WLAN CSMA/CA Performance in a Bluetooth Interference Environment

THESIS

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Randall B. Noel

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Abstract

IEEE 802.11 WLANs and Bluetooth piconets both operate in the 2.4 GHz Industrial Scientific and Medical (ISM) radio band. When operating in close proximity, these two technologies interfere with each other. Current literature suggests that IEEE 802.11 (employing direct sequence spread spectrum technology) is more susceptible to this interference than Bluetooth, which uses frequency hopping spread spectrum technology, resulting in reduced throughput. Current research tends to focus on the issue of packet collisions, and not the fact that IEEE 802.11 may also delay its transmissions while the radio channel is occupied by a Bluetooth signal. This research characterizes previously neglected transmission delay effects. Through analytic modeling and simulation, the impact of this interference is determined to identify all facets of the interference issues.

Results show that Bluetooth-induced transmission delays improve network performance in many scenarios. When isolating delay effects, the likelihood that WLAN STA signals collide with each other decreases, causing an overall increase in normalized throughput and decrease in expected delay for many network configurations.

As wireless communication technologies become an integral part of national defense, it is imperative to understand every performance characteristic. For instance, if the Air Force uses IEEE 802.11 and wants to incorporate a Bluetooth piconet as well, the impact of concurrent operation should be known beforehand. Since IEEE 802.11 and Bluetooth technologies could become vital for the Air Force to maintain its position of air superiority, all the strengths, weaknesses, and limitations of these systems should be understood.

WLAN CSMA/CA PERFORMANCE

IN A BLUETOOTH INTERFERENCE ENVIRONMENT

I. Introduction

1.1 Motivation

It has long been a goal for people to have access to computers even when mobile. Products implementing the IEEE 802.11 and Bluetooth standards offer a way to make this type of access realizable. IEEE 802.11 can be used to implement a wireless local area network (WLAN) where users may enter and leave the system, or move to different locations in the system without the restrictions inherent in wired communication. Users would be able to access the local network or the Internet from virtually anywhere. For instance, a given laptop would have access to the network whether the user is working in his office, or preparing a briefing in a conference room.

Bluetooth (BT) is designed to implement wireless personal area networks (WPAN) and supports voice and data communication over shorter distances than that envisioned for WLANs [HHN02]. A typical use would be to connect a wireless keyboard, mouse, or speakers to a computer. Use of a WPAN would allow the user to work without the confusing, restricting tangle of wires behind the computer.

It would be sensible to combine these two technologies to create a totally wireless environment. The coexistence of these technologies could greatly increase mobility. IEEE 802.11 itself provides freedom to move, but dealing with a tangle of wires while mobile severely impacts its utility. Likewise, BT alone provides a flexible wireless work area, but the user is still tied down by the LAN wiring. The combination of these two would support a totally wireless computing environment. Since both these technologies operate in the 2.4 GHz industrial, scientific, and medical (ISM) radio band, whether they can operate simultaneously is a valid concern.

1.2 Overview

IEEE 802.11 WLANs and BT WPANs both operate in the unlicensed 2.4 GHz band. When these technologies are employed in close proximity, mutual interference is a concern. This research characterizes the effects of BT interference on WLAN performance with respect to delayed transmissions due to BT-induced busy channel indications ("false positives") in a WLAN station's (STA) clear channel assessment (CCA) algorithm.

IEEE 802.11's physical layer is based on the direct sequence spread spectrum (DSSS) specification [P802.11]. BT, however, employs frequency hopping spread spectrum (FHSS) with a hop rate of 1600 hops per second, where the hops are evenly distributed over 79 1 MHz channels over time. BT devices transmit data over these channels at a rate of 1 Mbps, and have a range of 10 m [GoM01].

To explore coexistence issues between WLAN and BT, it is valuable to consider how BT signals affect different aspects of the IEEE 802.11 transmission protocol. Interference possibilities include retransmissions due to collisions and delayed transmissions induced by a node's CCA algorithm. Collisions occur when an IEEE 802.11 and a BT signal overlap both time and frequency. Interference without collisions occurs when the presence of a BT signal causes the CCA algorithm to determine the medium is busy. If a BT transmitter is close enough to an IEEE 802.11 network, it is shown that the probability a BT transmission overlaps the transmission frequency of WLAN is significant at about 0.25 [ChR00]. Considering these two cases, interference potentially occurs whenever a BT transmitter hops into the WLAN's spectrum. Since a WLAN's signal occupies 22 of the available 79 MHz in the 2.4 GHz band, 22 BT channels with a size of 1 MHz will fall within the WLAN's spectrum [She01].

The CCA algorithm is a carrier sense mechanism used to prevent collisions between IEEE 802.11 frames [P802.11]. One of three CCA algorithms can be used to determine if the channel if free, including, CCA algorithm #1: the channel is busy when detected energy exceeds a specified energy detection (ED) threshold, CCA algorithm #2: the channel is busy when an IEEE 802.11 signal is detected, and CCA algorithm #3: the channel is busy when conditions for both algorithms #1 and #2 are met. The ED threshold value is dependent on the transmission power of the STA. For a transmission power greater than 100 mW, the ED threshold is –80 dBm. For a transmission power between 50 mW and 100 mW, the ED threshold is –76 dBm. For a transmission power less than 50 mW, the ED threshold is –70 dBm.

Algorithms #2 and #3, in effect, use a higher CCA standard since they imply that an IEEE 802.11 STA is within range, whereas algorithm #1 simply declares a channel busy when an energy threshold is exceeded. Considering that algorithm #1 employs the weakest conditions to indicate a busy medium, this CCA algorithm is the most susceptible to BT interference. A BT-induced "false positive" occurs when the CCA indicates the channel is busy even though only a BT signal is present.

This research characterizes the effect of BT interference on WLAN performance due to BT induced "false positives" in the CCA. When the CCA algorithm determines the wireless medium is busy, the CSMA/CA protocol delays transmission and adversely impacts throughput and mean delay.

1.3 Thesis Organization

This chapter gives the motivation for this research and an overview of the subject. Chapter II provides a solid foundation in the research area. It contains an overview of the IEEE 802.11 and BT protocols, followed by a description of the coexistence issues. Previous work relating to the compatibility of WLANs and BT WPANs is presented, and an analytic model used as a basis for the development of the interference models in Chapter IV is described.

Chapter III discusses the methodology and approach used in this research. It defines system boundaries, services, performance metrics, system and workload parameters, and the factors studied. The evaluation technique and experimental design is presented.

Chapter IV contains the data analysis and results. It begins with the development of the analytic interference model and the simulation model. The resulting data is analyzed to characterize the effects of interference on WLANs.

Chapter V presents conclusions, reviews the results and significance of the research, and suggests possibilities for future study.

II. Literature Review

2.1 Background

2.1.1 Bluetooth Overview

Like IEEE 802.11, BT nodes communicate through radio transmissions in the 2.4 GHz ISM band. BT employs FHSS with a hop rate of 1600 hops per second over 79 channels, where the hops are equally distributed between each 1 MHz channel over time. BT devices transmit data over these channels at a rate of 1 Mbps using binary Gaussian Frequency Shift Keying (GFSK), and have a range of 10 m [GoM01].

When between two and eight BT nodes come together, they form an ad hoc network called a piconet. One node acts as the master and manages transmissions for the entire group. The remaining slaves must communicate with each other through the master. The master controls the medium using a polling scheme where master and slave alternate transmissions. In one 625 μs time slot, the master sends a poll packet to a particular slave. In the next slot, the slave responds with data [Spe99].

There are two types of links that can be maintained in a piconet. The first is a synchronous connection-oriented (SCO) link, a point-to-point link between the master and a single slave. This can be used for voice and other real-time applications with constant data streams. Retransmission of corrupted or lost packets is not useful for this type of application. The link is maintained by reserving time slots at regular intervals resulting in a voice transmission rate of 64 Kbps in each direction. The second type of link is an asynchronous connection-less (ACL) link. This is a point-to-point link for data packets that need to be transmitted reliably. An automatic repeat request (ARQ) procedure is applied to ACL packets that are lost or corrupted, and the transmitting node waits for an acknowledgement (ACK) as a final assurance that a packet was received successfully [GoM01].

When multiple piconets have one or more BT nodes in common they form a scatternet [JKK01]. These scatternets can communicate with each other via their common node(s). A scatternet can be established, for example, when there are three or more nodes in range of each other. A piconet is comprised of one master and up to seven slaves; any more requires the creation of a second piconet. A scatternet can also be used when two sets of nodes are out of range of each other, but there is a node that is in range of both. The two sets create their own piconets with the bridge node being a member of both. Different hop sequences used by the masters of each piconet allow coexistence of multiple piconets.

2.1.2 IEEE 802.11 Overview

IEEE 802.11 defines a particular wireless physical and medium access control standard. Using this technology, many stations can come together to form a network similar to Ethernet without wires. The Medium Access Control (MAC) layer uses a carrier sense multiple access with collision avoidance (CSMA/CA) algorithm to control the medium. When a WLAN STA has data to transmit, it will try to determine if other STAs are using the medium via carrier-sensing. Both virtual and physical carrier-sense mechanisms are used. The virtual mechanism is called the network allocation vector (NAV). The NAV is the integer number of slots a transmitting STA is reserving the channel. Based on that information, a STA that receives the packet will set a slot countdown timer. The countdown timer is set even when the STA receiving the packet is not the ultimate destination of the packet. The STA will not transmit until the timer reaches zero.

The physical carrier sense mechanism is called the clear channel assessment (CCA) algorithm. One of three CCA algorithms can be used to determine if the channel is busy. CCA algorithm 1: the channel is busy when channel energy is above a certain threshold. CCA algorithm 2: the channel is busy when an IEEE 802.11 signal is detected. CCA algorithm 3: the channel is busy when the conditions for both algorithms 1 and 2 are met. Both the virtual and physical carrier sense mechanisms must indicate the channel is idle, otherwise it is considered busy.

If, after monitoring the channel with these carrier sense mechanisms, the channel is determined to be idle for a time greater than a DCF inter-frame space (DIFS), the data frame is transmitted. When the frame is successfully transmitted, the destination STA responds with an ACK frame, completing the exchange. However, even with this collision avoidance scheme, unsuccessful transmissions may occur. For example, lost or timed out ACK frames are assumed to be the result of packet collisions and require the transmitting STA to resend the frame.

Upon an unsuccessful transmission, a STA waits the duration of the DIFS and then chooses a pseudo-random integer number of slots within the range of the contention window (CW) that the backoff timer must count down before retransmitting the data. If the channel becomes busy anytime during the backoff period, the backoff timer is suspended until the medium is idle for a DIFS duration. When the timer reaches zero, the STA transmits its data frame. If the transmission fails again, the size of the CW doubles and a new integer value is selected for the backoff timer which reduces the probability of another collision. Each unsuccessful retransmission causes the CW to double until it reaches a maximum value. After a predetermined number of failed transmissions, the STA drops the frame.

Unsuccessful transmissions affect more than just STAs trying to communicate. When other STAs observe a corrupted frame, an extended inter-frame space (EIFS) is used until an error free frame is observed. The length of the EIFS is 300 μs longer than the DIFS. Although the other STA observes a corrupt frame, the destination STA may have received it correctly. By waiting for the longer EIFS, other STAs allow enough time for the destination STA to respond with an ACK frame before they transmit.

One common communication problem that occurs in wireless networks is the hidden node problem [Vuk99]. If a STA has a frame to transmit, it could be that the destination STA is currently receiving a frame from another source. If that source is far enough away, the STA will not know the destination is busy and will transmit causing a collision. To reduce the possibility of a hidden node collision, a STA may begin communication by sending a request to send (RTS) frame to the destination STA. If that STA is free to receive the transmission, it responds with a clear to send (CTS) frame. If the CTS frame is received before the timeout, the transmitting STA sends the data over the medium.

IEEE 802.11 specifies three different physical (PHY) layers. One is infrared (IR), which requires direct line of sight with the destination STA. IR will not be discussed further since it is not susceptible to RF interference. Another PHY layer that can be used is FHSS, which operates in the 2.4 GHz ISM band. The FHSS PHY uses a 1 MHz channel separation and hops at a rate of 10 hops/second. It jumps pseudo-randomly over 79 channels. FHSS can operate at a rate of 1 Mb/s and 2 Mb/s, using differential binary phase shift keying (DBPSK) and differential quadrature phase shift keying (DQPSK) respectively.

The PHY layer that is most susceptible to RF interference is DSSS [Enn98]. DSSS operates in the 2.4 GHz ISM band and has a channel width of 22 MHz, allowing it to support up to three nonoverlapping channels. It was originally defined to transmit at 1 Mb/s (DBPSK) and 2 Mb/s (DQPSK), but has been extended in IEEE 802.11b. The extension defines data transmission rates of 5.5 Mb/s and 11 Mb/s using complementary code keying (CCK) for a total of four possible transmission rates.

2.1.3 Implications of Coexistence

The following section discusses issues that arise when IEEE 802.11 is operating in the presence of BT nodes. It is unlikely that interference will result in data loss since a transmitting STA will retransmit a frame up to seven times. This retransmission, however, reduces effective throughput. Effective throughput, then, is an essential metric to consider when analyzing the effects of BT interference.

Collision Interference:

Collisions occur when an IEEE 802.11 and a BT signal overlap in both time and frequency. In order to determine the effects of a collision, the BT signal is assumed to be strong enough to corrupt any IEEE 802.11 frame with which it collides. If a BT transmitter is close enough to an IEEE 802.11 network, it has been shown that the probability of overlapping in frequency is significant at 0.25 [ChR00].

The ISM band is 80 MHz wide, while BT uses 1 MHz channels for its transmissions. Let the 1 MHz channels be labeled zero to 79. Since the bandwidth of a WLAN signal is approximately 20 MHz wide, it will occupy, say, channels zero through 19. BT hop sequences are composed of several sub-sequences of 32 hops each. In each sub-sequence, 32 hop channels are chosen out of a possible 64. The first set of random hops is taken over channels 0 to 63. Since the WLAN and BT signals will overlap for sub-sequence hops chosen in the range channels 0 through 19, the probability of overlap is $\frac{20}{64}$. The second set of 32 hops is chosen from the range 16 through 79. Since the BT signal may overlap in channels 16 through 19, the probability of overlap is $\frac{4}{64}$. The third range of hops is taken from channels 32 through 79, and wraps around to channels 0 through 15. These signals could overlap in channels 0 through 15 with a probability of $\frac{16}{64}$. The fourth set of hops is taken from channels 48 through 79, wrapping around to channels 0 through 31. Possible overlaps exist in channels 0 through 19 for an overlap probability of $\frac{20}{64}$. The final set is taken from channels 64 through 79 and 0 through 47. Again, possible overlaps exist in channels 0 through 19, for an overlap probability of $\frac{20}{64}$. Each time, the beginning of the range increases by 16, and the 64 channels wrap if they extend beyond channel 79. It requires five sub-sequences to return to the beginning of the ISM band [ChR00]. Figure 2.1 shows the progression of the BT hop sequence. Thus, the

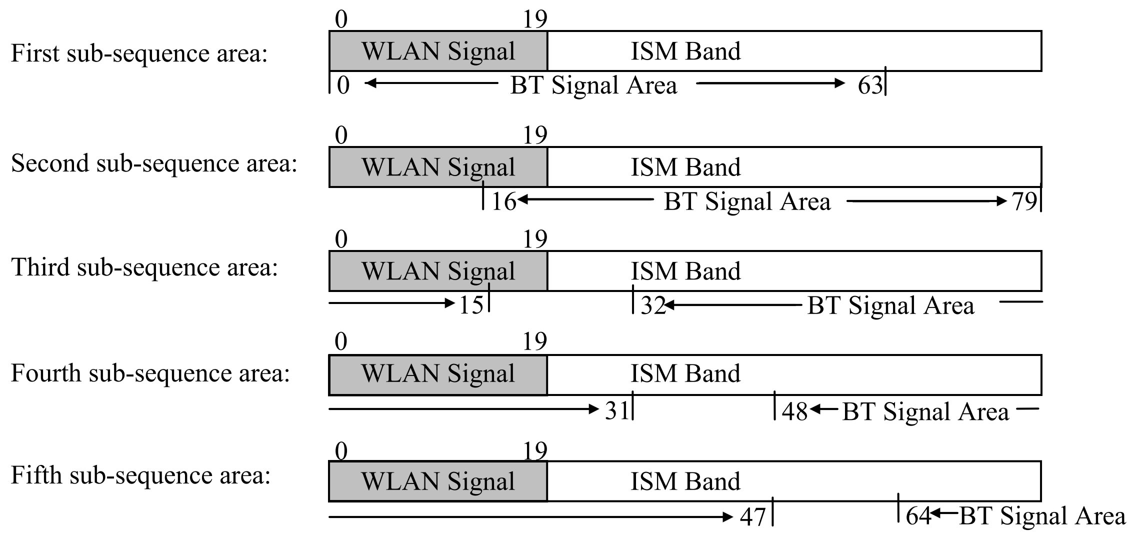

Figure 2-1. BT hop sub-sequence areas over the ISM Band.

probability of frequency overlap is [ChR00]

$$P_{overlap} = \frac{1}{5}\left(\frac{20}{64} + \frac{4}{64} + \frac{16}{64} + \frac{20}{64} + \frac{20}{64}\right) = 0.25. \qquad (2\text{-}1)$$

If a BT signal collides with a WLAN signal, it may collide with a RTS or CTS frame. If a collision occurs with an RTS frame, the destination STA will not be able to determine if the frame was a RTS or the intended destination STA. In these cases, the destination STA will switch from the DIFS to the longer EIFS, delaying transmission of its own data frames, and the CTS will time out at the source STA. The source STA will remain idle for a period of time before the timeout, and then it will have to contend to send the frame again.

The collision discussed above will cause another problem for a transmitting STA that involves its backoff timer. The transmitting STA selects a random integer value in the range [0, CW] and uses that for the backoff timer. Each failed transmission results in doubling the CW value. The CW value is reset to its minimum after successful transmission. This feature will reduce collisions between STAs in heavy traffic, but will also unnecessarily reduce a STA's throughput as well. Furthermore, the STAs attempting the RTS/CTS exchange aren't the only STAs affected. Any STA in range that observed the RTS frame as corrupted will also switch to the longer EIFS, which delays the potential transmission of their data frames. Finally, any STA in a position to observe the frame correctly will erroneously update its NAV counter to indicate a busy medium for the time the given RTS – CTS – Data – ACK sequence would have taken.

There is another collision that involves the CTS frame. The effects on the source STA and all other third party STAs remain the same; the source must contend to transmit again, and other STAs will either switch to EIFS or update their NAV. The only difference is how the destination STA is affected. After attempting to reply with a CTS frame, the destination STA will wait for the data transmission to begin. Any transmissions of its own will be put on hold for as long as it takes to determine the data frame is not following.

Another collision that can occur is with the data frame itself. The consequences of this event are similar to those stated above for an RTS collision. This means the source must resend when the time to receive an ACK is exceeded, and other STAs will delay due to EIFS or NAV. The only significant difference to note is the length of the data frame. Since RTS/CTS frames are short, the source STA can quickly determine the transmission failed and retry. In the case of a more lengthy data frame, however, it could be some time before the STA recognizes the failure and attempts to transmit again.

Furthermore, a collision with a data frame can cause data loss in the case of multicasts or broadcasts. These transmissions do not receive an ACK since the frame is sent to many STAs. The source STA will not be able to determine if the transmission was successful or not.

Finally, a collision can occur with an ACK frame. This will cause an ACK timeout at the source STA and lead to unnecessary retransmission of a lengthy data frame. The effect on third party STAs is the same as described above.

The result of all these collisions is reduced throughput. In particular, STAs that observed the frame as corrupted will switch to the EIFS and delay their transmissions, STAs in a position to observe the frame correctly will unnecessarily update their NAV, the source STA must attempt to resend the frame, and the destination STA may be affected in several ways.

One last consequence has to do with automatic data rate scaling. A STA will adjust its transmission rate according to environment and traffic conditions. It is possible that BT interference will cause the WLAN to scale to a lower rate. This in turn lengthens the duration of each frame, which may cause more collisions and another rate lowering. The WLAN could remain at 1 Mbps indefinitely in the presence of a BT interferer [She01].

Interference without Collision:

Interference without a resulting collision occurs when the presence of a BT signal causes the CCA algorithm to determine the medium is busy. The CCA is the physical carrier sense mechanism that is used together with the virtual carrier sense mechanism

(NAV) to prevent collisions between IEEE 802.11 frames. In the previous section, it was noted that a collision with a BT signal may cause a STA to indicate a busy medium when it is not necessary. The other carrier sense may also be affected by the BT signal.

A BT signal may cause a false positive in the WLAN's CCA. A STA will only transmit if the medium has been idle for the duration of DIFS or other appropriate inter-frame space (IFS). When the medium is determined to be busy during an IFS, the STA will not transmit. Once the medium is determined to be idle, the STA will wait for the entire duration of the IFS prior to transmitting again. As a result, a busy signal that occurs late in the IFS, in effect, doubles the wait time of the STA. This is in addition to the length of time the BT signal is present within the WLAN's bandwidth. Since a frame sent by BT remains at the same frequency until complete and since the next hop may also fall in the WLAN bandwidth, the interference could be present much longer than 625 μs.

A scenario with similar consequences occurs when a BT false positive causes a busy signal during a STA's backoff period. The backoff period will be paused for the length of the interference and will only resume when the medium is idle for the duration of the DIFS again. As a result, the time it takes to begin a transmission may be substantially longer than without BT interference.

These false positive scenarios can have even more consequences depending on what type of frame they delay. The delay of a CTS frame may cause a time out at the source STA. This results in the retransmission of the RTS and a lengthening of the CW. The same is true if an ACK is delayed and a timeout occurs. This can be worse than a CTS timeout because of the longer length of data frames compared to RTS frames.

The result of these different types of interference that do not involve collisions is reduced throughput. The direct delays of BT causing a medium busy status can significantly delay transmissions, and indirect delays due to induced retransmissions can further reduce network performance.

2.2 Current Research

Many articles examine IEEE 802.11 in the presence of BT interference. A difficulty in assessing performance degradation is determining a topology where IEEE 802.11 and Bluetooth coexist. Different scenarios and different traffic loads lead to different results.

One way to study the issue is empirically. Experimental evidence is essential to motivate the need for further study. Punnoose, Tseng, and Stancil [PTS01] use two configurations, an outdoor setup, and a laboratory setup. Both assume two STAs in the WLAN and two nodes in the piconet. In the outdoor experiment the aim "was to vary the Signal-to-Interference (S/I) ratio in a controlled manner and then measure the packet loss rates directly" [PTS01]. A laptop with an IEEE 802.11b transmitter and laptop with IEEE 802.11b receiver were placed in a football stadium at distance d_S from one another. In between, two laptops with BT cards carrying audio traffic were placed at distance d_I from the WLAN receiver and two yards apart from each other. Varying d_S varies the received signal level at the 802.11b cards. Varying d_I varies the interference at the 802.11b receiver [PTS01]. Figure 2-2 shows the setup used in the outdoor experiment.

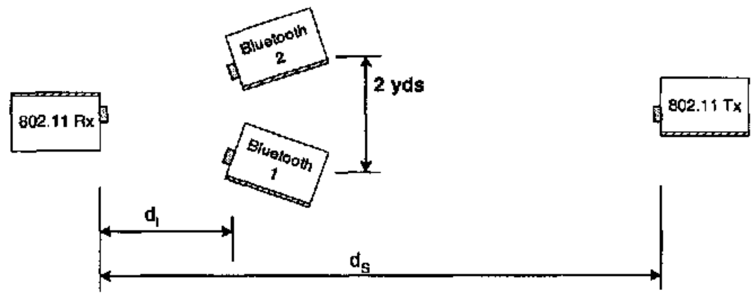

Figure 2-2. Experimental setup in [PTS01].

For the outdoor experiment, d_S was kept constant at 35 yds and d_I was varied. Smaller values of d_I resulted in greater packet loss. When the WLAN receiver is closer to the BT interference, the S/I ratio decreases and more frames were corrupted. Figure 2-3 shows the percentage of successful transmissions and Figure 2-4 shows the S/I ratio for a given a range of d_I values [PTS01].

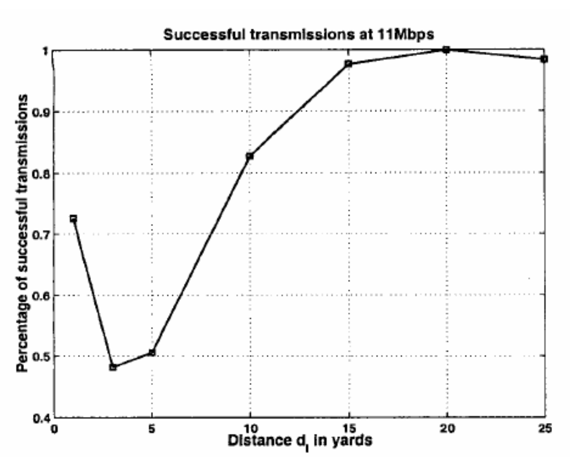

Figure 2-3. Experimental performance, d_s = 35 yards

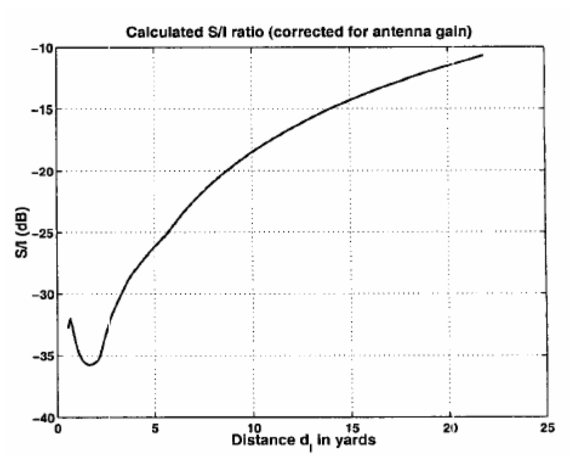

Figure 2-4. Computed S/I ratio, d_s = 35 yards

In the laboratory experiment, two IEEE 802.11b equipped laptops and two BT equipped laptops were used. Their internal antennas were disabled and external RF cables were used to connect them. This allowed the channel to be controlled by the RF components. The signal was sent through an attenuator and BT interference was added through an RF power splitter before sending it to the receiver. The BT signal passed through a variable RF attenuator to allow adjustment of the interference power. A piconet was formed between the BT nodes and audio traffic was begun. With low S/I ratios, the percent of lost 802.11 packets was 18%. Compared with the results from the outdoor experiment though, the "outdoor experiment exhibited more severe performance degradation than the laboratory measurement for similar S/I ratios" [PTS01]. The measurements associated with the outdoor signal levels were less precise, and the interference came from two BT nodes rather than just one as in the laboratory setup.

Lansford, Stephens, and Nevo [LSN01] configure a laptop with IEEE 802.11b and BT. The laptop interacts simultaneously with an 802.11b access point (AP) and another BT node. The WLAN nodes exchanged TCP/IP packets of size 1500 bytes, and the BT piconet maintained a DH5 link at 434 kbps. LT1 represents the remote WLAN AP, LT2 represents the laptop's WLAN STA, BT1 represents the laptop's BT node, and BT2 represents the remote BT node. The distance between LT2 and BT1 is fixed at the distance across the laptop, 10 cm. The distance between the laptop with LT2 and BT1 is fixed at 1 m. The variable in this experiment is the distance between LT1 and LT2; this allows the received signal strength to be varied. Figure 2-5 shows the setup.

In this setup, a STA less than 7 m or a signal strength less than –42.53 dBm suffered 25% degradation of throughput compared to a STA without BT interference. A decrease of over 50% is experienced at 30 m, -62.67 dBm point [LSN01]. Another empirical approach can be found in [HMG01].

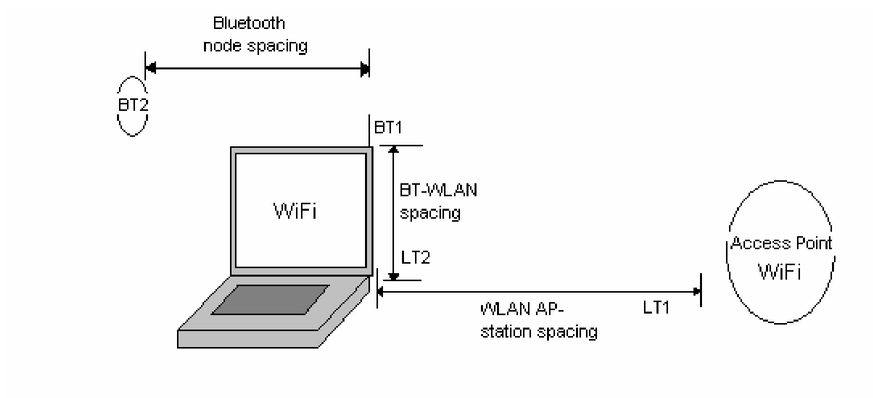

Figure 2-5. Lansford's configuration.

A different approach to network topology and traffic uses an 802.11 AP and a STA up to 20 meters from it [Zyr99]. It is assumed the average density of STAs is one every 25 sq meters. As a result, 50 STAs are associated with one AP. It is also assumed that there is one BT piconet consisting of two or more BT nodes associated with each STA. Based on the distance and signal strength of each STA to the AP, it can be determined how many piconets have the potential to interfere with each STA's transmissions [Zyr99]. For an AP at a distance of four meters, one BT interferer is within range. For an AP at a distance of ten meters, two BT interferers are within range. At a distance of 20 meters, 13 BT interferers are in range.

In the previous articles, the BT and 802.11 traffic is constant, which is very useful to determine worst-case scenarios (i.e., STA always have a packet to transmit). This, however, is not representative of a typical traffic load, which is also very important [Zyr99]. This article characterizes traffic loads over an eight-hour workday. Constant WLAN traffic is assumed, and each BT piconet pages one time per connection, transfers 15 emails a day at 10 Kbytes each, and handles ten telephone calls at one minute each.

When the BT piconet is not in one of these categories, it is assumed to be in standby mode. More can be found in [Gol01].

Although the instantaneous throughput is sometimes degraded, the change in network performance over the entire day is negligible [Zyr99]. Even the farthest WLAN STAs with the most vulnerability to interference have a clear channel 75% of the time, despite having up to 13 corrupting piconets in range. This suggests that the average case with respect to IEEE 802.11 in the presence of BT may be acceptable [Zyr99]. More analytic results can be found in [HoI01], [How01], and [KaB01].

2.3 Ziouva's Model of CSMA/CA

Bianchi developed a discrete-time Markov chain to model a WLAN STA's CSMA/CA protocol [Bia98]. This Markov chain specifically models the state of the backoff process. Each state is defined by two parameters, $b(t)$ and $s(t)$. The first, $b(t)$, is defined as "the stochastic process representing the size of the backoff window for a given time slot t" [Bia98]. This parameter can take a value in the range 0 to $2^i W - 1$, where i is the current backoff stage and $i \in (0, m)$, m is the maximum backoff stage, and W is the minimum size of the contention window. The second parameter, $s(t)$, is defined as "the stochastic process representing the backoff stage $(0, \ldots, m)$ of the station at time t" [Bia98].

The probability of a packet collision, p, is assumed to be independent of the backoff state of the STA, $s(t)$. This assumption is difficult to justify since the purpose of the protocol is to lower the probability of collisions as the backoff stage increases. However, it is reasonably valid as W and n grow larger, where n is the number of STAs in the system [Bia98]. Using that assumption, the bi-dimensional process {*s(t)*, *b(t)*} can be represented as a discrete-time Markov chain and is depicted in Figure 2-6.

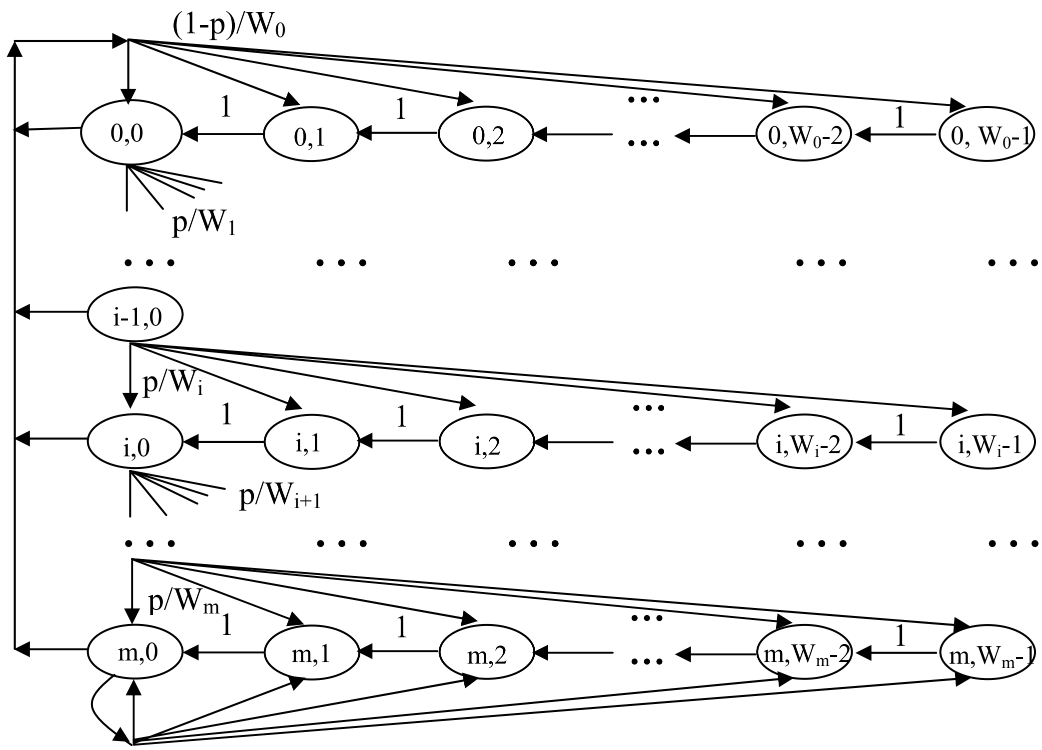

Figure 2-6. Bianchi's CSMA/CA Markov chain.

Ziouva and Antonakopoulos [ZiA02] expanded on this model of the CSMA/CA. Bianchi's model accounted for transition probabilities based on packet collisions. Ziouva added transition probabilities based on a STA's CCA. In Figure 2-6, note that $P\{i,k \mid i,k+1\} = 1$, since the backoff counter will decrement every time slot. With Ziouva's addition, $P\{i,k \mid i,k+1\} = 1 - p_b$, where p_b is the probability the STA senses the channel as busy. Now the Markov chain may transition to the same state if a busy medium is detected.

Ziouva also added one additional state, namely {-1, 0}. This models the STA's actions when the backoff counter is zero and the channel is idle for the duration of the

DIFS time. Under these circumstances, the STA will transmit its available frame without entering the backoff procedure. Figure 2-7 shows Ziouva's model, and a description of its main characteristics follows.

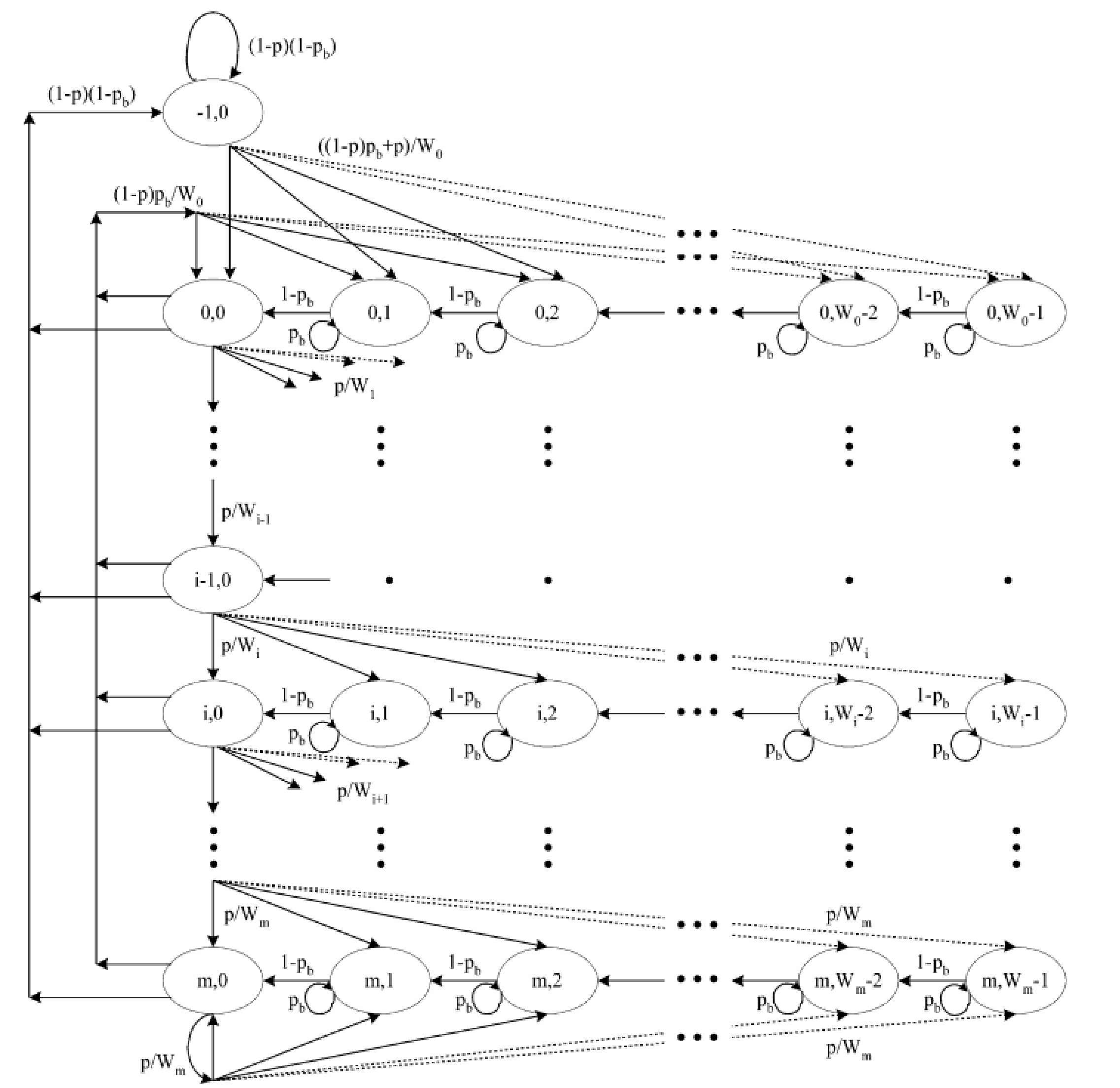

Figure 2-7. Ziouva's CSMA/CA Markov chain

It is assumed there is a network of *n* STAs contending to transmit a packet. A STA always has a packet ready for transmission. Like Bianchi, it is assumed that the probability of collision, p, and the probability of a busy channel, p_b, is independent of the backoff procedure for large W and n. The transition properties are [ZiA02]:

1. A station transmits its frame without entering the backoff procedure if it determines that its previous transmitted frame was successfully received and the channel is idle

$$P\{-1, 0 \mid -1, 0\} = (1-p)(1-p_b). \quad (2\text{-}2)$$

2. A station defers the transmission of a new frame and enters stage 0 of the backoff procedure if it has a successful transmission of its current frame and finds the channel busy or if a collision occurred

$$P\{0, k \mid -1, 0\} = \frac{(1-p)p_b + p}{W_0}, 0 \le k \le W_0 - 1. \quad (2\text{-}3)$$

3. The backoff counter freezes when a station senses that the channel is busy

$$P\{i, k \mid i, k\} = p_b,\ 1 \le k \le W_i - 1,\ 0 \le i \le m. \quad (2\text{-}4)$$

4. The backoff counter decrements when the station senses the channel idle

$$P\{i, k \mid i, k+1\} = 1 - p_b,\ 0 \le k \le W_0 - 2,\ 0 \le i \le m. \quad (2\text{-}5)$$

5. A station chooses a backoff delay from stage 0 if its current frame was transmitted successfully and it senses the channel busy when it tries to transmit a new frame

$$P\{0, k \mid i, 0\} = \frac{(1-p)p_b}{W_0}, 0 \le k \le W_0 - 1,\ 0 \le i \le m. \quad (2\text{-}6)$$

6. A station enters into the {-1, 0} state if it verifies a successful transmission and senses the channel idle

$$P\{-1, 0 \mid i, 0\} = (1-p)(1-p_b),\ 0 \le i \le m. \quad (2\text{-}7)$$

7. A station chooses a backoff delay from stage *i* after an unsuccessful transmission at stage *i* – 1

$$P\{i, k \mid i-1, 0\} = p/W_i,\ 0 \le k \le W_i - 1,\ 1 \le i \le m. \quad (2\text{-}8)$$

8. A station has reached the last stage of backoff procedure and remains in it after unsuccessful transmission

$$P\{m, k \mid m, 0\} = p/W_m,\ 0 \le k \le W_m - 1. \qquad (2\text{-}9)$$

What then is the probability that a STA is in a particular state $\{i, k\}$? Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}$ be the stationary distribution of the Markov chain. This leads to the following equations. Given a STA is in state $\{0, 0\}$, it takes i consecutive collisions to be in backoff stage i. Since the backoff counter will eventually decrement to zero, any selection of k will lead to the state $\{i, 0\}$. The probability of state $\{i, 0\}$ is

$$b_{i,0} = p^i b_{0,0},\ 0 \le i \le m - 1. \qquad (2\text{-}10)$$

To get to the maximum backoff stage from $b_{0,0}$, m or more consecutive collisions occur and the probability of state $\{m, 0\}$ is

$$b_{m,0} = \frac{p^m}{1-p} b_{0,0}. \qquad (2\text{-}11)$$

The probability of any state, $b_{i,k}$, is given by the probability of i consecutive collisions and a selection of a backoff value greater or equal to k (if a value greater than k is chosen, it will eventually reach k)

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot \frac{1}{1-p_b} b_{i,0},\quad 0 \le i \le m,\ 1 \le k \le W_i - 1. \qquad (2\text{-}12)$$

The probability of state $\{0, 0\}$ can be written in terms of state $\{-1, 0\}$, and the transitions that lead to the first backoff stage

$$b_{0,0} = \frac{p_b + p(1-p_b)}{1-p_b} b_{-1,0}. \qquad (2\text{-}13)$$

Since the sum of all state probabilities in a Markov chain must equal one,

$$b_{-1,0}+\sum_{i=0}^{m}\sum_{k=0}^{W_i-1}b_{i,k}=1. \tag{2-14}$$

Substituting (2-10) through (2-12) into (2-14) gives

$$b_{-1,0}+\frac{1}{1-p_b}\sum_{i=0}^{m-1}p^i b_{0,0}\sum_{k=0}^{W_i-1}\frac{2^iW-k}{2^{iW}}+\frac{1}{1-p_b}\cdot\frac{p^m}{1-p}b_{0,0}=1. \tag{2-15}$$

Substituting (2-13) into (2-15), and solving for $b_{-1,0}$ results in

$$b_{-1,0}=\frac{2(1-p_b)^2(1-2p)(1-p)}{\left(\begin{array}{c}2(1-p_b)^2(1-2p)(1-p)+\\(p_b+p(1-p_b))(1-2p)(W+1)+pW(p_b+p(1-p_b))(1-(2p)^m)\end{array}\right)}. \tag{2-16}$$

Once $b_{-1,0}$ is found, the probability of any state can be found. Equation (2-16) is in terms of p_b, p, W, and m. W and m are characteristics of the protocol and are known for a given implementation. The probabilities p and p_b are not known, but can be derived. Let τ be the probability that a STA transmits in a given time slot, and noting a STA must be in a state {i, 0}, τ can be represented by [ZiA02]

$$\tau=\sum_{i=-1}^{m}b_{i,0}=b_{-1,0}+\sum_{i=0}^{m-1}b_{i,0}+b_{m,0}. \tag{2-17}$$

To get τ in terms of p, and p_b, substitute (2-10) through (2-13) into (2-17) and the result is

$$\tau=\frac{2(1-p_b)(1-2p)}{2(1-p_b)^2(1-2p)(1-p)+(p_b+p(1-p_b))(1-2p)(W+1)+pW(p_b+p(1-p_b))(1-(2p)^m)}. \tag{2-18}$$

Now that τ is in terms of p and p_b, two other relations on τ are important to note. The probability of collision is the probability of multiple STAs transmitting in the same time slot. Since τ is the probability of transmission, p is

$$p=1-(1-\tau)^{n-1}, \tag{2-19}$$

where n is the number of STAs. The probability of that the channel is busy is the probability that at least one STA transmits during that time slot and is

$$p_b = 1 - (1 - \tau)^n . \tag{2-20}$$

By substituting (2-19) and (2-20) into (2-18), p and p_b are eliminated and only τ is left. After solving for τ, p and p_b can be found and therefore so can the stationary distribution.

Ziouva goes further to determine the throughput of the system. Assuming that each transmission is a renewal process, the throughput can be determined by examining a single renewal period. The throughput, S, can be expressed as

$$S = \frac{E[timeForSuccessfulTransmission]}{E[lengthBetweenTwoTransmissions]} \text{ or}$$

$$S = \frac{P_s E[P]}{E[\psi] + P_s T_s + (1 - P_s) T_c} \tag{2-21}$$

where P_s is the probability of a successful transmission, $E[P]$ is the average payload length, $E[\psi]$ is the expected number of slots before a transmission due to backoff, T_s is the average time the channel is captured during a successful transmission, and T_c is the average time the channel is captured during an unsuccessful transmission.

Ziouva assumes $E[P]$ is a constant, but it can be any stochastic distribution. T_s and T_c are determined by the type of channel access method used, and are measured in time slots. For the simple ACK scheme,

$$T_s = H + P + \delta + SIFS + ACK + \delta + DIFS, \text{ and} \tag{2-22}$$

$$T_c = H + P + \delta + DIFS. \tag{2-23}$$

For the RTS/CTS scheme,

$$T_s = RTS + \delta + SIFS + CTS + \delta + SIFS + H + P + \delta + SIFS + ACK + \delta + DIFS \tag{2-24}$$

and

$$T_c = RTS + \delta + DIFS. \tag{2-25}$$

H is defined as PHY_{hdr} + MAC_{hdr} and δ is the propagation delay.

The value, P_s, is the probability that only one station transmits in a given slot, so

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{2-26}$$

$E[\psi]$ is the mean number of consecutive idle slots and is defined by

$$E[\psi] = \frac{1}{p_b} - 1. \tag{2-27}$$

Given this information, the system throughput, *S*, can be put in terms of the number of WLAN STAs, *n*, the minimum size of the contention window, *W*, and the maximum number of backoff stages, *m+1*. Ziouva uses these formulas to graph different throughputs for different sets of *W*, *m* and *n* using the parameters shown in Table 2-1.

Table 2-1. Ziouva's System Parameters

System Parameters	
Payload Constant E[P]:	1023 bytes
MAC header:	34 bytes
PHY header:	16 bytes
ACK:	14 bytes + PHY header
RTS:	20 bytes + PHY header
CTS:	14 bytes + PHY header
SIFS:	10 µs
DIFS:	50 µs
Propagation delay:	1 µs
Slot time:	20 µs
Channel bit rates:	1, 5.5, and 11 Mbps

Figure 2-8 shows the system throughput as *W* and *n* vary. In each case, the RTS/CTS form of the CSMA/CA protocol results in higher throughput than the ACK scheme. The throughput of the ACK CSMA/CA protocol decreases as the number of

STAs increase, while the throughput of the RTS/CTS version stays relatively constant. Figure 2-9 shows the system throughput as *m* and *n* vary. The result is the same. The RTS/CTS protocol produces a higher network throughput. Figure 2-10 shows throughput as the bit rate and *n* vary. Although channel bit rate affects throughput, the same trend of constant throughput for the RTS/CTS scheme, and decreasing throughput for the ACK scheme as *n* increases is present.

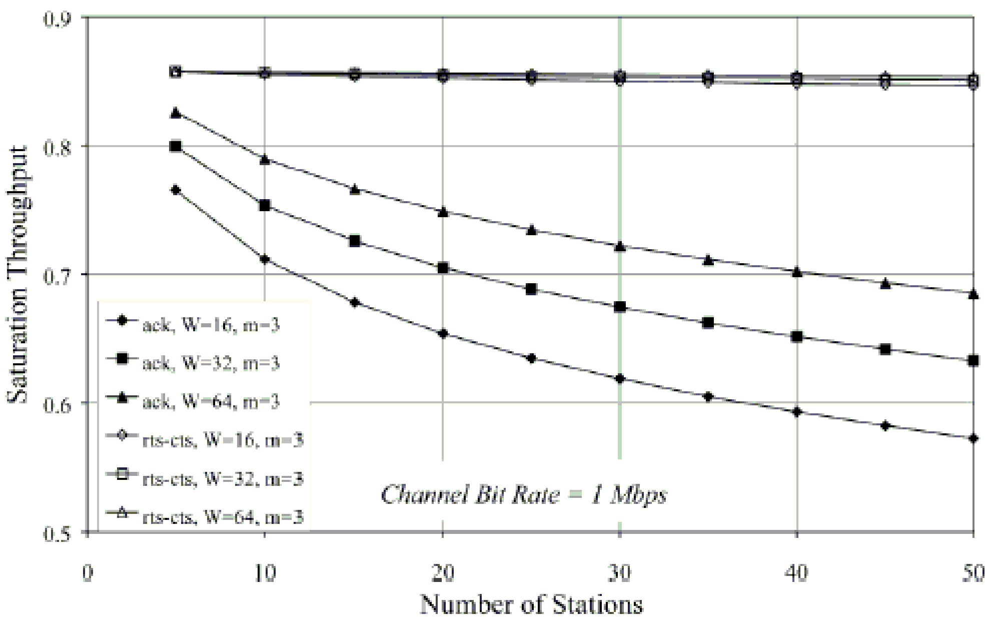

Figure 2-8. Saturation throughput for various initial contention window sizes

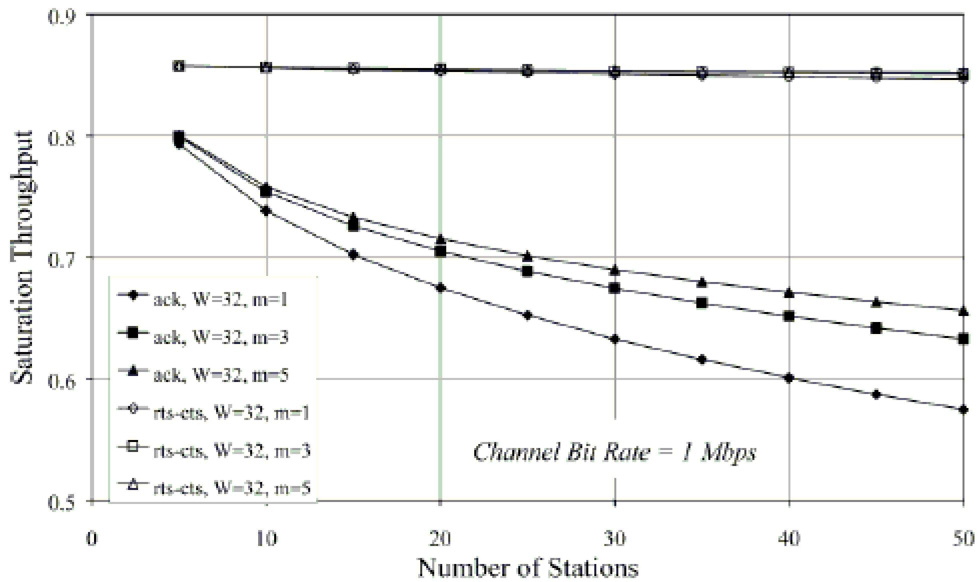

Figure 2-9. Saturation throughput for different numbers of backoff stages

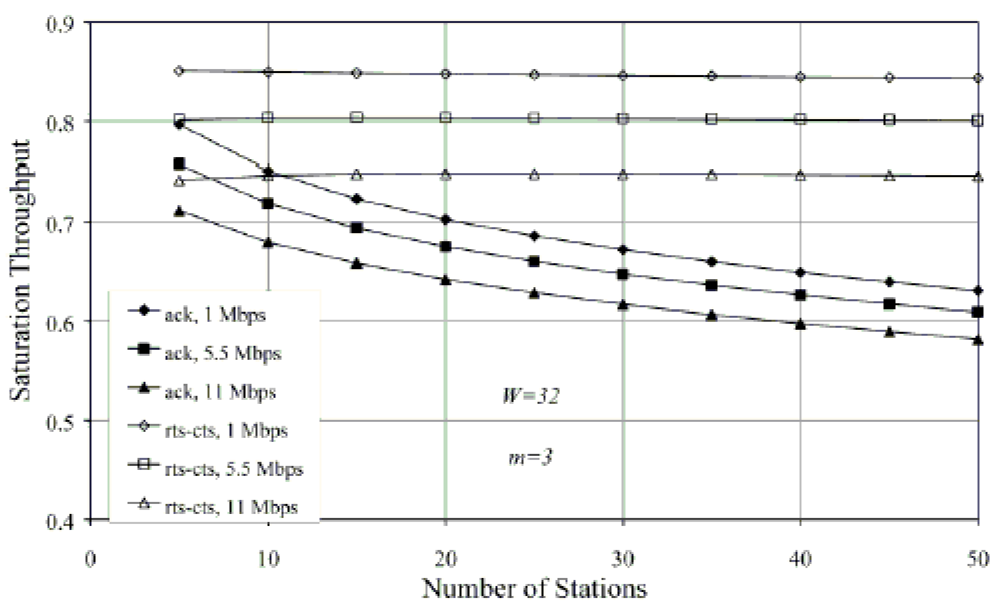

Figure 2-10. Saturation throughput for various channel bit rates

2.4 Summary

This chapter presents an overview of the IEEE 802.11 and BT protocols. It discusses coexistence issues that arise when WLAN and BT piconets are co-located.

Analysis demonstrates that a BT signal that hops into the bandwidth used by a WLAN can cause interference whether or not an actual collision takes place. Current research is summarized to give an understanding of the subject area. Research by Ziouva and Antonakopoulos is presented as a useful analytic model of the CSMA/CA protocol.

III. Methodology

3.1 Background

In Chapter II, current research into the effects of a BT signal on the throughput of an IEEE 802.11 network is presented. These studies show that the effects differ with different network topologies, but establish that issues concerning these technologies' coexistence are valid and should be explored further. Given the value of mobility in WLANs and the convenience of WPANs, co-location of IEEE 802.11 and BT will become common and the implications must be understood.

To further explore the coexistence issues, it is valuable to consider how a BT signal would affect different aspects of IEEE 802.11's transmission protocol. These interference possibilities are described in Section 2.1.3 and include interference scenarios such as delayed transmissions due to a node's CCA algorithm, and retransmissions due to actual packet collisions. Current research tends not to focus on the effects of these individual types of interference, but on the overall outcome of their combined effects. To gain a more complete understanding of the interference impact, the contribution due to each individual type of interference should be characterized.

The focus of this research is to explore the effects of a BT interferer on network performance with respect to delayed transmissions. Specifically, it will show how throughput and delay are affected when a BT signal causes the WLAN's CCA to incorrectly determine the transmission medium to be in use.

3.2 Problem Definition

3.2.1 Goals and Hypothesis

The goal of this thesis is to determine the effect a BT interferer has on the performance of a WLAN with respect to the issue in the CCA. At first glance, one might easily assume that the reduced throughput reported in current research is due solely to retransmissions caused by collisions between WLAN and BT packets. Granted, collisions are a major factor in reducing the overall throughput, but they don't account for everything. It is important not to overlook the contributions of other aspects of the interaction. An IEEE 802.11 STA's CCA will sense the medium in an attempt to detect whether or not another signal is present and currently transmitting. If the CCA determines the medium to be busy, the CSMA/CA protocol will delay transmission of its own frame. The presence of a BT signal may create a "false positive" in the CCA. This will cause the CCA to determine the medium is busy when a STA actually can transmit. The result is an unnecessary transmission delay and reduced throughput.

It is expected that the reduced throughput due to this interference scenario will be substantial. Every time the CCA determines the medium to busy, the next transmission is delayed and a transmission opportunity is missed. It may also be that the effect of delayed transmissions is equal or greater than the effect of collisions. Given that IEEE 802.11 uses DSSS, it has inherent interference suppression capabilities [Skl01]. The presumption is that these are enough to allow reliable communication in spite of the presence of a BT interferer.

3.2.2 Approach

Ziouva and Antonakopoulos, developed an analytic model of an IEEE 802.11 STA's CSMA/CA protocol (see Section 2.3). Using a discrete-time Markov chain, a model of the state of the transmission and backoff process is constructed. Figure 3-1 shows their model [ZiA02].

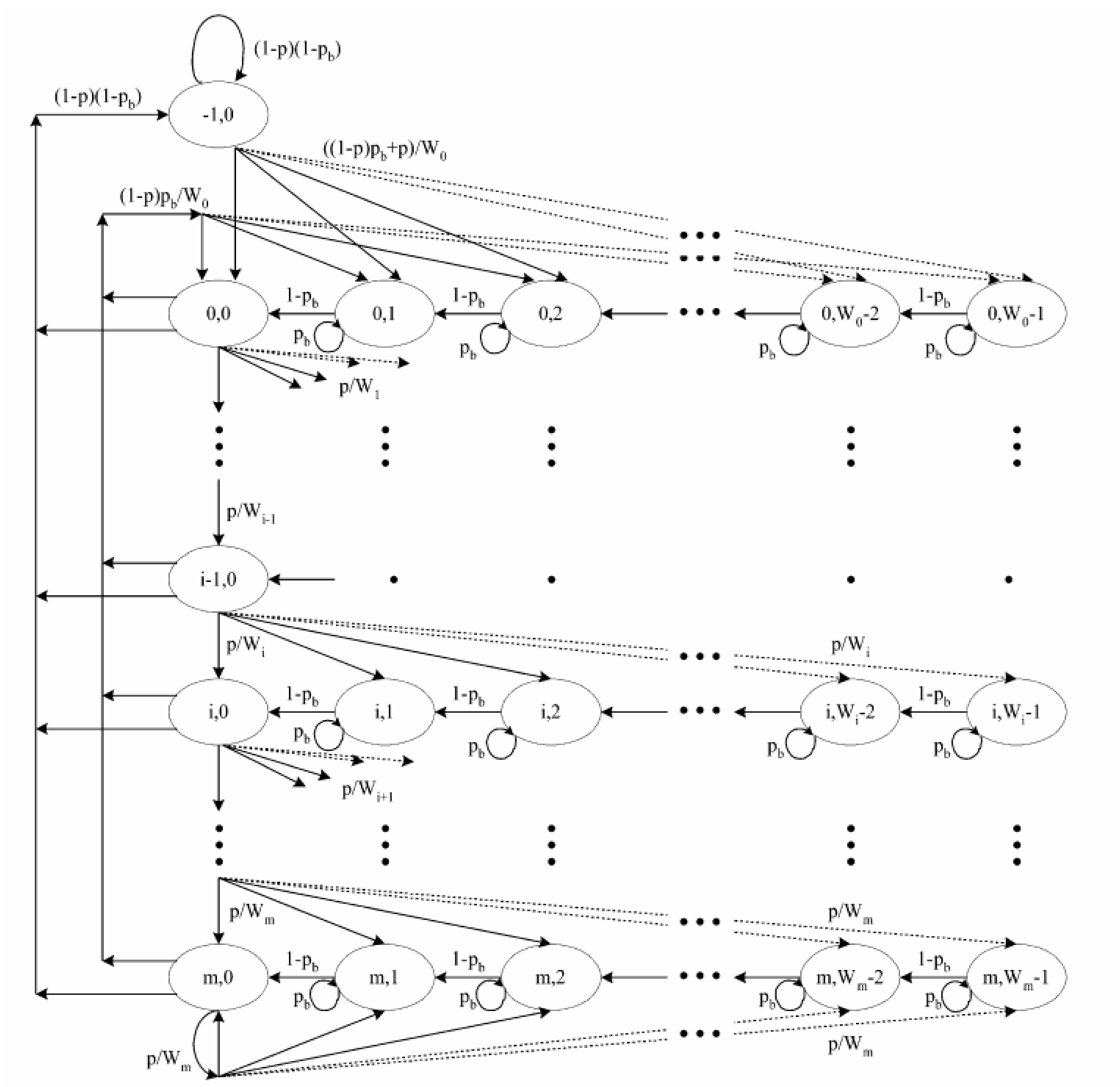

Figure 3-1. Ziouva's CSMA/CA Markov Chain

Based on an analysis of this model, an equation for the network throughput based on factors such as contention window size, number of backoff stages, and channel bit rates is developed. To meet the goals and test the hypothesis stated above, Ziouva's model will be enhanced to account for state transitions based on BT-induced false positives in the CCA. In the original model, transitions based on the probability of WLAN packet collisions and the probability of a WLAN induced busy channels are included. Transitions based on the probability of a BT-induced busy channel will be incorporated to investigate how BT false positives will affect network throughput. Using this enhanced model, expressions for throughput and delay are derived to determine how false positives in the CCA affect the performance of a WLAN.

3.3 System Boundaries

The focus of this thesis is to determine the effect BT false positives in the CCA have on the throughput of a WLAN network. The scenario includes a number of WLAN STAs that form a network where BT interference is an issue. Therefore, the system under test is a WLAN network with n stations susceptible to BT interference. Within this system, the component under test is the backoff procedure of a WLAN STA's CSMA/CA protocol.

There are limits to the scope of this study. One simplifying assumption in Ziouva's article is that the probability of a packet collision is independent of the backoff state of the STA. This assumption is difficult to justify since it is the purpose of the protocol to lower the probability of collision as the backoff stage increases. It becomes more valid, however, as the size of the contention window and the number of STAs in the network grows [Bia98]. This limits the scope of the model to scenarios where the conditions for making this assumption of independence are reasonable.

Another assumption is that no BT signal will be able to corrupt a WLAN packet in transmission. Basically, the probability of collision due to BT interference is zero. The DSSS interference suppression capability is assumed to be sufficient to prevent a BT signal from corrupting a WLAN frame. It is also assumed that no WLAN signal will interfere with the BT signals. This assumption ensures that the probability of BT transmission is independent of the WLAN network and allows the probability of BT interference to remain constant over time. Since BT uses FHSS, its interference suppression capability is assumed to be sufficient to prevent a WLAN signal from corrupting a BT frame. The scope of this thesis is limited to scenarios where this assumption is valid.

One final assumption is that each WLAN STA always has a packet ready for transmission. As soon as one is successfully transmitted, there is always another to send. This limits the scope of the study to situations where the traffic volume is high.

3.4 System Services

This system provides communication between the nodes of a WLAN network. The basic service offered is the transmission of data in packet form over a wireless medium. There are four outcomes given an attempted transmission. One possibility is success; the frame is sent and no collision occurs. Another possibility is a collision; the frame is sent but it collides with a different STA's frame. Another possibility is a delay due to a WLAN induced busy channel. This results in a backoff and another attempt at a later time. The last possible outcome is a delay due to a BT false positive in the CCA. This also results in a backoff and another transmission attempt at a later time.

3.5 Performance Metrics

A simplifying assumption in Ziouva's model is that no frame is discarded, and that a STA will stay at the maximum backoff stage until its current frame is successfully transmitted. As a result, there is no limit to the number of times a STA will attempt retransmission and no data is lost. These retransmissions, however, reduce effective throughput and increase mean delay.

Effective throughput and mean delay are the metrics considered in this research. When a BT signal causes the CSMA/CA protocol to back off before transmission, the frame delay increases and the mean delay of the system increases. This unnecessary backoff iteration also prevents a potentially successful transmission and reduces throughput over time. Consequently, effective throughput and mean delay are the essential metrics to consider when analyzing the effects of BT interference.

3.6 Parameters

3.6.1 System

The system parameter values in Table 3-1 are chosen to mirror the analysis in [ZiA02] which will be used to validate the developed model. The only exceptions to this are the values for the minimum contention window size and number of backoff stages, whose values are taken from Table 59 in the IEEE 802.11 standard [P802.11].

Table 3-1. System Parameters

System Parameters	
Payload Constant E[P]:	1023 bytes
MAC header:	34 bytes
PHY header:	16 bytes
ACK:	14 bytes + PHY header
RTS:	20 bytes + PHY header
CTS:	14 bytes + PHY header
SIFS:	10 μs
DIFS:	50 μs
Propagation delay:	1 μs
Slot time:	20 μs
Channel bit rates:	1, 2, 5.5, and 11 Mbps
Minimum *CW*:	32 slots
Number of backoff stages:	5 stages

3.6.2 Workload

Recall that IEEE 802.11 STAs always have a packet to transmit. BT STAs are modeled based on the probability of BT false positive on CCA, and range from 0.0 to 1.0.

The key to the analysis of interference and reduced throughput is the probability of a false positive in the CCA. The results of all the experiments will be highly dependent on this value.

3.7 Factors

Table 3-2 shows the factors to be varied. The channel bit rate levels are selected

Table 3-2. Factors Varied

Factors	
Channel bit rates:	1, 2, 5.5, 11 Mbps
Probability of BT false positive on CCA:	0.0 to 1.0

to be analogous to those presented in [ZiA02]. The probability of a BT false positive is added and the level will be varied from 0.0 to 1.0 in increments of 0.25. This range is utilized because it is not clear what particular values might be. It is expected that the levels equal or greater than 0.25 will be most significant. This is because it is expected that a single BT device's hop frequency will overlap a WLAN's frequency spectrum 25% of the time [ChR00]. When more than one BT interferer is present, this percentage will only rise. The extreme levels of 0.0 and 1.0 will be helpful in validating the model.

3.8 Evaluation Technique

To evaluate the system, two evaluation techniques are employed. The first is an analytical model of the CSMA/CA protocol. This is an extension of [ZiA02]. It is altered to account for the possibility of BT interference in the form of delayed transmissions. An analytical study is an appropriate evaluation technique because of the nature of the goals. Since the important aspect of the system is the BT effect from false positives in the CCA, it's not easily measured from existing systems. Given an experimental setup of WLAN STAs and BT interferers, reduced throughput can be easily obtained. However, the individual contributions from BT collision interference and BT induced delayed transmissions would be more difficult.

The second evaluation technique to be employed is a simulation. This simulation models the CSMA/CA and the impact of BT induced false positives on throughput. This is also an appropriate evaluation technique for the same reason as above. The individual contributions of different interference types may be indistinguishable given only the total reduction in throughput.

The purpose of using two evaluation techniques is to verify the validity of the models. Given the same parameters, the analytic and simulation models should perform similarly. The reduction in throughput given by the simulation over multiple repetitions should approach the value given by the analytic model. In addition, the extreme value of 0.0 for the probability of BT false positive should reduce the analytic model to the one presented by Ziouva. Given the factor levels, the analytic model should have the same results as the original. If the previous assertions hold true, a measure of validity is obtained.

3.9 Experimental Design

There are two factors in this experiment: channel bit rate and probability of BT induced busy medium. The first, bit rate, has four levels: 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps. The second can take on a range of values from 0.0 to 1.0. Five levels are chosen for the initial granularity of the BT probabilities. For the first phase of the experiment, the probability of BT interference begins at 0%, and is then increased to 25%, 50%, 75%, and finally 100%. The 100% level is used for verification and validation of the model and only needs to be run a single time to demonstrate that throughput is zero. The 0% level is also be used for verification and validation, but will need to be run with each of the possible bit rates. It is then compared to the values presented by Ziouva for accuracy and consistency.

Each of the three remaining levels is run with each bit rate. The result is four probability levels with four bit rates each, and one probability level with one bit rate for a total of 17 runs without replication. If the model behaves correctly, the variation between replications should be very small for a given bit rate and interference probability pair. Three replications is likely sufficient to determine a confidence interval indicating a statistical difference between the experimental mean and the base case of Ziouva's model without BT interference. Since the case where the probability of BT interference is 0% doesn't need to be repeated, there will be a total of 37 experiments required.

For the second phase of the experiment, a finer granularity of BT probabilities is introduced. By examining the range of outputs in the first phase, interest points are explored in greater detail. It is expected that throughput quickly approachs zero as the BT probability grows, and there may not be a statistical difference between the probability levels of 75% and 99%. If this is the case, it is more valuable to explore probabilities in the 25% to 65% range. By focusing on these interest areas, a better understanding of the effect of BT interference is determined.

After completing the trials, experimental error is measured against the analytic model with the same factor levels. The total sum of squares (SST) value is used to gain an estimate of variability of the response and attribute variation to each of the factors.

3.10 Analyze and Interpret Results

All data gathered from the experiments is used to calculate confidence intervals that are compared to the baseline. When considering a confidence interval based on a given bit rate and BT interference probability, it is compared to the corresponding value produced by the analytical model. It is expected that the response predicted by the analytical model falls within the confidence interval of the simulation model. Next, the confidence interval is compared with the predicted response from the original model that doesn't take into account BT interference. It is expected that the responses are statistically different from each other, and that the experimental model shows a significant reduction in throughput due to interference.

Using allocation of variation and corresponding techniques, the variation due to each factor is computed. Through this, the interaction between the factors is also described. A final analysis determines which variables and interactions contribute the most variation to the results.

3.11 Summary

The methodology for completing this thesis is outlined. Based on the goal to determine the impact of a BT interferer on the CCA, a procedure is proposed to guide the research and experimentation. This guide provides an approach to achieving the goals, and defines the system boundaries as a WLAN network with BT interferer. It also describes the system services and relevant performance metrics about the system.

Based on those established baselines, the system and workload parameters are chosen to describe the system in greater detail. From those parameters, specific factors and workload levels are selected to study, namely channel bit rate and BT interference probability. With this, the evaluation techniques are chosen to be an analytical model and a simulation model.

After selecting the amount and types of experiments to run, an analysis technique is put in place to interpret the significance of the results. This chapter presents the approach of the thesis and offers a guide to interpret the results in a meaningful way.

IV. Results and Analysis

4.1 Interference Model

4.1.1 Tau Derivation

Consistent with Ziouva's model, *b(t)* is defined as a stochastic process representing the backoff counter value for given time slot *t*. Parameter *b(t)* takes on values in the range $[0, 2^i W_0 - 1]$, where *i* is the current backoff stage, $0 \le i \le m$, *m* is the maximum backoff stage, and W_0 is the minimum contention window size. The second parameter, *s(t)*, is defined as the stochastic process representing backoff stage *i* at time *t* [ZiA02]. The bi-dimensional process {*s(t), b(t)*} is a discrete-time Markov chain with state transition diagram given in Figure 4-1. In this model, p_{wlan} is the probability that another WLAN STA is transmitting, and p_{busy} is the probability that the CCA algorithm determines the medium is busy due to the presence of another WLAN STA's transmission and/or the presence of a BT signal. In this model, $p_{busy} = p_{wlan} \vee p_{bt}$ or $p_{busy} = p_{wlan} + p_{bt} - p_{wlan} \cdot p_{bt}$ where p_{bt} is the probability that a BT signal is present.

The Markov model of Figure 4-1 assumes that the probability other WLAN STAs transmit, p_{wlan}, is independent of those nodes' backoff states, *s(t)*, over a given time period. This assumption is difficult to justify since the primary purpose of the protocol is to lower p_{wlan} as each STA's backoff stage gets higher. However, it is valid as *W* and the number of STAs in the system, *n*, becomes larger [Bia98].

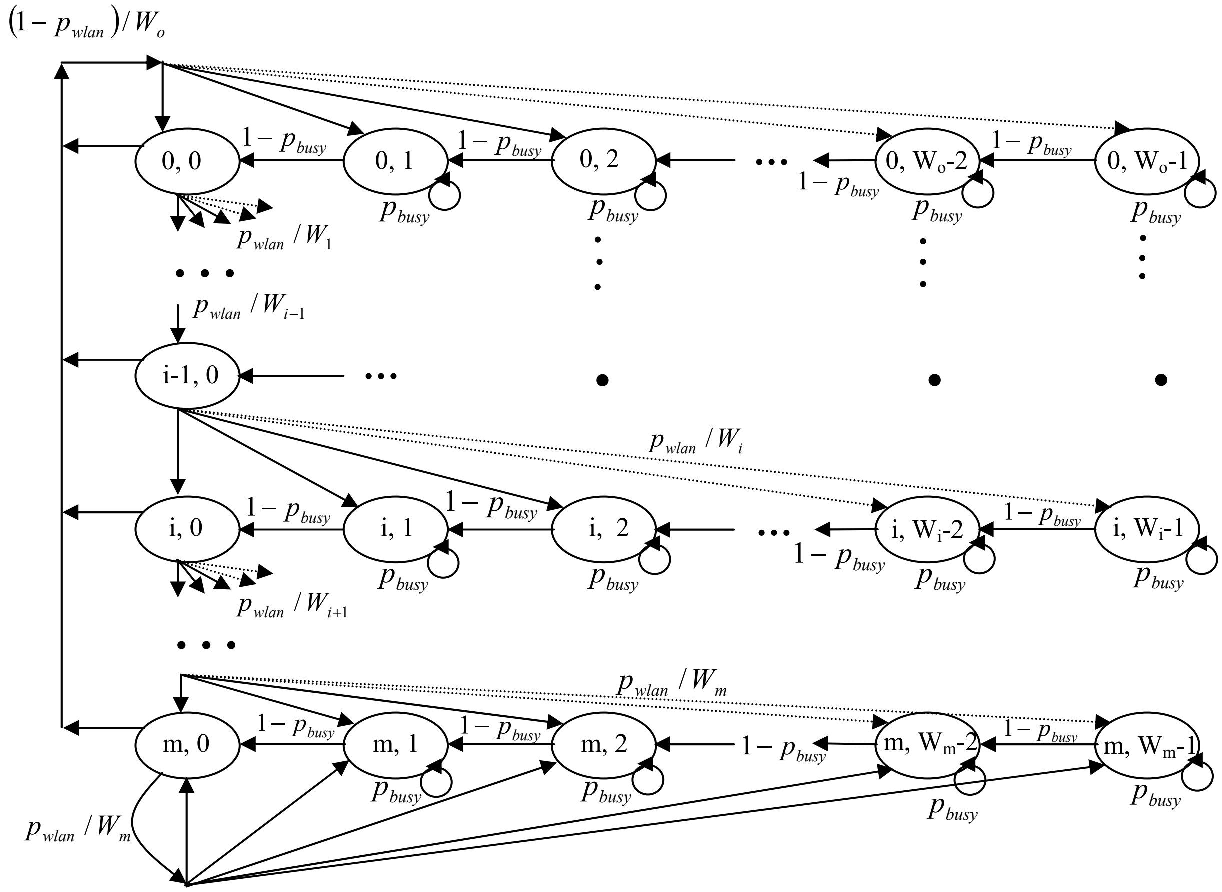

Figure 4-1. Markov chain model for a STA's CSMA/CA protocol.

To isolate the effects of a BT false positive from the effects of collisions, it is assumed that no BT signal can corrupt a WLAN packet in transmission. Basically, the probability of interference due to collisions with BT transmissions is assumed to be negligible. The inherent interference suppression capability of WLAN STA's DSSS modulation is assumed sufficient to prevent a BT signal from corrupting a WLAN frame [Skl01]. Likewise, it is assumed that no WLAN signal excessively interferes with BT signals. This assumption ensures that the probability of BT transmission is independent of the WLAN network and allows the probability of BT interference to remain constant over time. Since BT uses FHSS modulation, its inherent interference suppression capability is assumed sufficient to prevent a WLAN signal from corrupting a BT frame [Skl01]. One final assumption, the WLAN STA is transmitting under saturation conditions. That is, once a frame is successfully sent, there is always another in the queue awaiting transmission.

The {-1, 0} state presented in [ZiA02] is not used here since each transmission must be separated by at least one backoff interval [P802.11]. A STA in a $\{-1, 0\}$ state under saturation conditions as defined in [ZiA02] will continue to transmit and occupy the medium, starving all other STA's. Other STAs will suspend their counters with a backoff value greater than zero, will never decrement that value, and therefore will never transmit.

The resulting transition probabilities of the Markov chain are as follows [ZiA02]:

1. Whenever a WLAN and/or BT signal is present, the backoff counter is suspended

$$P\{i,k \mid i,k\} = p_{wlan} + p_{bt} - p_{wlan} \cdot p_{bt},\ 1 \le k \le W_i - 1,\ 0 \le i \le m. \quad (4\text{-}1)$$

2. When neither a WLAN nor a BT signal are present, the backoff counter decrements

$$P\{i,k \mid i,k+1\} = (1 - p_{wlan}) \cdot (1 - p_{bt}),\ 0 \le k \le W_i - 2,\ 0 \le i \le m. \quad (4\text{-}2)$$

3. If there is no other WLAN signal present during a transmission, i.e., no collision with the current frame transmission, stage 0 of the backoff procedure is entered

$$P\{0,k \mid i,0\} = \frac{(1 - p_{wlan})}{W_o},\ 0 \le k \le W_o - 1,\ 0 \le i \le m. \quad (4\text{-}3)$$

4. The STA proceeds to the next backoff delay stage if its current frame collides with another WLAN signal

$$P\{i,k \mid i-1,0\} = \frac{p_{wlan}}{W_i},\ 0 \le k \le W_i - 1,\ 1 \le i \le m. \qquad (4\text{-}4)$$

5. When in the highest backoff stage, any collision causes the STA to remain in that stage

$$P\{m,k \mid m,0\} = \frac{p_{wlan}}{W_m},\ 0 \le k \le W_m - 1. \qquad (4\text{-}5)$$

The probability a STA is in state $\{i, k\}$ can be calculated directly [ZiA02]. Let $b_{i,k} = \lim_{t\to\infty} P\{s(t)=i, b(t)=k\}$ for $0 \le i \le m$, and $0 \le k \le W_i - 1$, then

$$b_{i,0} = p_{wlan}^{i} b_{0,0},\ 0 \le i \le m-1, \qquad (4\text{-}6)$$

$$b_{m,0} = \frac{p_{wlan}^{m}}{1-p_{wlan}} \cdot b_{0,0}, \qquad (4\text{-}7)$$

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot \frac{1}{(1-p_{wlan})\cdot(1-p_{bt})} \cdot b_{i,0}, \text{ and} \qquad (4\text{-}8)$$

$$b_{0,0} = \frac{2\cdot(1-2p_{wlan})\cdot(1-p_{wlan})^2\cdot(1-p_{bt})}{\left(\begin{array}{l} W_0\cdot(1-p_{wlan})\cdot\left(1-(2p_{wlan})^m\right) - (1-2p_{wlan})\cdot\left(1-p_{wlan}^m\right) \\ +\,2(1-p_{wlan})\cdot(1-2p_{wlan})\cdot(1-p_{bt}) + (1-2p_{wlan})\cdot\left((2p_{wlan})^m W_0 - p_{wlan}^m\right)\end{array}\right)}. \qquad (4\text{-}9)$$

The previous analysis produces steady state probabilities based on the values of W_0, m, p_{wlan}, and p_{bt}. Of these, only p_{wlan} is unknown, but calculable. Consistent with [ZiA02], let τ be the probability that a STA transmits during a given time slot. Since the STA must be in state $b_{i,0}$ to transmit,

$$\tau = \sum_{i=0}^{m} b_{i,0} = \sum_{i=0}^{m-1} b_{i,0} + b_{m,0}. \qquad (4\text{-}10)$$

Using (4-6), (4-7), and (4-9) into (4.10), τ can be expressed as

$$\tau = \frac{2\left(1-2p_{wlan}\right)\cdot\left(1-p_{wlan}\right)\cdot\left(1-p_{bt}\right)}{\begin{pmatrix} W_0\cdot\left(1-p_{wlan}\right)\cdot\left(1-\left(2p_{wlan}\right)^m\right)-\left(1-2p_{wlan}\right)\cdot\left(1-p_{wlan}^m\right) \\ +2\left(1-p_{wlan}\right)\cdot\left(1-2p_{wlan}\right)\cdot\left(1-p_{bt}\right)+\left(1-2p_{wlan}\right)\cdot\left(\left(2p_{wlan}\right)^m W_0-p_{wlan}^m\right)\end{pmatrix}}. \tag{4-11}$$

Thus there is a relationship between τ and p_{wlan}. Given n WLAN STAs in the network, p_{wlan} is the probability that one or more of the remaining $(n-1)$ STAs are transmitting. From the point of view of a single STA, the probability p_{wlan} can be expressed as

$$p_{wlan}=1-(1-\tau)^{n-1}. \tag{4-12}$$

The probability that a STA transmits, τ, can now be expressed as a function of known parameters W_0, m, n, and p_{bt}. This expression is derived by substituting (4-12) into (4-11). Though it is difficult to solve algebraically for τ, it is easy to solve numerically.

4.1.2 Throughput Derivation

As noted in [ZiA02], throughput is calculated through analysis of a single renewal interval between two consecutive transmissions. Throughput, S, is the expected time used for successful transmission divided by the expected length between transmissions. S is defined as

$$S = \frac{E[\textit{time used for successful transmission}]}{E[\textit{length between transmissions}]}, \text{ or}$$

$$S = \frac{P_s \cdot E[P]}{E[\psi_{global}] + P_s \cdot T_s + (1-P_s)\cdot T_c} \tag{4-13}$$

where P_s is the probability a transmission is successful, $E[P]$ is the expected payload measured in slots, $E[\psi_{global}]$ is the expected number of slots before a WLAN transmission, T_s is the time the medium is occupied during a successful transmission, and T_c is the time the medium is occupied during an unsuccessful transmission.

To determine P_s, it is necessary to calculate the probability that only one of *n* STAs transmit, given that at least one STA attempts [ZiA02]. This is a function of τ and *n*, and is expressed as

$$P_s = \frac{n \cdot \tau \cdot (1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{4-14}$$

To determine $E[P]$ in slots, the time is takes to transmit the packet is divided by the duration of a slot. Noting that a slot duration is 20 μs, $E[P]$ can be determined for a given channel bit rate. Transmission overhead information is not included in $E[P]$. Although any payload distribution can be used, the payload is assumed to be constant at 1,024 bits, so for each bit rate,

$$\text{1 Mbps: } E[P] = 51.15 \text{ slots,} \tag{4-15}$$

$$\text{2 Mbps: } E[P] = 25.575 \text{ slots,} \tag{4-16}$$

$$\text{5.5 Mbps: } E[P] = 9.3 \text{ slots,} \tag{4-17}$$

$$\text{11 Mbps: } E[P] = 4.65 \text{ slots.} \tag{4-18}$$

The global view of the number of consecutive idle slots before a transmission, $E[\psi_{global}]$, is a function of τ and *n*, and is expressed as

$$E[\psi_{global}] = \frac{1}{1-(1-\tau)^n} - 1. \tag{4-19}$$

The time the channel is occupied during a successful transmission, T_s, is the sum of transmission overhead and payload, specifically,

$$T_s = H + E[P] + \delta + SIFS + ACK + \delta + DIFS \qquad (4\text{-}20)$$

where H is PHY_{hdr} + MAC_{hdr} and δ is the propagation delay. PHY_{hdr} = 16 bytes and MAC_{hdr} = 34 bytes, so H = 20.05 slots. ACK = 14 bytes + PHY_{hdr}, so ACK = 12 slots. $SIFS$ = 0.5 slots, $DIFS$ = 2.5 slots, and it is assumed that $\delta = 0.05$ slots.

The time the channel is occupied during an unsuccessful transmission, T_c, is expressed as

$$T_c = H + P + \delta + EIFS \qquad (4\text{-}21)$$

where $EIFS$ = 24.6 slots.

Inserting calculated values from (4-14) through (4-21) into (4-13), results in the normalized throughput of the network.

4.1.3 Delay Derivation

Following [ZiA02], expected delay is measured from the time the previous frame is successfully transmitted to the time the current frame is successfully transmitted. During a renewal interval, a packet experiences some number of collisions, $E[N_c]$, and backoff counter suspensions before successful reception. For each collision, the unsuccessful transmission time, T_c, and the expected backoff interval before the failed transmission, $E[BD]$, add to the delay. When the frame is successfully received, the final backoff interval and successful transmission time, T_s, also add to the total delay. Therefore, expected delay is

$$E[D] = E[N_c](E[BD] + T_c) + (E[BD] + T_s)\,. \tag{4-22}$$

The expected number of collisions, $E[N_c]$, is a function of P_s as defined in (4-14), namely,

$$E[N_c] = \frac{1}{P_s} - 1\,. \tag{4-23}$$

The expected backoff delay, $E[BD]$, consists of the time originally selected by the CSMA/CA protocol via the backoff counter, plus any counter suspensions induced by BT false positives and other WLAN transmissions. The expected backoff time selected by the CSMA/CA protocol without taking into account pauses is represented by $E[X]$. In a given interval, a STA's transmissions will collide some number of times before successful reception. Given the probability that *i* collisions occur and the STA reaches backoff stage *i*, the expected backoff time is the average value selected at that stage plus the average value selected during all the preceding stages that lead up to *i*. Recalling from Figure 4-1 and (4-4), the probability of collision is p_{wlan}, $E[X]$ is

$$E[X] = \sum_{i=0}^{m}\left(p_{wlan}^{i} \cdot (1 - p_{wlan}) \cdot \sum_{j=0}^{i} \sum_{k=0}^{W_j - 1} \frac{k}{W_j} \right)$$

$$E[X] = (1 - p_{wlan}) \cdot \begin{bmatrix} \dfrac{2W_0 \cdot (1 - (2p_{wlan})^{m+1})}{(1 - 2p_{wlan})} - \dfrac{(W_0 + 1) \cdot (1 - p_{wlan}^{m+1})}{(1 - p_{wlan})} \\ - \dfrac{p_{wlan}(1 - p_{wlan}^{m} - mp_{wlan}^{m} + mp_{wlan}^{m+1})}{(p_{wlan} - 1)^2} \end{bmatrix}. \tag{4-24}$$

$E[X]$ represents the expected backoff time before BT interference, BT delay is accounted for next. Let $E[\psi_{bt}]$ represent the number of consecutive idle slots between BT interference. $E[\psi_{bt}]$ is

$$E[\psi_{bt}] = \frac{1}{p_{bt}} - 1. \tag{4-25}$$

Let $E[BT]$ represent the number of additional delay slots induced by BT during the $E[X]$ period. Using (4-24) and (4-25), $E[BT]$ is

$$E[BT] = \max\left(\frac{E[X]}{E[\psi_{bt}]}, 1\right) - 1. \tag{4-26}$$

Next, the expected number of WLAN signals detected in the $E[X] + E[BT]$ duration is found. Let $E[\psi_{STA\_pov}]$ represent the expected number of consecutive idle slots between other WLAN transmissions from the point of view of a given STA, this value is similar to (4-19), except one station removed. $E[\psi_{STA\_pov}]$ is

$$E[\psi_{STA\_pov}] = \frac{1}{1-(1-\tau)^{n-1}} - 1. \tag{4-27}$$

Let $E[N_{Fr}]$ represent the expected number of WLAN signals detected in the duration of $E[X] + E[BT]$, then using (4-24), (4-26) and (4-27),

$$E[N_{Fr}] = \max\left(\frac{E[X] + E[BT]}{E[\psi_{STA\_pov}]}\right) - 1. \tag{4-28}$$

With the expected number of WLAN signals detected, the total delay induced by those signals is added. Each WLAN signal may represent either a successful or unsuccessful transmission, so using (4-14), (4-20), (4-21) and (4-28), $E[F]$ is the total delay due to WLAN busy signals,

$$E[F] = E[N_{Fr}] \cdot (P_s \cdot T_s + (1-P_s) \cdot T_c). \tag{4-29}$$

Finally, the total delay during backoff is the sum of the chosen backoff value, BT induced delay, and WLAN induced delay. Using (4-24), (4-26), and (4-29), $E[BD]$ is

$$E[BD] = E[X] + E[BT] + E[F]\ . \qquad (4\text{-}30)$$

Inserting calculated values from (4-20), (4-21), (4-23), and (4-29) into (4-22), results in expected delay.

4.2 Simulation

To verify the analytic model, it is compared with simulation results. The Markov chain model in Figure 4-1 is implemented as a WLAN STA object in Java. Upon creation, each STA object takes in a value for the initial CW size W_0, number of backoff stages m, probability of BT interference p_{bt}, and seed for its random number generator. Object state variables b_t_backoffCounter and s_t_backoffStage represent the backoff counter $b(t)$ and backoff stage $s(t)$ respectively and maintain the state of the STA object. During each time slot, if a random number generated by each STA falls below the probability of BT interference threshold, a BT interferer is assumed to exist in that slot for that STA. During each time slot, the driver class polls the network to determine how many STAs are beginning transmission, and informs each STA accordingly.

If a STA is in a state such that b_t_backoffCounter is greater than zero, the STA determines if either a BT or WLAN signal is present as described above. If either is present, the value of b_t_backoffCounter remains the same for the duration of the signal. If no signal is present, the value of b_t_backoffCounter is decremented and the STA does nothing else for the remainder of the time slot.

If the STA is in a state such that b_t_backoffCounter is zero, it begins to transmit. If no other WLAN STA begins a transmission during that slot, then the STA successfully acquires exclusive access to the medium and its transmission is successful. Upon completion, the backoff stage value s_t_backoffStage is reset to zero, and a number is taken from the random number generator within the interval of the initial CW for the new b_t_backoffCounter value. If another STA also begins transmission in that slot, a collision occurs. The STA increments the backoff stage, s_t_backoffStage, and randomly chooses a new b_t_backoffCounter value within the range of the new CW. If the STA is already at the maximum backoff stage, *m*, s_t_backoffStage is not changed and a new b_t_backoffCounter value is selected within the range of the maximum CW.

When the simulation program is started, the user has the opportunity to input values for the channel bit rate, the number of network STAs *n*, the initial CW size W_0, the number of backoff stages *m*, the duration of each simulation, the number of simulations to run, and an initial seed value. The program runs using the input parameters and changes the probability of BT interference from zero to one in increments of 0.05. Figure 4-2 shows a typical network configuration represented by the analytic and simulation models. Each WLAN STA has BT devices associated with it that cause that STA interference. The boxes labeled *BT network* around each computer represent bounds of each BT piconet's interference range, and the box labeled *WLAN Network* surrounding all the computers represents the bounds of that network.

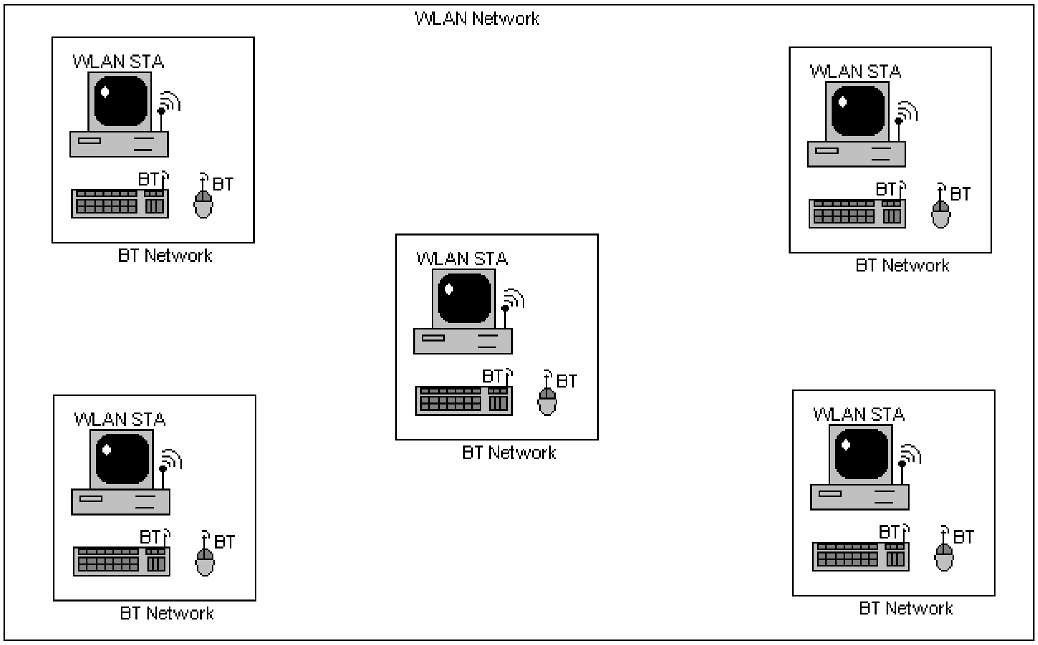

Figure 4-2. WLAN network with 5 STAs and BT interferers.

To gather simulation results for τ, each STA maintains a total count of how many states it has gone through. It also maintains a count of the times it was in a state preceding a transmission. Response variable τ is the ratio of transmission states to total states. Each STA has its own τ result, and the driver class averages values between STAs to produce a network τ in each simulation. The network τ is averaged across multiple simulations to produce the final value and confidence intervals.

To gather simulation results for throughput, the driver class records the total time simulated, and the time spent transmitting data frames. Normalized throughput is determined by the ratio of successful data transmission time to total simulation time. The network throughput values are averaged across multiple simulations to produce the final throughput value and confidence intervals.

To gather simulation results for delay, each STA maintains a count of how many packets it successfully transmitted over the course of the simulation. The driver class divides the total simulated time by the number of packets sent from a STA and determines the average packet delay for that STA. The delay values from the STAs are averaged together to produce a network delay result. The network delay values are averaged across multiple simulations to produce the final delay value and confidence intervals.

4.2.1 Verification and Validation

To verify the analytic model, it is compared with simulation results. The duration of each simulation is one million time slots and enough simulations with different seeds are run to produce at least one hundred values for τ. Since every STA generates its own value for τ and there are n STAs in each simulation, at least $100/n$ replications of each scenario are required. The initial CW size is $W_0 = 32$ based on the IEEE 802.11 standard. A maximum CW size of 1,023 corresponds to five backoff stages ($m = 5$). Initially, the number of STAs in the system is one ($n = 1$). This corresponds to a scenario where only one STA in a WLAN network can transmit, but any number of BT interferers may exist. The τ responses for different values of p_{bt} and $n = 1$ are plotted in Figure 4-3. A linear decrease in transmission probability results in this case.

It is evident from Figure 4-3 that the analytic model and simulation results are almost identical for $n = 1$. For clarity, the 95% confidence interval is not included in Figure 4-3, however its range is $\pm 2.0 \times 10^{-5}$.

The τ value for the trivial case of $p_{bt} = 0.0$ and $n = 1$ can be validated logically. With no other STAs and no BT interference present, the STA will always select a backoff

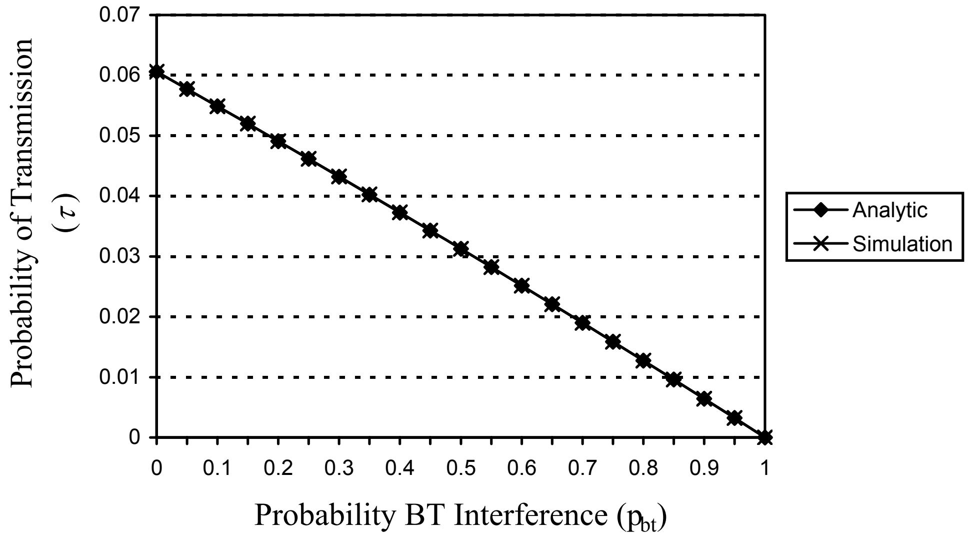

Figure 4-3. τ **as a function of BT interference and** $n = 1$ **STA.**

value between zero and 31, with an average of 15.5. This implies that a transmission takes place every 16.5 slots over time. One transmission for every 16.5 slots corresponds to $\tau = 0.\overline{06}$ as presented in Figure 4-3.

An increase in the probability of BT interference, p_{bt}, causes a linear decrease in the probability the STA transmits in a given time slot. This is a result of BT causing the backoff timer not to decrement due to a busy channel. The effect of BT-induced false positives in the CCA is substantial for even small amounts of interference. An increase in p_{bt} from zero to 0.1 causes a 10% decrease in transmission probability.

Figure 4-4 shows analytic and simulated results for normalized throughput as p_{bt} ranges from zero to one for $n = 1$, and a channel bit rate of 1 Mbps. Again, the two models behave almost identically. For clarity, the confidence intervals for the simulation results are not shown, but they range from $\pm 4 \times 10^{-8}$.

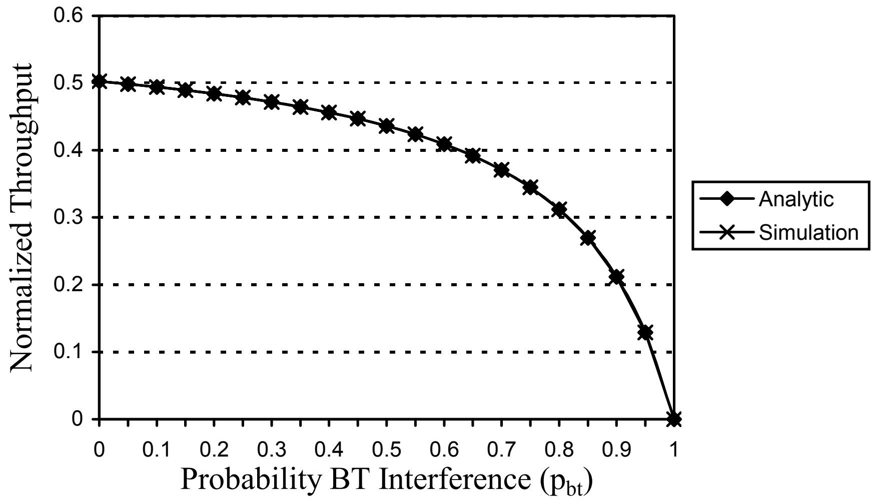

Figure 4-4. Normalized throughput as a function of BT interference, *n* = 1, channel bit rate = 1 Mbps.

Since there are never any collisions or backoff counter suspensions in the trivial case of $p_{bt} = 0.0$ in Figure 4-4, the normalized throughput response can be validated logically. The STA reaches state {0, 0} and transmits successfully, and then it chooses a new backoff value and counts down again. It never suffers a collision, so it never enters a backoff stage higher than zero. In addition, the decrementing of the backoff counter is never suspended, so the value selected in each renewal interval corresponds to the number of delay slots before another transmission. For the initial $CW = 32$, each transmission will take place after 15.5 backoff slots on average. The slots utilized are 51.15 per renewal period as described in (15), and the total number of slots is the utilized slots plus overhead slots plus backoff slots. In this case, throughput is

$$S = \frac{51.15}{51.15 + 35.15 + 15.5} = 0.5025. \qquad (4\text{-}31)$$

The result in (4-31) matches the output from both the analytic and simulation models.

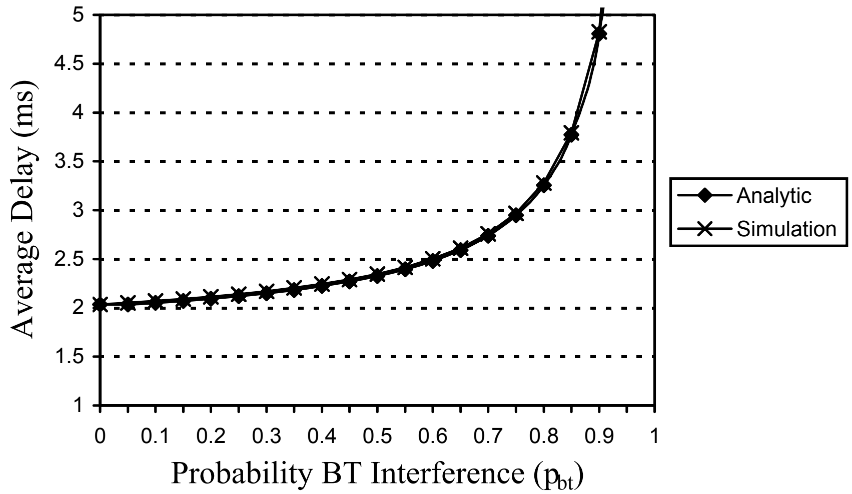

Figure 4-5. Average delay as a function of BT interference, *n* = 1, channel bit rate = 1 Mbps.

Figure 4-5 shows the analytic and simulated results for average delay as p_{bt} ranges from zero to one for $n = 1$, and channel bit rate = 1 Mbps. Again, the analytic and simulation models operate almost identically. The trivial case of $p_{bt} = 0.0$ can be validated logically. From the denominator in (4-31), it is seen that the total number of slots required for each transmission is 101.8. Given that each slot duration is 20 μs, each transmission will take on average 2.04 ms as depicted in Figure 4-5.

The simulation and analytic models begin to diverge for small values of p_{bt} as n grows larger as Figure 4-6 shows. The analytic model will slightly overestimate τ for small values of p_{bt} and with large values of n. The analytic model assumes collision

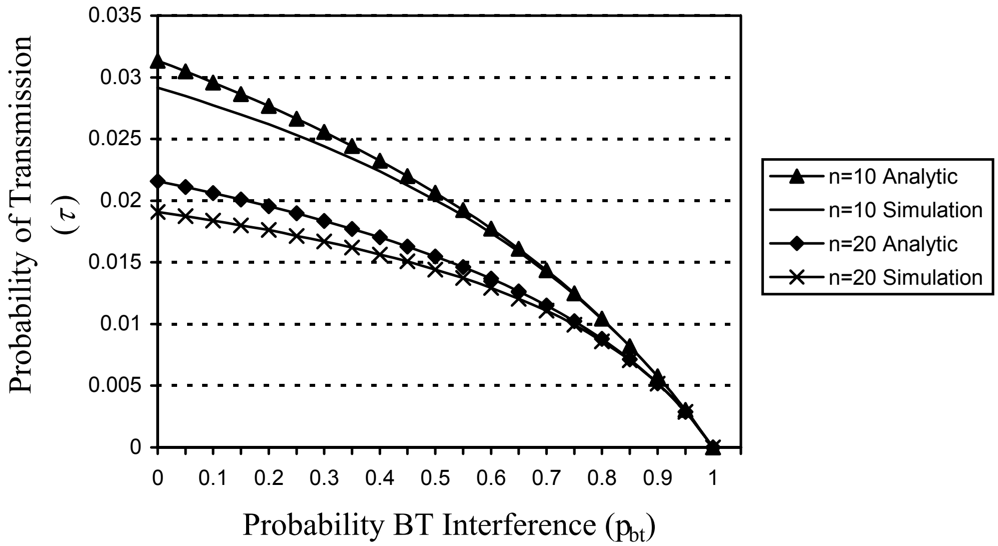

Figure 4-6. τ as a function of BT interference and *n* = 10, 20 STAs.

independence between STAs, but a dependency does in fact exist. In a time slot where multiple STAs are in state {i, 0}, every transmitting STA will suffer the effects of the collision. This is correctly modeled in the simulation, but not in the analytic model. In a time slot where multiple STAs are in state {i, 0}, collisions are "independently" calculated for each STA in the analytic model. This means that only a subset of these STAs could experience the effects of a collision. As p_{bt} increases, the effects of interference dominate the effects of this independence causing the models to converge. For the highest *n* value used, $n = 20$, the maximum divergence of τ at $p_{bt} = 0.0$ is 0.0025.

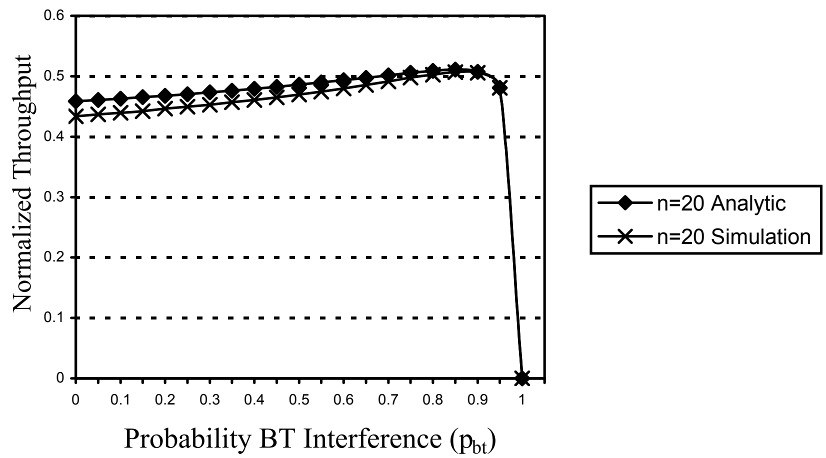

Figure 4-7. Normalized throughput as a function of BT interference, *n* = 20, channel bit rate = 1 Mbps.

With respect to throughput, the analytic model's maximum divergence is 0.025. Figure 4-7 shows the divergence when $n = 20$ and the channel bit rate is 1 Mbps. With respect to delay with the same factor levels, the analytic model's maximum divergence is 1.9 ms as depicted in Figure 4-8.

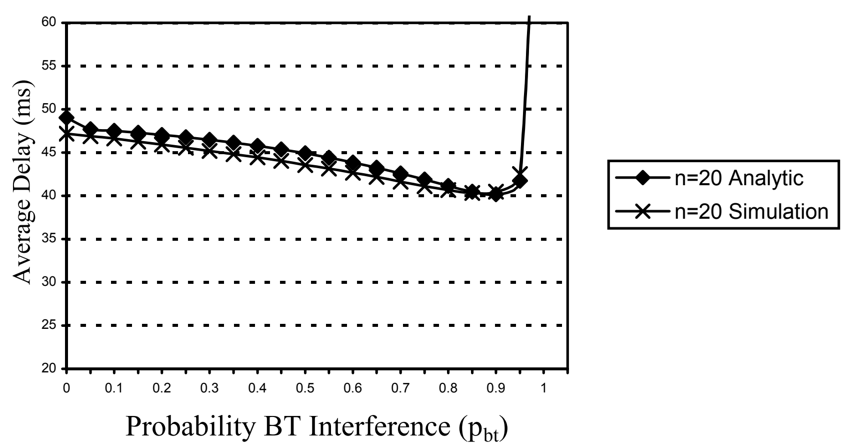

Figure 4-8. Average delay as a function of BT interference, *n* = 20, channel bit rate = 1 Mbps.

4.3 Results

4.3.1 Interesting Trends

A very interesting trend in the data is the effect on throughput as p_{bt} increases. One would intuitively expect that any interference would degrade throughput performance, but this is not always the case. In fact, BT interference improves network throughput in some cases. This trend is not present for $n = 1$, and is very subtle for $n = 5$. It is, however, apparent for $n = 10$ and $n = 20$ as depicted in Figures 4-9 and 4-10 respectively. For the case of $n = 10$ and a channel bit rate of 1 Mbps, BT interference is helpful up to a level of $p_{bt} = 0.7$. At this level, throughput has increased 4.9% over the case with no interference. For higher bit rates, the improvement is more subtle, and the highest beneficial p_{bt} is lower, but the tendency is still present.

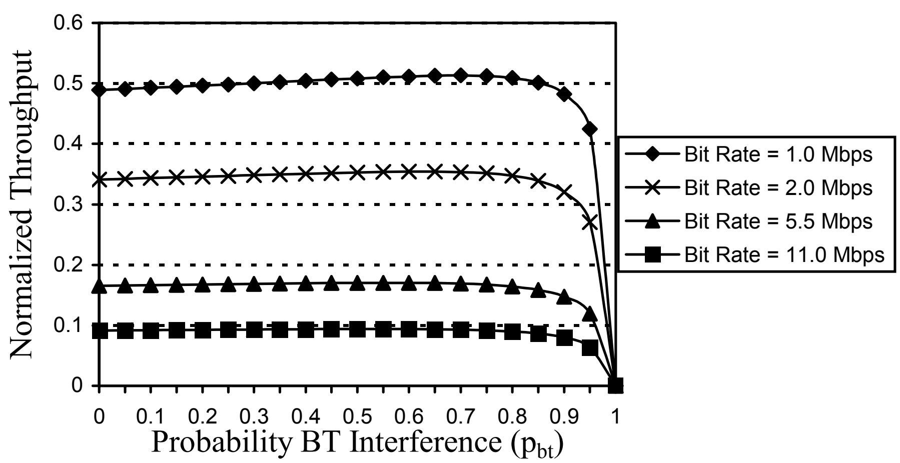

Figure 4-9. Normalized throughput as a function of BT interference, *n* = 10.

For the case of $n = 20$ and a channel bit rate of 1 Mbps, BT interference is helpful up to a level of $p_{bt} = 0.85$. At this level, throughput has increased 11.5% over the case with no interference. Although more subtle and allowing lower beneficial level of p_{bt} , the same trend even exists when higher bit rates are utilized. This is a substantial increase in network performance caused by an interferer originally expected to degrade performance.

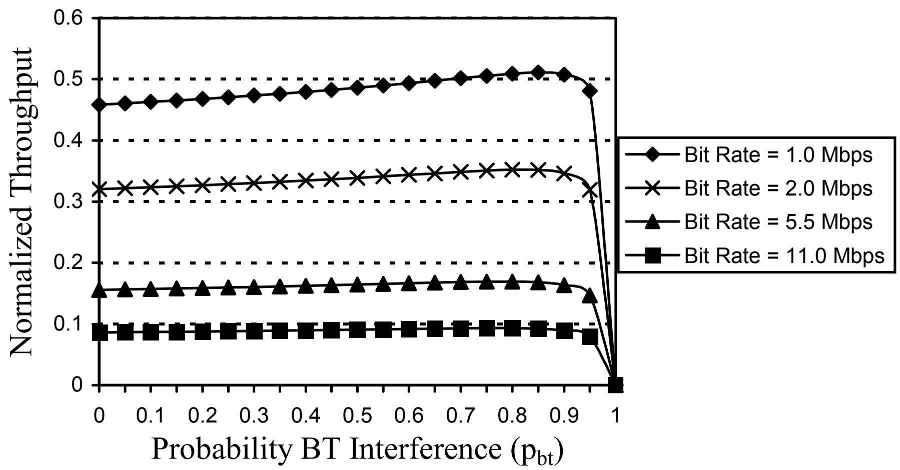

Figure 4-10. Normalized throughput as a function of BT interference, *n* = 20.

The explanation for this tendency rests in the protocol itself. Since the trend is not present when the number of STAs is small, the interaction between STAs in a larger network must play a part. The data implies that CSMA/CA protocol with exponentially increasing window sizes and initial window size of 32 is not sufficient to maximize network throughput. In any given time slot, some STAs may experience interference and others may not. This results from the fact that each STA independently determines if BT interference is present for it. During a STAs backoff period, any channel activity introduced by a BT interferer will increase the randomness of each STA's transmissions. For example, if two STAs choose a backoff value when $CW = 32$ slots, the probability they collide is 1/32. However, if a BT signal potentially causes a STA's backoff counter to suspend with a probability of 0.5 per slot, the probability of collision is much less than 1/32. The CW in this case can be thought of as being similar to 0 to 48 slots.

As a result of interference, the randomness of transmissions is increased and the probability of collision is decreased. This implies that an initial CW of size greater than 32 would increase network throughput as does the BT interference. To support this, the analytic model is used to determine the "best" value with respect to throughput for the initial CW size when no BT interference is present, $n = 10$, and a channel bit rate of 1 Mbps. An initial CW size of 104 produces the greatest increase in throughput over the standard 32 CW size. This increases normalized throughput from 0.489 to 0.513 for a five percent gain. Not surprisingly, this value corresponds to the highest throughput in the presence of BT interference when $p_{bt} = 0.7$ in Figure 4-8. This effect has been observed before. In fact, other research shows different initial CW sizes for different network sizes improve overall throughput. A smaller initial CW is more efficient with respect to throughput when the number of STAs is small, and a larger initial CW is more efficient when the number of STAs is large [BFO96] [CCG98]. More can be found on this subject in [Bha98].

One question that arises is why is the beneficial level of BT so high? This is because the one slot penalty of a backoff counter suspension is small compared to the slots saved by the resulting successful transmission. When considering a collision, the time wasted is substantial. First, the time for unsuccessful transmission is lost, for the case of 1 Mbps, $T_c = 95.85$ slots. Then, the protocol must enter a higher backoff stage where the CW doubles before another transmission attempt can take place. For the case where a STA is in lowest backoff stage initially, a collision will cause a loss of 95.85

transmission slots plus an expected 31.5 additional backoff slots for the second backoff stage. The BT interference must add 128 slots in the backoff period where the CW is only 32 before it equals the impact of one collision!

Finally, observe that the benefit of BT interference decreases as the channel bit rate increases. For the case where $n = 10$ with a channel bit rate of 11 Mbps, the throughput improvement is only 2.5% at a BT level of $p_{bt} = 0.55$. As the payload transmission speed increases, the penalty of a collision decreases and it takes less BT delay slots to equal it. For a STA in the initial backoff stage at 11 Mbps, $T_c = 49.35$ slots and the extra backoff is 31.5 slots. In this case, it takes a reduced 80.85 BT induced delay slots to equal one collision. Hence, less BT interference can be tolerated before network degradation occurs.

The fact that higher bit rates benefit less when analyzing larger values of *n* supports the explanation presented to account for the increased throughput. It is also supported by a similar trend in network delay.

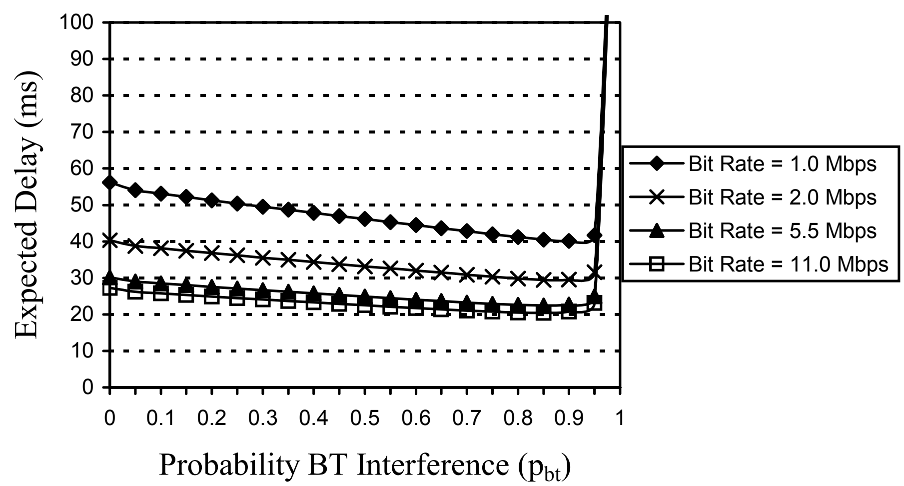

Figure 4-11. Expected delay as a function of BT interference, *n* = 20.

Figure 4-11 shows the trend of decreasing delay as p_{bt} increases. Expected delay benefits from BT interference up to the same p_{bt} level as the corresponding throughput and τ graphs. If throughput rises, but workload stays constant, it is expected that delay should lower. Figure 4-11 supports the analysis and trends presented in this section.

4.3.2 ANOVA

Simulation ANOVA results support the observations made in Section 4.3.1. For this analysis, the factor p_{bt} is taken to have four levels: 0.0, 0.25, 0.5, and 0.75. This factor is compared with bit rate levels of 1.0 Mbps, 2.0 Mbps, 5.5 Mbps, and 11.0 Mbps. The following sections characterize how normalized throughput, tau (τ), and expected delay are affected by the factors.

4.3.2.1 Effects on τ

Tables 4-1 through 4-6 show the ANOVA results for $n = 1, 10,$ and 20 respectively. For all values of n, p_{bt} explains almost 100% of the variation in τ. The effect due to channel bit rate and unexplained variation are negligible amounts. This is because τ is independent of the bit rate. From Figure 4-11 and (4-10), it is seen that τ is probability a STA is in a transmission state {i, 0}, but all states are assumed to have an equal duration in the calculation. Information about actual time spent in each state isn't introduced until the models for throughput and delay are developed. With this, τ is approximately constant across the different bit rate levels, and is only affected by the BT interference level.

Table 4-1. Computation of Effects for τ, *n* = 1

Tau *n*=1	p_{bt}						
Bit Rate	0	0.25	0.5	0.75	Row Sum	Row Mean	Row Effect
1	0.061	0.046	0.031	0.016	0.154	0.039	0
2	0.061	0.046	0.031	0.016	0.154	0.039	0
5.5	0.061	0.046	0.031	0.016	0.154	0.039	0
11	0.061	0.046	0.031	0.016	0.154	0.039	0
Column Sum	0.244	0.184	0.124	0.064			
Column Mean	0.061	0.046	0.031	0.016			
Column Effect	0.023	0.008	-0.008	-0.023			

Table 4-2. ANOVA Table for τ, *n* = 1

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	*F*-Computed	*F*-Table
y	0.028					
$y..$	0.024					
$y - y..$	0.004	100	15			
Interference (p_{bt})	0.004	100	3	0.001	1.09×10^7	2.8
Channel Bit Rate	0	0	3	0	0.06	2.8
Errors	0	0	9	0		

Table 4-3. Computation of Effects for τ, *n* = 10

Tau *n*=10	p_{bt}						
Bit Rate	0	0.25	0.5	0.75	Row Sum	Row Mean	Row Effect
1	0.029	0.025	0.02	0.012	0.086	0.0215	0
2	0.029	0.025	0.02	0.012	0.086	0.0215	0
5.5	0.029	0.025	0.02	0.012	0.086	0.0215	0
11	0.029	0.025	0.02	0.012	0.086	0.0215	0
Column Sum	0.116	0.1	0.08	0.048			
Column Mean	0.029	0.025	0.02	0.012			
Column Effect	0.0075	0.0035	-0.0015	-0.0095			

Table 4-4. ANOVA Table for τ, *n* = 10

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	*F*-Computed	*F*-Table
y	0.008					
$y..$	0.008					
$y - y..$	0.001	100	15			
Interference (p_{bt})	0.001	100	3	0.0002	1.4×10^6	2.8
Channel Bit Rate	0	0	3	0	0.11	2.8
Errors	0	0	9	0		

Table 4-5. Computation of Effects for τ, n = 20

Tau n=20	p_{bt}						
Bit Rate	0	0.25	0.5	0.75	Row Sum	Row Mean	Row Effect
1	0.019	0.017	0.014	0.01	0.06	0.015	0
2	0.019	0.017	0.014	0.01	0.06	0.015	0
5.5	0.019	0.017	0.014	0.01	0.06	0.015	0
11	0.019	0.017	0.014	0.01	0.06	0.015	0
Column Sum	0.076	0.068	0.056	0.04			
Column Mean	0.019	0.017	0.014	0.01			
Column Effect	0.004	0.002	-0.001	-0.005			

Table 4-6. ANOVA Table for τ, n = 20

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	F-Computed	F-Table
y	0.004					
$y_{..}$	0.004					
$y - y_{..}$	0.0002	100	15			
Interference (p_{bt})	0.0002	100	3	> 0	9.3×10^5	2.8
Channel Bit Rate	0	0	3	0	3.2	2.8
Errors	0	0	9	0		

4.3.2.2 Effects on Normalized Throughput

The ANOVA results for throughput are interesting and support observations of Section 4.3.1. For the case of $n = 1$, 6.1% of the variation is attributed to BT interference, 92.5% is attributed to the bit rate, and 1.4% is unexplained as shown in Tables 4-7 and 4-8. When only one STA exists in the network, it will never collide with another WLAN transmission. Any interference is going to cause the throughput to go down. The initial CW is 32, and any interference causes the actual backoff time to increase. Even though the average backoff interval selected is 15.5, the average backoff time experienced will be greater than 15.5. The transmission time will never change because collisions will never occur, so the final result is always slots lost and lower throughput.

Table 4-7. Computation of Throughput Effects, *n* = 1

Throughput n=1	p_{bt}						
Bit Rate	0	0.25	0.5	0.75	Row Sum	Row Mean	Row Effect
1	0.502	0.478	0.436	0.345	1.761	0.440	0.210
2	0.336	0.314	0.279	0.208	1.137	0.284	0.054
5.5	0.155	0.143	0.123	0.087	0.508	0.127	-0.103
11	0.084	0.077	0.066	0.046	0.273	0.068	-0.162
Column Sum	1.077	1.012	0.904	0.686			
Column Mean	0.269	0.253	0.226	0.172			
Column Effect	0.039	0.023	-0.004	-0.058			

Table 4-8. ANOVA Throughput Table, *n* = 1

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	F-Computed	F-Table
y	1.210					
$y_{..}$	0.846					
$y - y_{..}$	0.363	100	15			
Interference (p_{bt})	0.022	6.1	3	0.007	12.7	2.8
Channel Bit Rate	0.336	92.5	3	0.112	194.3	2.8
Errors	0.005	1.4	9	0.001		

For the cases of $n = 5,\ 10,$ and 20, less than one percent of the variation is explained by BT interference. 99% of the variation is explained by bit rate and less than one percent in unexplained. ANOVA for n = 20 is shown in Tables 4-9 and 4-10. This also supports the observations made in Section 4.3.1. Here, the variation due to BT interference is still significant because it is much greater than the unexplained variation, but plays a much smaller role than before. Unlike the case of $n = 1$, BT interference does not always lower throughput. Interference up to a high level, as discussed in previous sections, actually improves network performance. The probability that STAs' transmissions collide lowers up to certain interference levels. For the factor levels chosen, throughput slightly increases as p_{bt} ranges from zero to 0.75. The obvious drop in throughput experienced when $n=1$ is not present here. A relatively modest increase in throughput is apparent over the range of the p_{bt} factor levels.

Table 4-9. Computation of Throughput Effects, *n* = 20

Throughput *n*=20	p_{bt}						
Bit Rate	0	0.25	0.5	0.75	Row Sum	Row Mean	Row Effect
1	0.434	0.449	0.470	0.498	1.851	0.463	0.206
2	0.302	0.313	0.326	0.344	1.285	0.321	0.065
5.5	0.146	0.151	0.158	0.166	0.621	0.155	-0.101
11	0.081	0.084	0.087	0.091	0.343	0.086	-0.171
Column Sum	0.962	0.997	1.042	1.099			
Column Mean	0.241	0.249	0.260	0.275			
Column Effect	-0.016	-0.007	0.004	0.019			

Table 4-10. ANOVA Throughput Table, *n* = 20

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	*F*-Computed	*F*-Table
y	1.399					
$y_{..}$	1.050					
$y - y_{..}$	0.348	100	15			
Interference (p_{bt})	0.003	0.8	3	0.001	8.3	2.8
Channel Bit Rate	0.345	98.9	3	0.115	1085	2.8
Errors	0.001	0.3	9	0.000		

Bit rate plays a major role in determining normalized throughput. As bit rate increases, the duration of a data payload decreases for a given payload size. Given that the time duration of header information, handshake information, and backoff intervals are constant across different bit rate levels, the ratio of data to overhead reduces, causing a considerable drop in normalized throughput. The maximum theoretical throughput for a channel bit rate of 1 Mbps can be calculated by dividing the data frame duration by total time. Assuming all transmissions are successful and that consecutive transmissions have no time spacing between them, the maximum throughput is defined using (4-15) and (4-20) and is

$$S = \frac{E[P]}{T_s} = \frac{51.15}{87} = 0.59\,. \qquad (4\text{-}32)$$

The same calculation can be performed to determine the maximum theoretical throughput for a channel bit rate of 11 Mbps. Using (4-18) and (4-20), throughput is defined as

$$S = \frac{E[P]}{T_s} = \frac{4.65}{40} = 0.12\,. \qquad (4\text{-}33)$$

From (4-32) and (4-33), it is evident that higher bit rates are less efficient when it comes to utilizing the medium. Given this, bit rate dominates the variation in throughput. Although the throughput in bits per second may be greater when the channel bit rate increases, the change in throughput is not proportional to the change in bit rate.

4.3.2.3 Effects on Expected Delay

The ANOVA results with respect to delay are similar to the throughput results. For the case of $n = 1$, 49.6% of the variation is explained by BT interference, 50.4% is explained by bit rate and less than one percent is unexplained as shown in Tables 4-11 and 4-12. By the same argument given for throughput, BT interference plays a significant role in determining expected delay. Since no collisions can occur and the transmission time is constant, any additional delays in the backoff interval directly translates into increased delay.

For the case of $n = 5,\ 10,$ and 20, variation due to interference is at most 2.8% and the unexplained variation is less than one 1 %. While the effect of interference is still significant, bit rate dominates the variation. By the same argument given for

Table 4-11. Computation of Delay Effects, n = 1

Delay n=1	p_{bt}						
Bit Rate	0	0.25	0.5	0.75	Row Sum	Row Mean	Row Effect
1	2.036	2.139	2.346	2.967	9.488	2.372	0.570
2	1.525	1.628	1.834	2.454	7.441	1.860	0.058
5.5	1.199	1.302	1.509	2.129	6.139	1.535	-0.267
11	1.106	1.209	1.416	2.035	5.766	1.442	-0.361
Column Sum	5.866	6.278	7.105	9.585			
Column Mean	1.466	1.570	1.776	2.396			
Column Effect	-0.336	-0.233	-0.026	0.594			

Table 4-12. ANOVA Delay Table, n = 1

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	F-Computed	F-Table
y	56.2					
$y_{..}$	52.0					
$y - y_{..}$	4.20	100	15			
Interference (p_{bt})	2.08	49.6	3	0.694	6.34×10^6	2.8
Channel Bit Rate	2.12	50.4	3	0.706	6.46×10^6	2.8
Errors	0	0	9	0		

throughput, an increase in p_{bt} causes a modest decrease in the probability of WLAN collision and delay. ANOVA for n = 20 is shown in Tables 4-13 and 4-14.

Table 4-13. Computation of Delay Effects, n = 20

Delay n=20	p_{bt}						
Bit Rate	0	0.25	0.5	0.75	Row Sum	Row Mean	Row Effect
1	47.205	45.548	43.561	41.129	177.443	44.361	13.836
2	33.943	32.758	31.351	29.714	127.766	31.941	1.417
5.5	25.491	24.621	23.550	22.437	96.100	24.025	-6.499
11	23.089	22.287	21.344	20.361	87.081	21.770	-8.754
Column Sum	129.728	125.214	119.807	113.641			
Column Mean	32.432	31.303	29.952	28.410			
Column Effect	1.908	0.779	-0.573	-2.114			

Channel bit rate is the dominant factor when considering expected delay. Noting that the backoff intervals and collision probabilities are constant across different bit rates for a given p_{bt} value, the only varying quantity is the duration of a transmission. As bit rate increases, the duration of a packet's payload decreases. All other things being equal, a decrease in payload duration translates directly to a decrease in delay.

Table 4-14. ANOVA Delay Table, *n* = 20

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	*F*-Computed	*F*-Table
y	16,200					
$y..$	14,900					
$y - y..$	1,290	100	15			
Interference (p_{bt})	36.2	2.8	3	12.1	28.5	2.8
Channel Bit Rate	1250	96.9	3	416	983	2.8
Errors	3.81	0.3	9	0.424		

V. Conclusion

5.1 Problem Summary

IEEE 802.11 WLAN's and BT networks operate in the unlicensed 2.4 GHz band. Coexistence and mutual interference becomes a concern when they are employed in close proximity. The aspect of interference analyzed here occurs when BT signal presence causes a WLAN STA's CCA to declare the medium is busy. When a WLAN STA has data to transmit, the CSMA/CA protocol will enter a backoff interval before transmitting. During that interval, it tries to determine if other STAs are using the medium via carrier-sensing. In one CCA algorithm, energy detection above a specified threshold is sufficient to declare another WLAN signal is present. If BT signal energy is sufficient to cause a "false positive" in the WLAN's CCA, the STA needlessly delays its data transmission.

The original research goal was to isolate BT interference effects with respect to BT-induced "false positives" in the CCA from BT induced collisions. Previous research made no distinction between interference types, rather, combined effects were investigated. The initial hypothesis was that BT induced false positives would adversely impact network throughput and expected delay.

5.2 Results Summary

One would intuitively think that BT interference would lower network throughput and increase expected delay. It turns out that in cases where two or more STA's are present, BT false positives in the CCA actually improved network performance. As presented in Section 4.3.1, $p_{bt} = 0.85$, $n = 20$, and a channel bit rate of 1.0 Mbps results in an 11.5 % increase in throughput over the case where $p_{bt} = 0.0$. Furthermore, the CSMA/CA protocol's default selection of an initial *CW* = 32 was suboptimal with respect to throughput and delay. When a large number of STA's form a network, a larger initial *CW* increases efficiency. This effect is mimicked by the presence of BT interference and demonstrates that BT is not necessarily a hindrance to a WLAN.

5.3 Model Utility

The models developed in this research are powerful and flexible, effectively predicting WLAN performance in the presence of interference before time and money is spent on implementation. This is a valuable asset to industry and the Air Force where budgets must be considered. The implementation cost of wireless systems is not justified without assurance that the system will operate efficiently. These models provide accurate predictions of network throughput and delay for many scenarios. Noting that BT interference is parameterized, it can actually represent interference from many sources including cellular phones, cordless phones, and microwaves operating in the 2.4 GHz band.

The analytic model is ideal for a rapid assessment of possible network scenarios. There are virtually no model implementation costs and results are instantaneous. The number of STAs and expected interference levels are all that is needed to predict WLAN efficiency. Based on these results, it becomes quickly evident whether or not pursuing a system configuration is warranted.

Using the simulation model, results received from the analytic model can be verified. Additional flexibility can easily be added to the simulation to represent dependencies and circumstances not embodied in the analytic model. Further, the simulation can be readily modified to take new conditions into account. As a result, a powerful and accurate tool is available. Beginning with a quick initial analytic test, implementers can decide whether continued network development is viable. Following this, a more diverse finely tuned tool can be employed to handle more network conditions.

As already mentioned, the default $CW = 32$ value does not maximize throughput or minimize delay in many cases. Since these and other protocol parameters can be varied, the models can be used to find values providing better network performance for a given scenario. Once determined, these values can be used to create a modified CSMA/CA protocol better adapted to its network environment.

5.4 Future Work

The model developed is useful for predicting WLAN network performance quickly and efficiently when BT interference is a concern. It allows the forecast of performance in large networks before investing time and money on those systems. A scenario that this model is well-suited to predict is one where each STA in a WLAN is a desktop or laptop PC with BT equipment associated with it. Each computer may have a BT wireless keyboard, mouse, and speakers whose signals cause false positives in the CCA of the STA’s CSMA/CA protocol. In this scenario, the interference due to BT devices is localized to the STA it is attached to, so the probability of interference p_{bt} is independent between STAs.

The model can be expanded to include frame corruptions due to collisions with a BT transmission. With this modification, it is possible to analyze the effect of BT-induced false positives in the CCA or BT-induced collisions independently. By setting the probability of either event to zero, the effect of the other on network efficiency can be examined. The combined effects and interactions of both events can be characterized using nonzero values. Also, the payload for this research is assumed constant at 1,024 bits. It would be interesting to replace this with a more representative data distribution function.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

IEEE 802.11 WLANs and Bluetooth piconets both operate in the 2.4 GHz Industrial Scientific and Medical (ISM) radio band. When operating in close proximity, these two technologies interfere with each other. Current literature suggests that IEEE 802.11 (employing direct sequence spread spectrum technology) is more susceptible to this interference than Bluetooth, which uses frequency hopping spread spectrum technology, resulting in reduced throughput. Current research tends to focus on the issue of packet collisions, and not the fact that IEEE 802.11 may also delay its transmissions while the radio channel is occupied by a Bluetooth signal. This research characterizes previously neglected transmission delay effects. Through analytic modeling and simulation, the impact of this interference is determined to identify all facets of the interference issues.

Results show that Bluetooth-induced transmission delays improve network performance in many scenarios. When isolating delay effects, the likelihood that WLAN STA signals collide with each other decreases, causing an overall increase in normalized throughput and decrease in expected delay for many network configurations.

As wireless communication technologies become an integral part of national defense, it is imperative to understand every performance characteristic. For instance, if the Air Force uses IEEE 802.11 and wants to incorporate a Bluetooth piconet as well, the impact of concurrent operation should be known beforehand. Since IEEE 802.11 and Bluetooth technologies could become vital for the Air Force to maintain its position of air superiority, all the strengths, weaknesses, and limitations of these systems should be understood.

15. SUBJECT TERMS

Wireless Communications, Local Area Networks, Personal Area Networks, Network Interference, Network Performance, Network Throughput, Network Delay, Interference Effects

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