RICE UNIVERSITY

Opportunistic Two-Way Protocols for Random Access Networks

by

Pedro Santacruz

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Contents

Chapter 1

Introduction

In most communication networks, each one of the users acts as a transceiver that is interested in both receiving and transmitting data. Because of this characteristic, communication networks are inherently composed of two-way communication links. The two-way nature of these links can be described in two different aspects. The links are two-way in terms of data. A destination node might have data that it wants to send to the transmitting node. Also, it can be said that the links are two-way in terms of the channel. When a link is established in one direction, the channel in other direction can have similar characteristics since both channels are spatially colocated and have the same physical characteristics. The concept of the two-way channel described above was first introduced by Shannon in [14] and later analyzed more in detail by a large number of publications including [6], [8], [9], [12] and [10].

In this work, we look at the opportunity to exploit the two-way nature of networks at the medium access layer (MAC). In the context of a network with a random access protocol, once contention for the medium is resolved and the channel is accessed, the two-way phenomenon could be used to achieve data flow in two directions instead of just one. Considering that MAC design is an essential part of a wireless communication network, it becomes important to maximize its efficiency. The details of the techniques implemented in this layer have an important effect on the perfomance of the overall network. The introduction of the IEEE 802.11x standard [1] provided guidelines for protocols that are currently widely used. The performance of these protocols was analyzed in depth by Bianchi [4]. Bianchi used the *normalized throughput*, S, as one of the metrics of performance. Normalized throuhgput, which is expressed in

Equation (1.1), is basically a measure of the amount time spent transmitting payload information with respect to the total amount of time require to send it. This measure provides information about the overhead produced by a specific protocol.

$$S = \frac{E[\text{payload information transmitted in a slot time}]}{E[\text{length of a slot time}]} \tag{1.1}$$

Increasing the normalized throughput would provide a desirable improvement in the performance of the communication network because more time would be spent transmitting relevant information rather than on overhead that does not contirbute to the objective of the network. Some work ([7], [3], and [13]) has been done to try to exploit certain aspects of the IEEE 802.11 framework. In the case of [13], the idea of channel opportunism is explored. Channel opportunism can be best described as taking advantage of the immediate channel conditions to try to increase the normalized throughput.

In this work, we explore *source opportunism* and *channel opportunism*. The main concept is to opportunistically take advantage of knowledge of the immediate queueing states of the network nodes and channel state of the inter-node links to increase the performance of the network. We call source opportunism to the instance when a node has a queueing state in which it has information that it needs to send to another node in the network from which it is currently receiving information. Channel opportunism refers to the ability to use the presence of a "good" channel to transmit as a higher rate, or use the "good" channel for a longer period of time. This concept has been explored in [7] with a protocol called Receiver Based Auto Rate (RBAR), in [13] with an Opportunistic Auto Rate (OAR), and, to a certain extent, in [5] and [11]. In summary, we take the inherently time-varying nature of the nodes' queue states and adapt to them and use them to improve the performance of the network. The same is done in case of the time-varying channel states.

Chapter 2

System Model

Consider a multi-hop mesh network (as shown in Figure 2.1). It shows several

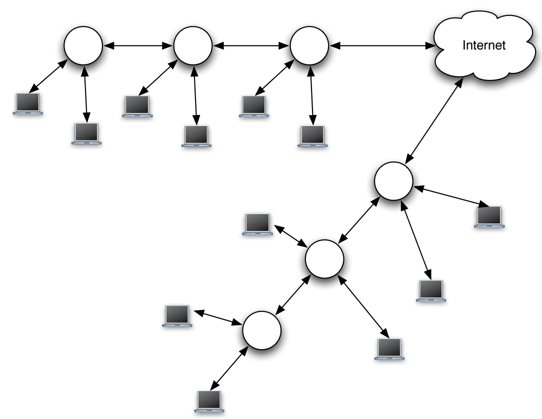


Figure 2.1: Multi-hop Network

users connected to a gateway. The nodes are connected in a multi-hop fashion until the string of nodes is able to establish communication with a gateway wired base station that provides access to the Internet. We concentrate on final connection between the nodes and base station and this becomes topologically equivalent to the network scenario described above (see Figure 2.2).

Thus, our focus will be a many-to-one network topology with $N - 1$ user nodes and one base station, for a total of N nodes. Each one of the user nodes has information for the base station and the base station has information for each of the nodes. Therefore, there are information flows in both directions, uplinking to the base station and dowlinking to the users. The uplink and downlink transmission are time-division multiplexed and only one node is able to transmits at any specific time. As in the IEEE 802.11 standard, each transmitting node contends for the right to use the channel, so the uplink flow contends with the dowlink flow.

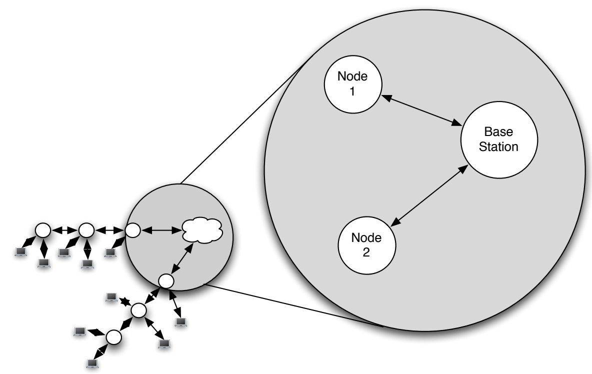


Figure 2.2: Focus on the Base Station and Adjacent Nodes

The model that will be used generally throughout this paper will be the case when there is one base station and 2 nodes ($N = 2$) to make the exposition easier to follow, but the results apply to the case of N nodes, unless specifically stated otherwise.

2.1 SNR Symmetric Channel

In this model, the channels from base station to a node and from a node to the base station are assumed to be SNR (signal-to-noise ratio) symmetric. This means that the SNR of the channel from node n to the base station is the same as the SNR of the channel from the base station to the node n, over the coherence time T. This assumption is easily justified in the case of wideband systems (like IEEE 802.11) and has been observed in experiments over the air in the Center for Multimedia Communication (CMC) Lab [15].

The channel can be described mathematically as follows. Let h_{Bn} be the fading coefficient of the channel from the base station to node n. Similarly, let h_{nB} be the fading coefficient of the channel from node n to the base station.

Then the received signal at the destination is

$$y_{\mathsf{Bn}} = h_{\mathsf{Bn}} x_{\mathsf{B}} + \eta_{\mathsf{B}} \tag{2.1}$$

$$y_{\mathsf{nB}} = h_{\mathsf{nB}} x_{\mathsf{n}} + \eta_{\mathsf{n}} \tag{2.2}$$

where x is the source symbol to be transmitted and n is the noise at the corresponding node. The SNR symmetric assumption is met by assuming that the channels have equal gain both directions, $\gamma_{\mathsf{n}} = |h_{\mathsf{Bn}}| = |h_{\mathsf{nB}}|$. It is important to note that we only require the magnitudes of the channel gains to be equal. In general, the h are complex numbers, but the assumption only involves SNR and does not require the phases to be perfectly aligned.

2.2 Queues

Our model is comprised of $N = 2$ users and a base station. Each one of the user nodes has a queue for the base station. The analysis performed does not assume that the queues must be backlogged, therefore the network is a stable system.

At the base station, the structure of the queue is a little more complex. We could look at the base station queue in different levels. First, there is the possibility of distiguishing queues at the base station in a per application manner. At a lower level, we could differentiate among the queues for each one of user nodes. Finally, we could look at the base station queue as one big multiplexed queue into which all the data that base station must transmit is directed. Typically, it is the case that the queue at the base station is a multiplexed queue, but currently, there is no hardware limitation that would prevent the creation of dedicated queues per node at the base station. In our model for the rest of this work, we assume that the base station has a dedicated queue for each one of the user nodes.

2.3 IEEE 802.11 MAC Protocol

The IEEE 802.11 Distributed Coorination Function (DCF) is a random access mechanism that allows nodes in a network to obtain the medium to transmit. This DCF serves as the basis for the protocol proposed in this work.

We will consider two popular variants of random access protocols in this paper which are based on the carrier sense multiple access with collision avoidance (CSMA/CA). One of the variants does not include any type of medium resevation techniques and the other uses an RTS/CTS handshaking protocol in which the transmitter first sends a short message to request the channel before sending the actual data packet.

2.3.1 Basic MAC Protocol

This section briefly describes the basic MAC (medium access control) protocol along with its main features. The 802.11 standard [1] contains the complete details of the scheme.

The nodes in the network wish to use the medium if they have some information that needs to be transmitted. To do this, they monitor the network to find out if it is idle or other node is transmitting. If it is idle for period equal to the distributed interframe space (DIFS), then the node transmits. If the medium is busy, then node needs to wait and keep monitoring until it is idle for another DIFS. When this happens, the node starts a random backoff interval before tranmitting. This is done to reduce the probability of collision. The backoff interval in chosen uniformly from a range $(0, w-1)$. w is called the contention window and it is equal to CW_{min} during the first transmission attempt. Now, if a packet transmission is unsuccesful, the range from which the backoff interval for each node in chosen is doubled, so that now $w = 2CW_{min}$. This is repeated for each unsucessful transmission until a value of $CW_{max} = 2^m CW_{min}$ is reached.

When a node successfully gains control of the medium, it simply sends the data information along with the header and waits for an acknowledgement packet (ACK) from the destination. If the destination recieved the packet correctly, it waits a short interframe space (SIFS) and then sends the ACK. The complete exchange is portrayed in Figure 2.3.

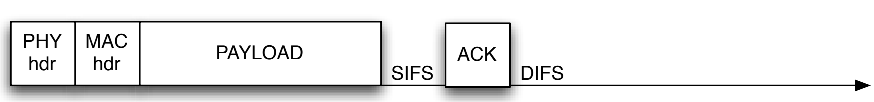


Figure 2.3: Transmitted Packets During Successful Transmission in Basic MAC Protocol

2.3.2 RTS/CTS MAC Protocol

The RTS/CTS access mechanism follows the same contention guidelines as described for the basic case. A diagram of the complete RTS/CTS exchange is shown in Figure 2.4. The main difference between the basic and RTS/CTS protocols is a handshaking mechanism that precedes the transmission of payload bits.

When a node succesfully gains access to the medium, instead of sending the payload data packet, it transmits a short request to send (RTS). The destination then receives the the RTS and replies with a clear to send (CTS) after a SIFS. If the CTS is received successfully by the source node, then it begins the basic exchange as before after a SIFS. The RTS and CTS packets have information about the packets being transmitted in the exchange. This way, all the listening nodes know for how long the medium will be busy and therefore avoid collisions. Each one of the listening nodes not involved in the exchange use this information to update their network allocation vectors (NAV).

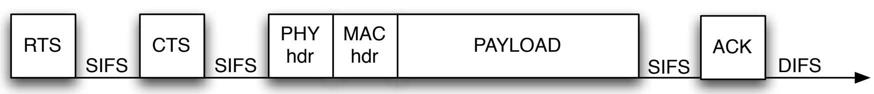


Figure 2.4: RTS/CTS MAC Protocol

2.3.3 Multi-rate IEEE 802.11

The 802.11 standard has the capability to transmit at several different rates. These rates can be adapted to the channel conditions to use higher rates if the channel presents good characteristics. The 802.11a and g standards allows possible rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps and the 802.11b standard provides support for 1, 2, 5.5 and 11 Mbps. This multi-rate adaptation capability will be used later in an opportunistic manner to get benefits from channel conditions.

Chapter 3

Opportunistic Two-Way Protocol

The main concept behind the proposed protocol is to opportunistically take advantage to the innate two-way nature of a communications link. As described in Chapter 2, typically, there are information flows in both directions, uplink and downlink. Also, there are instances when channel conditions will constraint a node to transmit at a low base rate, but at some other instances, the channel can support higher rates. This protocols exploits the existence of favorable conditions, either in terms of a source having data to send or good channel parameters or both, to increase the performance of the network.

3.1 Source Opportunism

Consider the 802.11 mechanism as the basis for the MAC protocol. In the currently used protocols, there is a contention resolution time before a user can access the medium. When a node accesses the medium, it transmits one data packet. So, there is a relation of one data packet per one contention time. The proposed procotol tries to take advantage of the possibility of two-way traffic to send more data packet per contention time.

Once a communication link has been established by one of the nodes accessing the medium, the destination node can look at its queue and see if there is a data packet that needs to be transmitted to the node from which it just received a packet. If this is the case, then the destination node can reply with an ACK and piggyback the data that it needs to transmit. This way we have saved contention time and the handshaking strategies in the case of RTS/CTS. Of course, the opportunistic nature of this protocol comes from the fact that the destination can only send packets back if it has them in its queue. More generally, we can say that we can establish a policy for each node which depends on the queues at the source and destination that determines how many packets can be exchanged per contention resolution. Let us define this policy as

$$f_{\mathsf{n}}(\overline{q_{\mathsf{B}}}, q_{\mathsf{n}}) \tag{3.1}$$

for node n and

$$f_{\mathsf{B}}(\overline{q_{\mathsf{B}}}, q_{\mathsf{n}}) \tag{3.2}$$

for the base station B. The queue at node n is q_{n} and $\overline{q_{\mathsf{B}}}$ is the vector of queues at the base station. The main difference between the queues arises from the fact that the nodes can only have a queue for the base station, but the base station has n different queues, one for each node. Let us illustrate how this policies are used with an example. Assume that at some instant, node 1 receives a packet, but it does not have any data to send. It automatically checks its policy with $q_1 = 0$, and in this case $f_1(\overline{q_B}, 0)$ would return a result of 0. A time digram of a successful source opportunistic exchange is shown in Figure 3.1.

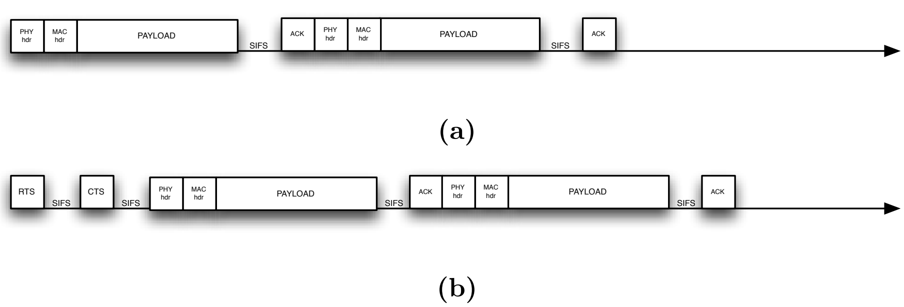


Figure 3.1: Source Opportunistic Exchange - Basic (a) and RTS/CTS (b)

3.2 Channel Opportunism

In addition to the source opportunism previously described, the proposed protocol provides the ability to capitalize on channel opportunism. In [13], the authors take advantage of good channel conditions, not only by transmitting packets at a higher rate, but also by stringing packets back to back from a node that has gained medium access. That strategy is called Opportunistic Auto-Rate or OAR. This work proposes that the protocol be adapted to take advantage of two-way communications as well.

Consider the network is employing the OAR protocol. If a node is trasmitting on a good channel, it will string several packets together and send them at a high rate. Since the channel is assumed to be SNR symmetric, the destination also sees a good channel and can transmit several packets in an OAR fashion. We are assuming that the channel changes in a longer time scale than two base rate packet transmissions.

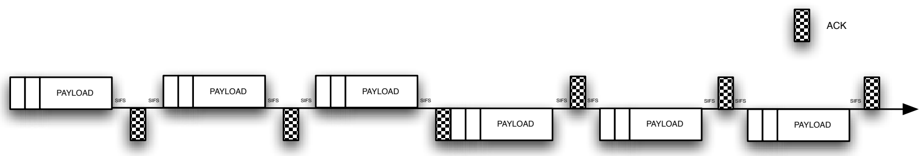
In this case, we now redefine the policy established in Eqs. 3.1 and 3.2 to include the dependance on the channel conditions. The new policies are written as follows

$$f_{\mathsf{n}}(\overline{q_{\mathsf{B}}}, q_{\mathsf{n}}, \gamma_{\mathsf{n}}) \tag{3.3}$$

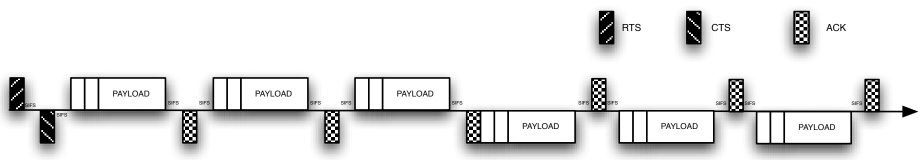
$$f_{\mathsf{B}}(\overline{q_{\mathsf{B}}}, q_{\mathsf{n}}, \gamma_{\mathsf{n}}) \tag{3.4}$$

The exact way in which these policies determine how many packets will be opportunistically exchanged will be discussed in a later section. Simply to illustrate the main concept behind these policies, we make use of an example. During some slot time, assume that node 1 has a queue state $q_1 > 6$ and sees a channel with a gain beyond some threshold ($\gamma_1 > SNR_{11}$) that allows it to send packets at a rate of 11 Mbps (which is approximately 6 time faster than the base rate) in that slot time. So, given these parameters, the policy $f_1(\overline{q_{\mathsf{B}}}, q_1 > 6, \gamma_{\mathsf{n}} > SNR_{11})$ will indicate that 6 packets should be transmitted in the time slot for that exchange. The objective of these definitions is to show what are the variables involved these policies. It is also important to note that, depending on the type of protocol being used, some nodes might not have access to all three variables described in these policies. In that case, the policies are only determined by the known variables.

We have now described the concepts of source opportunism and channel opportunism. Each one of these concepts can be applied in a protocol indepentdently or in tandem to produce higher gains. Notice, however, that in a combined protocol, source opportunism takes a primary role. One cannot establish two-way channel opportunism if the destination does not have data to send (an instance of source opportunism). Figure 3.2 portrays the time sequence in which a succesful two-way source *and* channel opportunistic exchange takes place.



(a)



(b)

Figure 3.2: Source and Channel Opportunistic Exchange - Basic (a) and RTS/CTS (b)

Chapter 4

Analysis

4.1 Normalized Throughput

The analysis of the performance of the network will be done using the *normalized throughput* metric defined in Equation (1.1). As in [4], let τ be the probability of a node transmitting in a specific slot time. This τ is directly related to the probability of collision, p. A transmitted packet encounters a collision if at least one of the other $N-1$ nodes trasmits. Therefore, p becomes

$$P = 1 - (1-\tau)^{N-1}. \tag{4.1}$$

In order to obtain an analytical expression for the normalized throughput, the following terms are defined. Let P_{tr} be the probability of at least one transmision occuring in a specific slot time. Since there are N total nodes and each one transmits with probability τ,

$$P_{tr} = 1 - (1-\tau)^{N}. \tag{4.2}$$

Also, let P_s be the probability of a successful transmission given that at least one node is transmitting, which occurs if only one node transmits. Therefore,

$$P_s = \frac{N\tau(1-\tau)^{N-1}}{P_{tr}} = \frac{N\tau(1-\tau)^{N-1}}{1-(1-\tau)^{N}}. \tag{4.3}$$

Having defined these terms, we are now able to generate an expression of the numerator and denominator of Equation (1.1). The expected value of the payload information in a slot time is equal to $P_{tr}P_sE[P]$, where $E[P]$ is the expected value of the length of the packet. This follows fromt the fact that a successful transmission occurs with probabilty $P_{tr}P_s$. For the denominator, we notice that the average length of a slot time is a follows. There is a $1 - P_{tr}$ probability of the slot being empty, a $P_{tr}P_s$ probability of a successful transmission, and a $1 - P_s$ probability of a collision. With this we have that (1.1) becomes

$$S = \frac{P_s P_{tr} E[L]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s)T_c}, \tag{4.4}$$

where T_s and T_c are the average time the channel is sensed busy because of a successful transmission and the average time the channel is busy due to a collision, respectively. Also, σ is the duration of an empty slot. The values for T_s and T_c depend on what type of MAC protocol is being used. Following the model described in Chapter 2, the values are described as follows

$$T_s^{bas} = H + E[L] + SIFS + \delta + ACK + DIFS + \delta \tag{4.5}$$
$$T_c^{bas} = H + E[L] + DIFS + \delta, \tag{4.6}$$

where δ is the propagation delay. Similarly, we have that

$$\begin{aligned} T_s^{rts} &= RTS + SIFS + \delta + CTS + SIFS + \delta \\ &+ H + E[L] + SIFS + \delta + ACK + DIFS + \delta \end{aligned} \tag{4.7}$$
$$T_c^{rts} = RTS + DIFS + \delta \tag{4.8}$$

4.2 Source Opportunism

Now that we have defined a metric to analyze the performance of the proposed protocol in the network, we procede to generate the analytic expression for the normalized throughtput of the a protocol with source opportunism.

Let us define a random variable η_s to represent whether or not the opportunity for two-way communications is present. The value of η_s is determined by the policies established in equations (3.3) and (3.4). Now let η_c be the number of packets that the source node is able to transmit in a slot time, depending on the channel state. A value of $\eta_c > 1$ means that the channel supports a higher rate. The next section describes the properties of this variable. Therefore,

$$\eta_s = \begin{cases} 1 & \text{if } q_D < \eta_c \\ 2 & \text{if } q_D \geq \eta_c \end{cases} \tag{4.9}$$

where q_D is the queue at the destination. If node n is the destination, then $q_D = q_{\mathsf{n}}$. If the base station is the destination, q_D is the element of $\overline{q_B}$ that correspond to the source node.

In general, $\eta_s = 1$ means data exchange in one slot will only take place in one direction. Also, $\eta_s = 2$ means that during that slot time, there will be a two-way opportunistic exchange.

4.3 Channel Opportunism

To capture the concept of channel opportunism, we define the variable η_c described in the previous section. η_c is equal to the number of packets a node is able to transmit during one slot time considering the conditions of the channel.

For example, consider the 802.11b standard. As explained in [13], sending 1 packet at 2 Mbps, 3 packets at 5.5 Mbps, or 5 packets at 11 Mbps takes approximately the same amount of time. Let us define this slot time length at T_b. Now, η_c could be the number of packets that a node can transmit in T_b amount of time. In this case, η_c would have the following distribution

$$p(\eta_c = 1) = p(R = 2) = p(SNR_2 \leq SNR < SNR_{5.5}) \tag{4.10}$$

$$p(\eta_c = 2) = p(R = 5.5) = p(SNR_{5.5} \leq SNR < SNR_{11}) \tag{4.11}$$

$$p(\eta_c = 5) = p(R = 11) = p(SNR_{11} \leq SNR) \tag{4.12}$$

where SNR_2, $SNR_{5.5}$, and SNR_{11} are the minimum required SNR to support a rate of 2, 5.5, and 11, respectively.

4.4 The Modified Normalized Throughput Equation

We have now defined two variables η_s and η_c that capture the ability to opportunistically exchange more than one packet per contention resolution. In this section, we modify the normalized throughput expression to account for these variables. For ease of notation and without loss of generality, we assume that all packets have the same length, so that $E[L] = L$.

Let us first consider the case of source opportunism only. In the numerator of Equation (4.4), the exchange could possibly carry two times as much information bits. In the denominator of Equation (4.4), however, the length of a successful transmission also increases as shown in Figure 3.1. Hence,

$$S_{Sopp} = \frac{P_s P_{tr} L \eta_s}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s)T_c} \tag{4.13}$$

and

$$T_s^{bas/opp} = \eta_s T_s^{bas} \tag{4.14}$$

for the basic protocol. For the RTS/CTS protocol, we have that

$$\begin{aligned} T_s^{rts/opp} &= RTS + SIFS + \delta + CTS + SIFS + \delta \\ &+ \eta_s[H + L + SIFS + \delta + ACK] + DIFS + \delta \end{aligned} \tag{4.15}$$

Equation (4.13) presents the normalized throughput of a network that uses a protocol that takes advantage of source opportunism. It is important to notice that if $\eta_s = 1$, $S_{Sopp} = S$ as it is defined in [4].

In addition to source opportunism, the variable η_c allows us to include channel opportunism in the normalized throughput measure to explore its performance. Simililarly, consider a protocol that includes a combination of source opportunism *and* channel opportunism

$$S_{Copp} = \frac{P_s P_{tr} L \eta_s \eta_c}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s)T_c} \tag{4.16}$$

where

$$T_s^{bas/opp} = \eta_s \eta_c T_s^{bas} \tag{4.17}$$

for the basic protocol, and

$$\begin{aligned} T_s^{rts/opp} &= RTS + SIFS + \delta + CTS + SIFS + \delta \\ &+ \eta_s \eta_c[H + L + SIFS + \delta + ACK] + DIFS + \delta \end{aligned} \tag{4.18}$$

for the RTS/CTS protocol.

At this time, we provide a description of the gains provided by the proposed protocol. The protocol provides two major differences when compared to the previous work. By sending more packets per contention resolution, we avoid the ratio of one packet per contention resulution. In addition to the improvement of that ratio, the two-way protocol improves the ratio of payload data sent per total length of slot required to send that data (i.e., the ratio of $\eta_s \eta_c P$ to T_s).

4.5 Overhead

To quantify the gains given by the protocol we look at the overhead in each case. Let us define the overhead, O, as the amount of non-payload data per slot time. Then,

$$\mathsf{O} = T_s - \eta_s \eta_c L. \tag{4.19}$$

Let us consider the combined opportunistic protocol and compare it to the existent protocols. The overhead for the existing protocols is

$$\begin{aligned} \mathsf{O}_{\mathsf{bas}} &= T_s^{bas} - \eta_s \eta_c L && (4.20)\\ &= T_s^{bas} - L && (4.21)\\ &= H + SIFS + \delta + ACK + DIFS + \delta && (4.22) \end{aligned}$$

$$\begin{aligned} \mathsf{O}_{\mathsf{rts}} &= T_s^{rts} - \eta_s \eta_c L && (4.23)\\ &= T_s^{rts} - && (4.24)\\ &= RTS + SIFS + \delta + CTS + SIFS + \delta + \mathsf{O}_{\mathsf{bas}}. && (4.25) \end{aligned}$$

The computation of the overhead for the combined opportunistic protocol is as follows

$$\begin{aligned}
\mathsf{O}_{\mathsf{bas}}^{\mathsf{opp}} &= T_s^{bas/opp} - \eta_s\eta_c L &(4.26)\\
&= \eta_s\eta_c T_s^{bas} - \eta_s\eta_c L &(4.27)\\
&= \eta_s\eta_c[H + SIFS + \delta + ACK + DIFS + \delta] &(4.28)\\
&= \eta_s\eta_c \mathsf{O}_{\mathsf{bas}}. &(4.29)
\end{aligned}$$

For the reservation-based opportunistic two-way protocol, the overhead is

$$\begin{aligned}
\mathsf{O}_{\mathsf{rts}}^{\mathsf{opp}} &= T_s^{rts/opp} - \eta_s\eta_c L &(4.30)\\
&= \eta_s\eta_c T_s^{rts} - \eta_s\eta_c L &(4.31)\\
&= \eta_s\eta_c[H + SIFS + \delta + ACK + DIFS + \delta] &(4.32)\\
&= RTS + SIFS + \delta + CTS + SIFS + \delta + \eta_s\eta_c \mathsf{O}_{\mathsf{bas}}. &(4.33)
\end{aligned}$$

This example illustrates that, in this case, there is no gain with respect to overhead in the basic case. We have an overhead of $\mathsf{O}_{\mathsf{bas}}$ in the normal protocol for one packet, and an overhead of $\eta_s\eta_c\mathsf{O}_{\mathsf{bas}}$ in the opportunistic protocol for $\eta_s\eta_c$ packets. In contrast, in the RTS/CTS protocol there is an overhead gain. In this protocol, the initial handshaking mechanism is only performed once. Therefore, while the rest of the overhead has a multiplicative factor of $\eta_s\eta_c$, the handshake appears only once. It is important to emphasize the overhead gain is only an additional source of gain and that gain has already been obtained thanks to the delivery of several packet per contention time. Hence, the basic opportunistic protocol will exhibit some gains but the RTS/CTS opportunistic protocol will add the overhead gains resulting in a bigger improvement. This observation is summarized in the following theorem:

Theorem 1 *Consider a network with N user nodes and one base station and constant packet length, L. Let T_{tot} be the total time required to service the packets currently in q_n and $\overline{q_\mathsf{B}}$ using the normal protocol and T_{tot}^{opp} be the total time required to service those packets. Then, for all q_n, $\overline{q_\mathsf{B}}$, and γ_n,*

$$E[T_{tot}^{opp}] \leq E[T_{tot}]$$

Proof 1 *As described before, let T_s^{opp} be the time required to successfully transmit a packet using the opportunistic protocol and T_s using the normal protocol.*

Now we introduce the variable Δ which is equal to the time required to resolve a contention for the medium. It follows directly that

$$E[T_{tot}] = \sum_{\mathsf{i}=1}^{N} q_{\mathsf{i}}(T_s + \Delta) + q_{\mathsf{Bi}}(T_s + \Delta)$$

where q_{Bi} is the queue at the base station dedicated for node i.

Now, the opportunistic protocol carries out an exchange of $\eta_s \eta_c$ packets per contention time Δ in the time slot T_s^{opp}. This is equivalent to having an average of contention time per packet of $\Delta/\eta_s\eta_c$ and a service time of $T_s^{opp}/\eta_s\eta_c$ per packet. Therefore, in a similar way to the previous case,

$$E[T_{tot}^{opp}] = \sum_{\mathsf{i}=1}^{N} q_{\mathsf{i}}(\frac{T_s^{opp}}{\eta_s\eta_c} + \frac{\Delta}{\eta_s\eta_c}) + q_{\mathsf{Bi}}(\frac{T_s^{opp}}{\eta_s\eta_c} + \frac{\Delta}{\eta_s\eta_c})$$

First, let us look at the basic case. Recall that in Equation (4.17), $T_s^{bas/opp} = \eta_s\eta_c T_s^{bas}$. Therefore, we have that by substituting for $T_s^{bas/opp}$

$$E[T_{tot}^{opp}] = \sum_{\mathsf{i}=1}^{N} q_{\mathsf{i}}(T_s^{opp} + \frac{\Delta}{\eta_s\eta_c}) + q_{\mathsf{Bi}}(T_s^{opp} + \frac{\Delta}{\eta_s\eta_c})$$

which is clearly less the $E[T_{tot}]$.

Moving now to the RTS/CTS case, in order to compare $E[T_{tot}^{opp}]$ and $E[T_{tot}]$ in a clear manner, let $HS = RTS + SIFS + \delta + CTS + SIFS + \delta$ be the the amount of time required for the handshaking mechanism. With this simplification we now have that $T_s^{rts} = (HS + T_s^{bas})$ and $T_s^{rts/opp} = (HS + \eta_s\eta_c T_s^{bas})$. Finally, the equations which need to be compared simplify to

$$E[T_{tot}] = \sum_{\mathsf{i}=1}^{N} q_{\mathsf{i}}(HS + T_s^{bas} + \Delta) + q_{\mathsf{Bi}}(HS + T_s^{bas} + \Delta)$$

and

$$E[T_{tot}^{opp}] = \sum_{\mathsf{i}=1}^{N} q_{\mathsf{i}}(\frac{HS}{\eta_s\eta_c} + T_s^{bas} + \frac{\Delta}{\eta_s\eta_c}) + q_{\mathsf{Bi}}(\frac{HS}{\eta_s\eta_c} + T_s^{bas} + \frac{\Delta}{\eta_s\eta_c}).$$

Once again, it is shown that $E[T_{tot}^{opp}] \leq E[T_{tot}]$ and the proof is completed.

Based on the Theorem 1 and with a similar structure of the proof, we provide a corollary that compare the normalized throughput S in both protocols.

Corollary 1 *Considering the same network as before. Let S be the normalized throughput using the normal protocol and S_{Copp} be the normalized throughput using the combined opportunistic protocol. Then, in average over different time slots,*

$$S_{Copp} \geq S$$

Proof 2 *The proof is done by construction, following the steps descibed above. Compare equations 4.4 and 4.16. Given that all other parameters are constant, the only part of the expressions to be considered is the ratio $(\eta_s \eta_c P)/T_s$.*

First look at the basic protocol. It is obvious that

$$S = \frac{P_s P_{tr} P}{(1 - P_{tr})\sigma + P_{tr} P_s T_s^{bas} + P_{tr}(1 - P_s)T_c}$$

is less than or equal to

$$S_{Copp} = \frac{P_s P_{tr} P \eta_s \eta_c}{(1 - P_{tr})\sigma + P_{tr} P_s \eta_s \eta_c T_s^{bas} + P_{tr}(1 - P_s)T_c}$$

for all possible values of η_s and η_c. In the case of the RTS/CTS protocol, let $HS = RTS + SIFS + \delta + CTS + SIFS + \delta$ be the the amount of time required for the handshaking mechanism (to make the comparison clearer). It is clear from the preceding sections that

$$S = \frac{P_s P_{tr} P}{(1 - P_{tr})\sigma + P_{tr} P_s (HS + T_s^{bas}) + P_{tr}(1 - P_s)T_c}$$

is also less than or equal to

$$S_{Copp} = \frac{P_s P_{tr} P \eta_s \eta_c}{(1 - P_{tr})\sigma + P_{tr} P_s (HS + \eta_s \eta_c T_s^{bas}) + P_{tr}(1 - P_s)T_c}$$

since $T_s^{rts} = (HS + \eta_s \eta_c T_s^{bas})$. Again, this is true for all possible values of η_s and η_c and the corollary is proven.

Chapter 5

Results

Theorem 1 and Corollary 1 show that the opportunistic protocol performs better than or equal to the normal protocol over all possible queue and channel states. Simulations were performed to compare the performance with respect to the probability of collision and the number of users. It could be seen from Figure 5.1 that the proposed protocol has a better performance accross all probabilities of collision on both cases, the basic and RTS/CTS. Figure 5.2 shows the same pattern across different number of users.

A surprising behavior of the proposed protocol is displayed in Figure 5.3. It shows that as the number of users increases, the difference between S_{Copp} and S increases. The difference grows significantly up to 10 user and remains relatively constant beyond that point. The reason for this behavior comes from the gains the protocol produces with respect to the contention times. As the number of nodes increases, the probability of a successful transmission decreases, so each contention resolution cycle becomes more “valuable”. Since the protocol is sending more packets over a more “valuable” link, the protocol exhibits gains. This means that in average over several time slots, a network using the oppostunistic two-way protocol would service its queues in a smaller amount of time and more throughput could be pushed across the network.

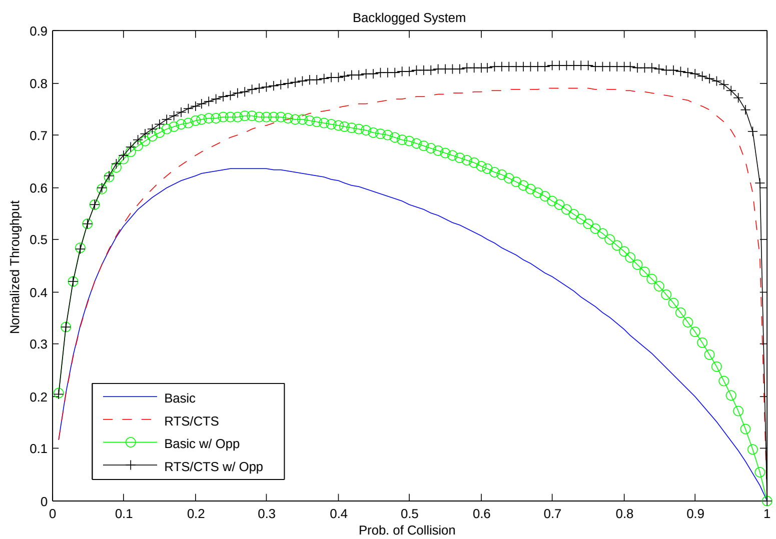


Figure 5.1: Normalized Throughtput with Respect to Prob. of Collision

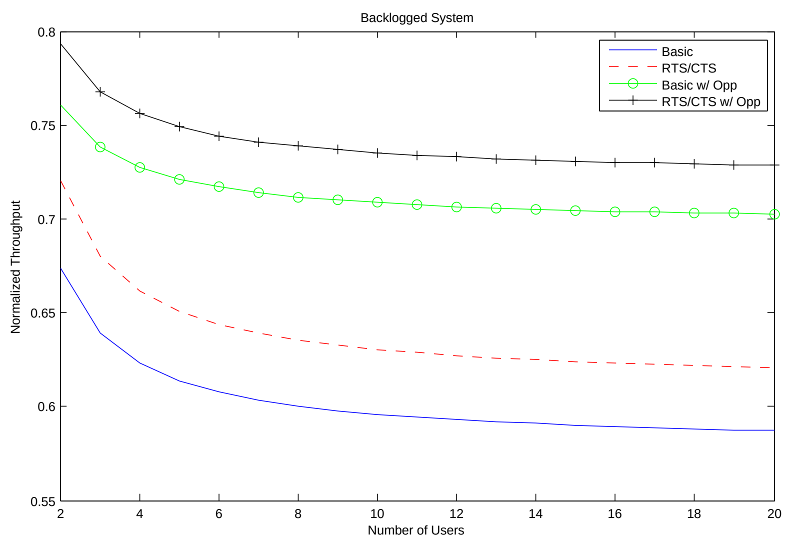


Figure 5.2: Normalized Throughtput with Respect to Number of Users

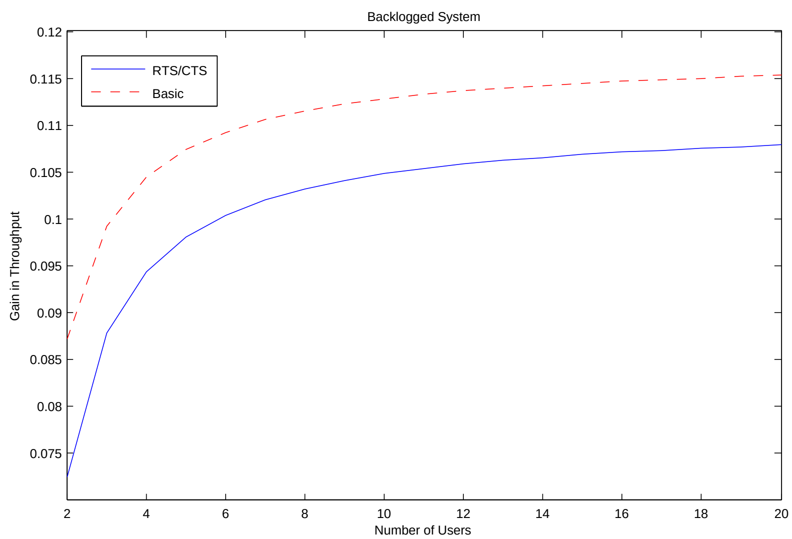


Figure 5.3: Difference in Norm. Throughputs with Respect to Number of Users

Chapter 6

Future Work

One of the key characteristic of the two-way opportunistic protocol is that it uses the 802.11 MAC protocol as its basis. Also, because of its practically, part of the future work is to implement this protocol in a hardware platform. The WARP [2] platform is a perfect candidate for implementation. Experiments over the air with time-varying queues and channel states would be helpful to validate the theoretical and simulation results presented in this work.

Another aspect that can be explored in the near future is the possibility of node to node communication, not just through the base station (as in Figure 6.1). Currently, the policies established do not account for the possibility of user nodes being able to have some knowledge about the queue states of other nodes. Having this knowledge might provide additional gain if the nodes are capable of addapting to the global queue state of the network.

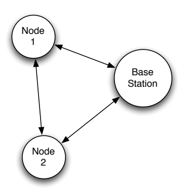


Figure 6.1: Network showing communication through the base station and node-to-node communication

Finally, a more generalized version of the normalized throughput equations could be developed in order to allow asymmetric exchanges. In this work, the exchanges between two nodes contained the same number of packets in each direction. The drawback to this approach is that the probability of a two-way exchange decreases as the number of OAR-type packets from a source increases. With an asymmetric exchange, the uplink and downlink transmissions could be related by some ratio, appropriate to the nature of the network.

Chapter 7

Conclusion

The results obtained so far show that the proposed protocol gives a improvement in normalized throughput with respect to the normal 802.11 protocol and even in comparison with the OAR protocol. The main reason for these gains is the ability to exploit two-way communications. We have shown that for all queue and channel states, the proposed protocol performs, at worst, at the same level than the previous protocols. In addition to that, our protocol displays an increasing improvement as the number of users increase.

This concept is very much applicable to currently deployed wireless networks and implementation only requires few modifications to established MAC protocols.

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