* is the state when the node successfully transmits DATA frame to all of neighbor nodes, and *collision* is the state when a node collides with other nodes.

At the beginning of each time slot, node x leaves the *wait* state with probability p'. Thus the transition probability P_{ww} is given by

$$P_{ww} = 1 - p'$$

and, the duration of a node in *wait* state T_{wait} is τ. The durations of *success* and *collision* states are equal to the frame transmission time, thus T_{succ} and T_{coll} are $\delta_{data} + \tau$. After *success* or *collision* state, node x always enter the *wait* state, thus P_{sw} and P_{cw} are 1.

Let Φ_w, Φ_s, and Φ_c denote the steady-state probabilities of state wait, success, and collision, respectively. From the above Markov chain we have

$$\Phi_w = \Phi_w P_{ww} + \Phi_s P_{sw} + \Phi_c P_{cw} = \Phi_w P_{ww} + 1 - \Phi_w \tag{1}$$

Hence, we have:

$$\Phi_w = \frac{1}{2 - P_{ww}} = \frac{1}{1 + p'}$$

Based on the above condition, transition probability P_{ws} can be

$$P_{ws} = P_1 P_2 P_3 \tag{2}$$

where

$$P_1 = \text{Prob}\{\text{node } x \text{ transmits in a slot}\}$$

$$P_2 = \text{Prob}\{\text{All of node } x\text{'s neighbor nodes do not transmit in the same slot}\}$$

$$P_3 = \text{Prob}\{\text{Nodes in potential hidden nodes area do not transmit for } 2\delta_{data} + \tau\}$$

The reason for the last term is that the *vulnerable period* for an data frame is only $2\delta_{data} + \tau$. As you see in the Fig. 5, this is because the collide from node in *potential hidden node* happen during the period that begin δ_{data} before sending node x begins its transmission and ends one slot after x completes its transmission.

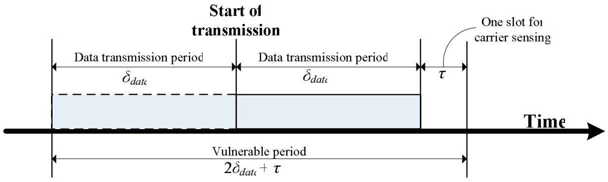


Fig. 5. The vulnerable period for IEEE 802.11 broadcast scheme

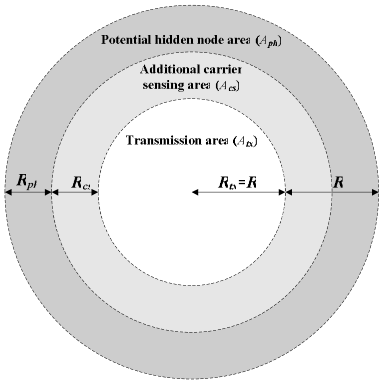


Fig. 6. Illustration of transmission area, additional carrier sensing area, and potential hidden nodes area

Obviously, $P_1 = p'$, while P_2 can be obtained by

$$P_2 = \sum_{i=0}^{\infty}(1-p)^i \frac{(\lambda\pi R^2)^i}{i!} e^{-\lambda\pi R^2} = e^{-p'\lambda\pi R^2} = e^{-p'N}$$

To calculate P_2, we first approximate the number of node in the *potential hidden node area*. Let A_{tx}, A_{cs}, and A_{ph} denote the transmission area, *additional carrier sensing area*, and *potential hidden node area*, respectively. As you see in the Fig. 6, *additional carrier sensing area* is the physical carrier sensing area that is outer of transmission area. We assume that the physical carrier sensing area is larger than transmission range and smaller than *potential hidden node area*. Thus, we have

$$0 \leq A_{cs} \leq 3\pi R^2$$

And, the *potential hidden node area* can be

$$A_{ph} = 2\pi(2R)^2 - A_{tx} - A_{cs} = 2\pi(2R)^2 - \pi R^2 - A_{cs} = 3\pi R^2 - A_{cs}$$

Hence,

$$0 \leq A_{ph} \leq 3\pi R^2$$

Let N_{ph} denotes the number of node in potential node area. As we assume that, nodes are uniformly distributed, thus N_{ph} can be

$$N_{ph} = \lambda A_{ph}$$

$$0 \leq N_{ph} \leq \lambda 3\pi R^2$$

$$0 \leq N_{ph} \leq \lambda 3N \tag{3}$$

With Eq. 3, P_3 is given by

$$P_3 = \{\sum_{i=0}^{\infty}(1-p)^i \frac{(N_{ph})^i}{i!} e^{-N_{ph}}\}^{(2\delta_{data}+\tau)} = e^{-p' N_{ph}(2\delta_{data}+\tau)}$$

Therefore, Eq. 2 can be expressed as

$$P_{ws} = p' e^{-p' N} e^{-p' 3N_{ph}(2\delta_{data}+\tau)} = p' e^{-p'(N+3N_{ph}(2\delta_{data}+\tau))}$$

From the Fig. 4, we have $P_{ws} = 1 - P_{ww} - P_{ws}$ and $P_{cw} = P_{sw} = 1$ Hence, the steady-state probability of state succeed, Φ_s, can be expressed as

$$\Phi_s = \Phi_w P_{ws} = \frac{P_{ws}}{1+p'}$$

According to the definition [2], the throughput equals the fraction of time in which the channel is engaged in successful transmission of user data. Therefore, the throughput Th is equal to the limiting probability that the channel is in state in success.

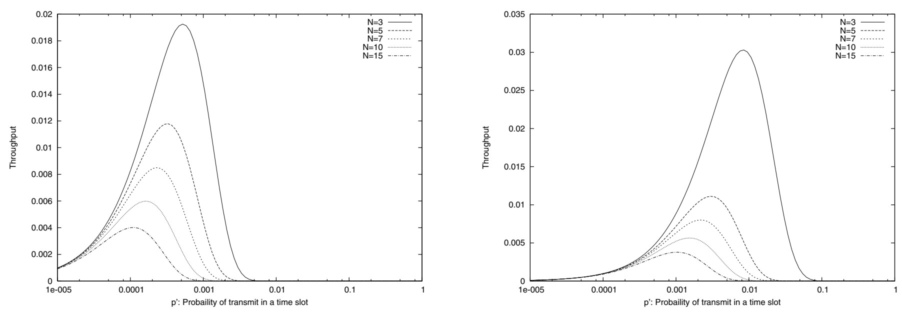
$$Th = \frac{\Phi_s \delta_{data}}{\Phi_s T_{succ} + \Phi_c T_{coll} + \Phi_w T_{wait}} = \frac{\Phi_s \delta_{data}}{\Phi_s T_{succ} + (1 - \Phi_s - \Phi_w) T_{coll} + \Phi_w T_{wait}} \tag{4}$$

$$= \frac{P_{ws}\delta_{data}}{p' T_{coll} + T_{wait}} = \frac{(p' e^{-p'(N+3N_{ph}(2\delta_{data}+\tau))})\delta_{data}}{\tau + p'(\delta_{data}+\tau)}$$

3 Numerical Results

In this section, we show numerical results based on the models introduced in the previous section. To see the effect of data frame length on throughput performance, we show results relatively large data frames and relatively small data frames. For the long data frame case, we use 100τ as the frame size. For the small frame case, we use 10τ.

We first study the performance of the IEEE 802.11 broadcast scheme by varying the average number of neighboring node (N) and transmission attempt probability (p'). In this scenario, we fix the *potential hidden node area* (R_{ph}) as $3\pi R^2$, which is the worst case.



(a) Long data frame: $\delta_{data} = 100\tau$

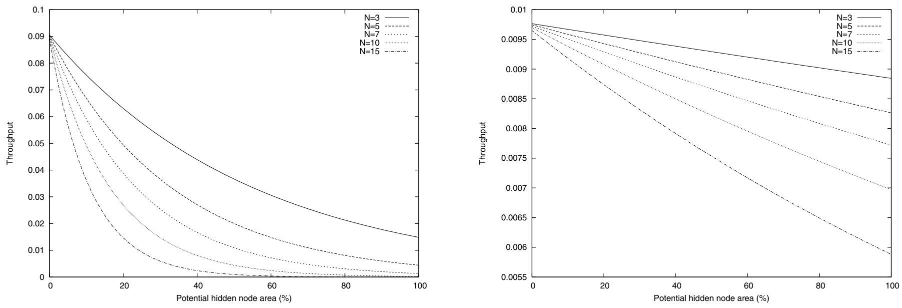
(b) Short data frame: $\delta_{data} = 10\tau$

Fig. 7. The throughput of IEEE 802.11 broadcast scheme varying N and p' (R_{ph}=100%=$3\pi R^2$)

Fig 7 shows the throughput results for the IEEE 802.11 broadcast scheme with different frame sizes. As the average number of neighboring node increases, both case of the IEEE 802.11 broadcast scheme shows very poor throughput performance. The main reason is that the probability of collisions becomes higher as the number of node becomes larger. And as N is increased, p' achieving optimum throughput decreases. This means that, as the number of competing nodes within a region increases, IEEE 802.11 scheme becomes more ineffective. When data frame length is long, the throughput of IEEE 802.11 broadcast scheme is very low. This is the fact that the vulnerability period ($\delta_{data} + \tau$) in equation for P_3 becomes twice the length of the data frame.

Next, we investigate the throughput performance of both case when the *additional carrier sensing area* varies. This is important because IEEE 802.11 broadcast scheme only relies on physical carrier sensing. In this scenario, we fix the probability of transmission in a time slot (p') as 0.001. To see the effect of varying the *additional carrier sensing area* (A_{cs}), we vary the *potential hidden node area* (A_{ph}) since this value is inversely proportional to A_{cs}.

Fig. 8 shows, the throughput versus the percentage of A_{ph} for the IEEE 802.11 broadcast scheme for 3,5,7,10,15 average neighboring nodes. In this result, when the percentage of A_{ph} is 0, i.e., A_{cs} is $3\pi R^2$, throughput performance have maximum value. This means that, by achieving maximum value of A_{cs}, the IEEE 802.11 broadcast scheme minimizes the possibility of hidden node problem. So it is beneficial to set the carrier sensing range large for broadcast communication. However, for unicast communication, a large carrier sensing range leads to reduced spatial reuse, so minimizing hidden node effect and increasing spatial reuse becomes a tradeoff which must be studied further. As the percentage of *potential hidden node area* and number of nodes increase, we observe that throughput of both case decreases more deeper. This again means that IEEE 802.11 broadcast scheme becomes more ineffective as the number of competing nodes within a region increases.



(a) Long data frame: $\delta_{data} = 100\tau$ (b) Short data frame: $\delta_{data} = 10\tau$

Fig. 8. The throughput of IEEE 802.11 broadcast scheme varying N and R_{ph} (p'=0.001)

Our results reveal that hidden terminals degrade the performance of IEEE 801.11 broadcast scheme beyond the basic effect of having larger *potential hidden node area*.

4 Conclusion

Broadcast is an efficient paradigm for transmitting a data from sender to group of receivers. In this paper, we present a performance of the IEEE 802.11 broadcast scheme. To derive the throughput, we have used a simple model based on Markov chains. The result shows that overall performance of IEEE 802.11 broadcast scheme degrades rather rapidly when the number of competing nodes allowed within a region increase.

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