Computer Science 380y Final Report

Performance of TCP/IP over Bluetooth

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1.0 Introduction

With the public's ever-increasing desire for portable, high-speed devices such as laptop computers and mobile phones, a large number of new products are entering the market every year. However, many people are now encountering the problem of interoperability. A user may have a number for a friend in a telephone directory on their personal organizer, but have no way to easily dial that number on their mobile phone because the two devices are unable to communicate without cumbersome, expensive, and proprietary data cables.

This is the type of situation for which the Bluetooth protocol was designed. Bluetooth allows theeasy interconnection of many types of computing and communications devices. Bluetooth removes wired connections between devices, replacing them with automatic wireless links.

One of the major benefits of Bluetooth technology is the ability for people to use their mobile phones in order to access the Internet from a laptop or handheld computer. The third-generation (3G) mobile phone systems will allow for high speed wireless connectivity, and Bluetooth-enabled 3G phones will provide support for simple connection to other devices. This means that for the first time, mobile users will have high-speed, wireless internet access anywhere they have mobile phone service.

Bluetooth also holds promise as a cheap solution to wireless connectivity in the home. Desktop and laptop PCs with Bluetooth cards can easily communicate with one another. Once one of these computers is equipped with an Internet connection, it can be easily configured to act as a gateway to the Internet for other machines.

With the increasing use of TCP/IP based applications over Bluetooth links as is described above, there is a growing interest in the performance of TCP/IP over Bluetooth. Unfortunately, TCP/IP connections over wireless protocols such as Bluetooth can suffer dramatic performance degradation when faced with channel fading and other inescapable effects in the wireless environment. The main goal of this project is to provide a performance evaluation of TCP/IP in such situations, in order to better understand the limitations of Bluetooth technology. Because of the difficulty in deriving an accurate analytical model describing the wireless channel, a simulation-based model will be developed. Various types of Bluetooth configurations will be studied.

2.0 Problem Overview

The TCP/IP protocol suite [8] was designed to be used in wired networks, where, in normal operating conditions, the only source of packet loss is network congestion. When TCP/IP is used on wireless links, effects such as channel fading [9] cause degraded performance. Because TCP/IP was not designed to be resistant to such effects, they can severely decrease the throughput of TCP/IP connections. Since TCP/IP has become the dominant standard in network connectivity, developers are hesitant to use another protocol in wireless devices. It is also difficult to make major changes to the TCP/IP implementation, due to the necessity of interoperation with existing systems.

The propagation of radio waves in a wireless environment is extremely difficult to characterize analytically. Many other devices operate in the 2.4 GHz Industrial, Scientific and Medical (ISM) band used by Bluetooth, and may cause interference. Some examples include wireless Ethernet cards, cordless phones, and radiation from microwave ovens. Degraded quality in the channel can also be caused by other things, such as signal attenuation due to obstructions (walls and other forms of barriers), and multipath reflections.

Because of the difficulty in characterizing the wireless channel analytically, research has focused on creating statistical models to explain the effects present in the channel. Many studies have been done to determine the parameters of different statistical models used for approximating the channel. such statistical models are important for an accurate performance analysis of a wireless protocol such as Bluetooth.

Bluetooth is a short-range wireless communications protocol [10], designed to facilitate *ad-hoc* wireless connections between low-powered portable devices such as mobile phones, PDAs and laptop computers. Bluetooth networks are arranged in a master-slave configuration, with all Bluetooth devices capable of acting either as a master and as a slave. Two different connection types are specified by the Bluetooth standard: asynchronous connectionless link (ACL) and synchronous connection-oriented (SCO). ACL connections allow for higher-rate data transmission in one direction, with speeds dependent on the number of devices operating in the piconet. On the other hand, SCO connections allow for transmission in both directions at the same speed, and provide quality-of-service guarantees about the data rate of the connection.

Bluetooth allows for one master and up to seven slaves to form a “piconet” at distances of up to ten meters, where each slave communicates with the master in a time-division multiplexing manner. The maximum data rate (using an ACL link) is approximately 700 kbps. A Bluetooth device can be part of several piconets at the same time, and switch between the piconets of which it is a member. Several Bluetooth piconets can be loosely joined to form “scatternets”, which allow for more devices to be linked.

The Bluetooth standard [10] specifies a protocol by which devices can automatically discover one another and establish connections. No user intervention is required for this process, although for security reasons, devices may be configured so that the user is prompted before connections are established.

Bluetooth employs an Automatic-Repeat-reQuest (ARQ) system [11] and Forward Error Correction (FEC) [9] at the link layer to counteract the effects of channel fading and other sources of packet loss. The ARQ system provides a retry-until-sent mechanism for dealing with packet transmission errors, while the use of FEC provides redundancy in the Bluetooth packets, allowing for protection against bit errors during transmission. The interaction between the link-layer ARQ/FEC mechanisms and the backoff/recovery schemes of TCP/IP has not been studied in great detail. It is possible that certain combinations of ARQ and FEC schemes, along with the proper selection of TCP/IP implementation, can allow for reasonable performance even in fading channel situations.

The *Bluehoc* simulator [21] has been developed by a group at IBM Labs in India in order to study the performance of Bluetooth. This simulator is an extension of the network simulation package *ns-2* [22]. The *Bluehoc* package allows the modeling of the performance of various TCP/IP-based applications running over Bluetooth connections. However, the wireless channel model used in this simulator is the most basic, non-correlated model, based on the assumption that the packet losses are distributed randomly in time (*i.e.* the probability of error for any packet is completely independent of that for any other packet). It is known that this model is an inaccurate representation of wireless propagation at high frequencies, such as the 2.4 GHz ISM band used by the Bluetooth protocol.

3.0 Literature Review

The literature can be broadly divided into three categories: work on the measurements and modeling of the wireless fading channel, papers related to the simulation and analysis of Bluetooth, and reports examining TCP performance over wireless channels.

Central to the development of an accurate performance simulator for Bluetooth is a good model of the wireless radio channel. Statistics about fading in the channel can be found in Rappaport *et al.* [7]. Hashemi [15] provides an excellent tutorial on the statistical modeling of the wireless channel. The Gilbert-Elliot model, often used in the simulation of channel fading, is detailed in [23].

Many researchers have applied wireless fading models to different protocols and environments. Zorzi *et al.* [16] analyse the accuracy of the Gilbert-Elliot model in approximating the error stream of a fading mobile channel. Xu *et al.* [17] provide a comparison of the performance of ARQ and non-ARQ systems in a fading channel environment, using a Gilbert-Elliot model. In [18], Zorzi and Rao use a Gilbert-Elliot model to study an ARQ system over a channel with fading in both the forward and reverse directions.

Publications about the technological aspects of Bluetooth are predominantly descriptive and not research-oriented. Publications such as [10] provide large amounts of detail concerning the protocols and interfaces used in Bluetooth, but do not carry out performance evaluations of the protocol. Articles such as [3] cover the Bluetooth protocol in less detail, and provide usage scenarios in order to explain the usefulness of Bluetooth. They primarily provide background information about Bluetooth and give an estimate of the range of performance expected from the protocol.

Literature about the simulation and analysis of Bluetooth can be grouped into two sub-categories: publications that take an analytical approach, and those that use simulations. Those using an analytical approach generally make certain assumptions which are not valid in the general case. For example, in [6] Karnik and Kumar provide a theoretical analysis of the physical layer of the Bluetooth protocol. However, they only consider interference between piconets, disregarding other types of interference. This limitation hinders the application of the theory to other situations. In [12], El-Hoiydi provides an upper bound on the packet error rate in a Bluetooth network. However, the assumption is made that any interference causes the packet to be lost, which is not true in all cases, specifically if FEC-protected Bluetooth packets are used (as is often the case).

Of more interest to this study are those papers that use numerical simulation. In [2], Das *et al.* analyse the performance of data traffice over Bluetooth links. While the channel model used is Gilbert-Elliot, the model does not take into account distance between nodes, different Bluetooth packet types, or the spatial correlation between seperate master-slave connections. Nichols and Amin [14] discuss the use of a Rician distribution to model fading in the wireless channel, but do not provide any simulation results. Koomullil in [13] provides results with and without channel fading, but no details are given about the type of channel model used for the fading channel simulation.

The final category of literature is that addressing the issue of TCP performance over wireless channels. Much work has been done in this area, with several studies of direct interest to the research at hand. Holland and Vaidya examine the performance of TCP over a mobile, *ad-hoc* network [4]. Kumar [5] examines the performance of different variations of the TCP protocol in a lossy wireless channel. The performance analysis of TCP with link-layer FEC and ARQ is presented by Chockalingam and Zorzi [1]. Zorzi *et al.* study TCP performance in a channel with memory (*i.e.* a correlated channel) in [19]. Finally, in [20] Chaskar *et al.* present a study of TCP over a fading channel with a link-level error control system.

4.0 Development of an error model

4.1 Purpose

In order to study the effect of channel fading on the performance of the Bluetooth protocol, a model is needed to characterize the wireless channel. One such model is the Gilbert-Elliot (GE) model [23]. The GE model classifies the channel as being either in a “good” state or a “bad” state. It has been shown that the GE model is a good approximation of channel behaviour [16]. When using a GE model to study the channel, statistics must be analysed to determine the average probability of error, noted as P_B. The *Bluehoc* simulator uses a table of P_B values (for different distances and packet types) which were calculated based on the data given by Rappaport *et al.* [7].

4.2 The Gilbert-Elliot model for a single channel

In the case of a single master-slave connection, a GE model can be used to approximate the channel state. The Gilbert-Elliot error model treats the channel as being in either a “good” state (G) or a “bad” state (B). In each state, there is a certain probability of a packet having an error. For now, it is assumed that when the channel is in the Good state the packet probability of error is $h_g = 0$, and when in the Bad state the probability of error is $(1 - h_b) = 1$. Note that for the Bad state, h_b is defined as the probability of *no error*.

The model defines a transition matrix between states, T, as follows:

$$T = \begin{bmatrix} P_{GG} & P_{GB} \\ P_{BG} & P_{BB} \end{bmatrix} = Q - d(E - Q) \qquad (1)$$

where the various P elements are the transition probabilities, d is the correlation between successive states, E is the 2x2 identity matrix and Q is defined as:

$$Q = \begin{bmatrix} (1-P_B) & P_B \\ (1-P_B) & P_B \end{bmatrix} \tag{2}$$

with P_B being the probability of a packet error in a memoryless channel. From these definitions, it is obvious that:

$$P_{GG} = 1 + P_B(d-1) \qquad P_{BB} = d + P_B(1-d) \tag{3}$$

and also

$$P_{GB} = 1 - P_{GG} \qquad P_{BG} = 1 - P_{BB} \tag{4}$$

Note that when $d = 0$ (meaning the channel is memoryless), (3) reduces to $P_{GG} = 1 - P_B$ and $P_{BB} = P_B$, which is as we would expect.

From (3) and (4) a sequence of channel states can be generated, given d and P_B. In this analysis, d is the variable of interest and P_B (the probability of error of a packet) is a function of the Bluetooth packet type and the distance between nodes. The probabilities of error for different packet types and distances are given in the *Bluehoc* software package, having been determined based on the Rappaport model [7].

The problem with the Gilbert-Elliot model as given above is that the probability of error P_B for a single packet is assumed to remain constant in time. However, for a flow of Bluetooth packets this is not the case. A Bluetooth link constantly sends different packet types depending on the traffic passing over the link. Thus, the model must be modified to take this factor into account. This will be done by modifying h_b, the probability of no error when the channel is in a Bad state.

If the probability of error for different types of packets is examined, it can be seen that the packet type DH5 (data packet, five time slots, no FEC protection) has the highest probability of error. This probability shall be called P_{max}, and we will use the value of P_{max} in place of P_B in (3) and (4). It is assumed that for this packet type $h_b = 0$, meaning that in a Bad channel state, all packets of this type have an error.

It can be shown that for any other packet type, the probability of an error P_{err} is given by $(1 - h_b)P_{max}$. Thus, in the revised Gilbert-Elliot model for varying probabilities of packet error, the probabilities h_g and h_b are given by:

$$h_g = 0 \qquad h_b = (P_{max} - P_{err}) / P_{max} \tag{5}$$

This method gives a general procedure for calculating a packet error sequence for any type of packet. The first step is to use (3) and (4) to calculate the state transition (by simple random number generation). Once the next state has been determined, the error occurence can be determined by (5).

The *Bluehoc* simulator has been extended to implement the model described above. With the modified simulator, the effect of the fading channel can be studied by varying d, the correlation between packets. When $d = 0$, there is no correlation between successive packets (meaning the channel is memoryless). As d increases, successive packets are correlated and thus channel errors start occurring in bursts. When $d \to 1$, the successive packets are completely correlated in time and thus the channel never transitions between states.

4.3 The two-channel model

In the situation where two Bluetooth master-slave connections are operating simultaneously, the model of section 4.2 must be extended to take into account the correlation between channels. There are numerous generalizations of the single-channel Gilbert-Elliot model [23-27] to incorporate a larger number of states and more complicated correlation than that defined by a simple Markov chain. Here the GE model is extended to the case of a vector channel, allowing it to model both spatial and time correlation.

The simplest extension of the GE model which takes into account multiple channels is a model which treats each channel as independent. This model works well if separation in space and/or frequency for each channel is large. However, this is not true for small pico-cell environments, where, for example, a few channels can be obstructed simultaneously. In addition, a single mobile user may utilize several channels, thus providing coherent changes in the signal magnitude and Doppler shift. In this case it is possible to assume that probability P_G of the "Good" state (and hence the probability P_B of the "Bad" state) in different channels are the same or very similar. Here the analysis is limited to a model with two channels, which allows the modeling of a Bluetooth network with a master and two slaves, transmitting at the same time.

Two states of each channel $G1$, $B1$, $G2$, $B2$ can be assembled into four aggregate states $G1G2$, $G1B2$, $B1G2$, and $B1B2$, with probabilities defined by the following equations:

$$P_{G1G2} = \alpha P_{G1}^2 + (1-\alpha)P_{G1} \tag{6}$$

$$P_{G1B2} = \alpha P_{G1}(1-P_{G1}) \tag{7}$$

$$P_{B1G2} = \beta P_{G1}(1-P_{G1}) \tag{8}$$

$$P_{B1B2} = \beta(1-P_{G1})^2 + (1-\beta)(1-P_{G1}) \tag{9}$$

Here P_{G1} is the probability of a “Good” state and constants α and β have yet to be determined. It can be easily see that:

$$P_{G1G2} + P_{G1B2} = P_{G1}, P_{B1G1} + P_{B1G1} = P_{G1} \tag{10}$$

thus (6)-(9) are consistent with the single channel description. In order to satisfy the condition that both channels have the same probability of the “Good” state, a constant β must be chosen equal to the constant α.

Let us now consider a Markov chain with the steady-state probabilities

$$P_{st} = \left[P_{G1G2}\ P_{G1B2}\ P_{B1G2}\ P_{B1B2}\right]^T = \begin{bmatrix} \alpha P_{G1}^2 + (1-\alpha)P_{G1} \\ \alpha P_{G1}(1-P_{G1}) \\ \alpha P_{G1}(1-P_{G1}) \\ \alpha(1-P_{G1})^2 + (1-\alpha)(1-P_{G1}) \end{bmatrix} \tag{11}$$

and the transition probability matrix

$$T = (1-d)Q + dI \tag{12}$$

where $0 < d < 1$, I is an 4×4 identity matrix, and

$$Q = \begin{bmatrix} P_{G1G2} & P_{G1G2} & P_{G1G2} & P_{G1G2} \\ P_{G1B2} & P_{G1B2} & P_{G1B2} & P_{G1B2} \\ P_{B1G2} & P_{B1G2} & P_{B1G2} & P_{B1G2} \\ P_{B1B2} & P_{B1B2} & P_{B1B2} & P_{B1B2} \end{bmatrix} \tag{13}$$

It is well known that a Markov chain, described by the transition matrix (12) describes an exponentially correlated chain, since the second biggest eigenvalue of the matrix T is equal to d [28].

As the next step let us show that the parameter α governs spatial correlation between the two channels. Indeed, it can be easily seen that

$$\frac{P(G_1, B_2)}{P(G_1)P(B_2)} = \frac{P(B_1, G_2)}{P(B_1)P(G_2)} = \frac{\alpha P_G(1 - P_G)}{P_G(1 - P_G)} = \alpha \tag{14}$$

If $\alpha = 1$, the states of the first and second channels are independent:

$$P(G_1|B_2) = \frac{P(G_1, B_2)}{P(B_2)} = P(G_1) \tag{15}$$

while if $\alpha = 0$, both channels must be in the same state:

$$P(G_1, B_2) = P(B_1, G_2) = 0 \tag{16}$$

5.0 Simulation methodology

The models described in sections 4.2 and 4.3 were implemented in the *Bluehoc* simulator, using the C++ programming language. The existing memoryless error calculation routines were removed, and a state-based error determination system was implemented. The state-based system consisted of a channel memory which retains the previous state of the channel(s), as well as an error sequence generator, used to determine the state transitions for each packet.

This code was built as part of the packet-receipt routines in *Bluehoc*. When the Bluetooth system receives a packet, it is immediately passed to the channel modeling code, which determines whether or not the packet has been received correctly (by examining the current state of the channel). If the packet has been sucessfully received, it is passed to the higher layers of the protocol stack. Otherwise, the error modeler reports that the packet has been lost.

Once the error model was complete, it was tested in the degenerate case (channel correlation being 0) against the results of the original simulator. The results of both the old and new simulation systems were the same in the degenerate case. As well, various statistical tests were run to make sure that the simulator was generating error sequences correctly.

Once the simulator was programmed and tested, simulations were run for both single-channel and two-channel scenarios, with various distances for each scenario. The generated data was analysed using a combination of custom-built scripts and commercial software (Matlab, Xgraph and Gnuplot were used).

6.0 Results

The results below have been grouped into two broad categories: the single-channel (*i.e.* one master-slave connection) results, and the two-channel results. The simulator software works slightly differently for the two scenarios, but the results generated correspond to the models as outlined in sections 4.2 and 4.3.

6.1 The single-channel model

Using the model as described in section 4.2, a series of simulations were run in order to examine network throughput as a function of both the correlation between successive states and the distance between nodes. Figure1 on page17 shows the effect both variables for a Bluetooth network consisting of one master and one slave running an FTP connection. We can see from the figures that as the correlation increases, at a certain point it causes the throughput to fall dramatically. We also note that as the distance increases the throughput also falls. While the latter case is easily understandable (it occurs due to the larger probability of packet error at larger distances) the first case (increased correlation) requires slightly more analysis.

Because the Bluetooth protocol [10] incorporates an ARQ system, the link-layer of the Bluetooth stack automatically retransmits packets which are lost as a result of a bad channel. However, as the correlation increases, the error sequences tend to come in long bursts, and thus when the channel is in a Bad state it tends to stay in that state for longer, causing long delays in the transmission of data packets. When these long delays occur, the sender's TCP/IP layer times out before receiving an acknowledgment (ACK) packet from the receipient, either because the data is still in the process of being transmitted, or because the data has been transmitted but the ACK packet hasn't been fully received. When the TCP/IP layer starts timing out on transmits, it reduces its window size [8], which causes the connection throughput to drop dramatically.

This can be thought of as the Bluetooth ARQ protocol "hiding" errors from the TCP/IP protocol above it. This provides a benefit in terms of performance (because errors have a chance to be corrected at a layer below the TCP stack). However, when the channel conditions become so bad that the TCP timeouts occur, the performance drops off rapidly because of TCP's "congestion back-off" feature.

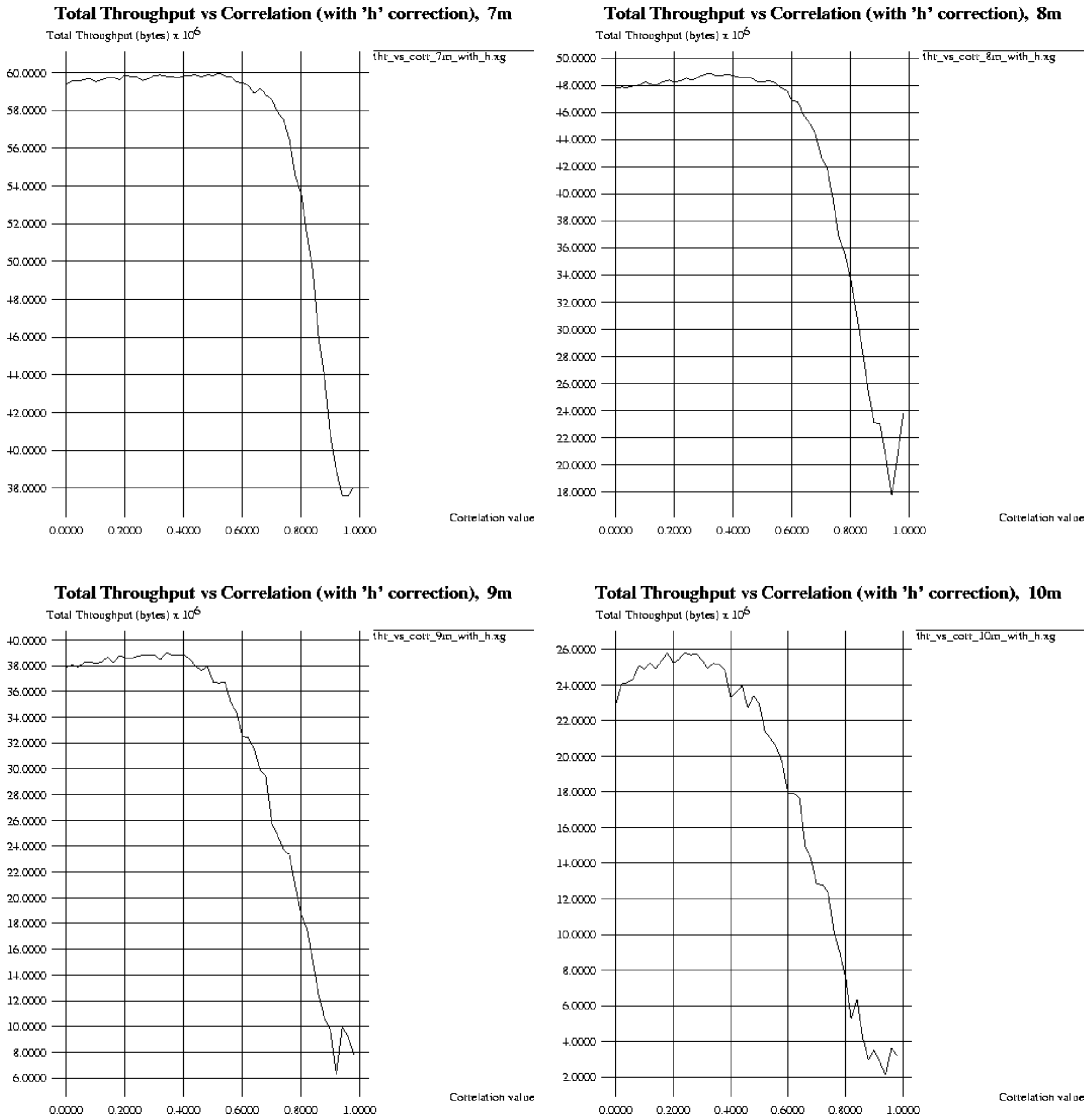
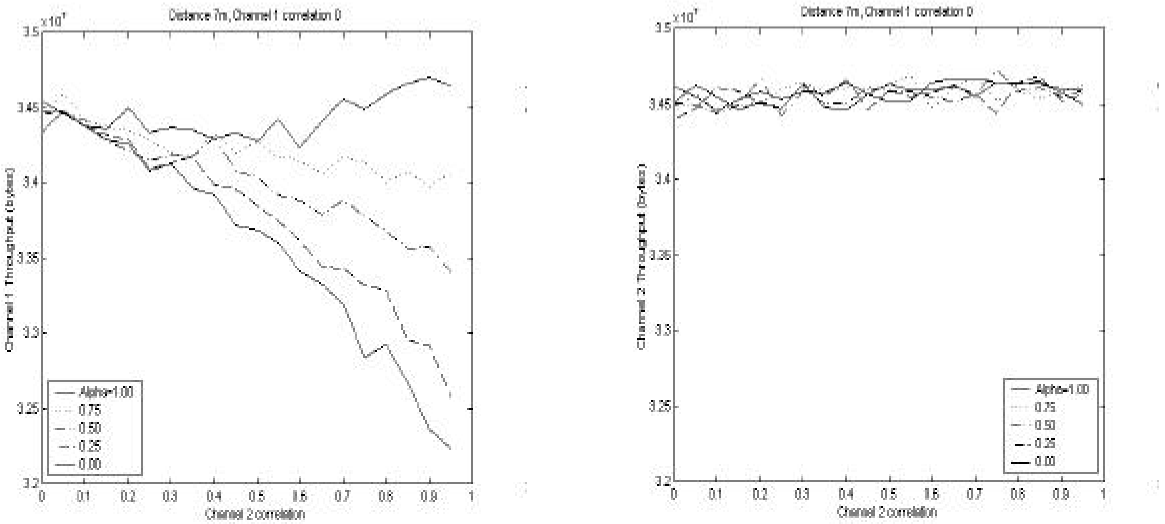


FIGURE 1. The effect of correlation on total throughput, for various distances

6.2 The two-channel model

For the two channel case, the model as detailed in section 4.3 was used. Four parameters were varied: α, the correlation of each of the two channels, and the distance (from 7 to 10 meters). Figure 2 on page18 shows the change in throughput in both channels found by varying α and the channel 2 correlation, while keeping the channel 1 correlation and the distance fixed.

A very interesting result can be observed. Since the channel 1 correlation is set at 0 (the uncorrelated case), and the spatial correlation can be seen as projecting some of the channel 1 errors onto channel 2, the introduction of spatial correlation does not affect the performance of channel 2. However, channel 1 performance is affected by the increase in spatial correlation. We can understand this by considering the effect of this correlation. The end result of introducing spatial correlation is to "share" the temporal correlation between the two channels. Since channel 1 is temporally uncorrelated, when the spatial correlation is introduced, the net effect is to increase the temporal correlation of that channel, which was shown in the single-channel case to decrease performance. Thus spatial correlation can be understood as "correlation sharing".



(a) (b)

FIGURE 2. (a) The effect of spatial and temporal correlation on Channel 1 throughput, (b) on Channel 2 throughput

6.3 Summary of Results

In a TCP/IP connection over a Bluetooth wireless link, the temporal correlation of errors improves performance slightly at low error rates. However, above a certain correlation value (dependent on the distance between nodes), performance decreases dramatically due to TCP/IP timeouts, retransmits, and window shrinking. These effects show a major deviation between the results that are generated using an un-correlated error model (as was the case in the original *Bluehoc* error modeler) and a correlated model such as the one described in sections 4.2 and 4.3.

When two channels are modelled, taking both spatial and temporal correlation into account, the channels experience “correlation sharing”, the effect of which can readily be seen in Figure2 on page18. Correlation sharing can be understood as a situation whereby the error sequence from one channel is projected onto the error sequence of the other channel. When this happens, the effective correlation of the channels changes, causing the throughput to change as well.

7.0 Future work

Several possible extensions to the models and simulations described above are possible. The first possible extension is to create an n -channel model, similar to the models derived in sections 4.2 and 4.3. Ideally, this model would provide the ability to set correlations between any pair of channels (j, k), as well as set a global correlation between all channel pairs.

Another possibility for extension is to create an n-state Markov model (with $n > 2$). This type of model has the possibility of more closely approximating the actual error model of Bluetooth’s wireless channel.

The final possibility of extension is to extend the *Bluehoc* simulator to provide per-bit error modeling. This would simplify the error models of sections 4.2 and 4.3, because no packet-type error rate compensation such as is given in (5) would be necessary. However, the increased computational costs associated with per-bit modeling might make this type of extension infeasible.

8.0 Conclusions

This project has shown that the application of a correlated-error channel model to the simulation of TCP/IP traffic on a Bluetooth link provides a more accurate measure of the performance of the link. Effects such as the performance drop-off at high correlations described above can only be modeled using a correlated channel simulator.

It should be noted that the work described in this report has been accepted for publication [29].

9.0 References

[1] A. Chockalingam and M. Zorzi, “Wireless TCP Performance with Link Layer FEC/ARQ”, *Proc. IEEE ICC'99*, Vancouver, June 1999.

[2] A. Das, A. Ghose, A. Razdan, H. Saran and R. Shorey, “Enhancing Performance of Asynchronous Data Traffic over the Bluetooth Wireless Ad-hoc Network”, *IEEE INFOCOM 2001*, pp. 591-600, 2001.

[3] J. Haartsen, “BLUETOOTH - The universal radio interface for *ad hoc*, wireless connectivity”, *Ericsson Review*, no. 3, pp. 110-117, 1998.

[4] G. Holland and N. Vaidya, “Analysis of TCP Performance over Mobile Ad Hoc Networks”, in *Mobile Computing and Networking*, pp. 219-230, 1999.

[5] A. Kumar, “Comparative Performance Analysis of Versions of TCP in a Local Network with a Lossy Link”, *IEEE/ACM Transactions of Networking*, vol. 6, no. 4, pp. 485-498, 1998.

[6] A. Karnik and A. Kumar, “Performance Analysis of the Bluetooth Physical Layer”, *IEEE ICPWC 2000*, pp. 70-74, 2000.

[7] T. Rappaport, S.Y. Seidel and K. Takamizawa, “Statistical Channel Model Impulse Response Models for Factory and Open Plan Building Radio Communication System Design”, *IEEE Transactions on Communications*, vol. 39, no. 5, pp. 794-807, 1991.

[8] W.R. Stevens, *TCP/IP Illustrated, Volume I: The Protocols*, Addison Wesley, 1994.

[9] J. Proakis, *Digital Communications, Third Edition*, McGraw-Hill, 1995.

[10] Bluetooth Special Interest Group, “Specification of the Bluetooth System 1.1, Volume 1: Core,” *http://www.bluetooth.com*, Feb. 2001.

[11] S. Lin, D.J. Costello, and M.J. Miller, “Automatic-repeat-request error control schemes,” *IEEE Communications Magazine*,vol. 22, no. 12, pp. 5-16, 1984.

[12] A. El-Hoiydi, “Interference Between Bluetooth Networks - Upper Bound on the Packet Error Rate”, *IEEE Communications Letters*, vol. 5, no. 6, pp. 245-247, 2001.

[13] G. Koomullil, “Performance Analysis of Bluetooth Systems in the Presence of AWGN, Fading, Multipaths, and Inband Interference”, *IEEE ICCE 2000, Digest of Technical Papers*, Los Angeles, pp. 294-295, 2000.

[14] R. Nichols and M. Amin, “Modeling Systems Based on Bluetooth Wireless Connectivity”, *Microwaves & RF*, August 2000.

[15] H. Hashemi, “The Indoor Radio Propagation Channel”, *Proceedings of the IEEE*, vol. 81, no. 7, pp. 943-968, 1993.

[16] M. Zorzi, R. Rao, and L. Milstein, “On the accuracy of a first-order Markov model for data transmission on fading channels”, *Proc. ICUPC’95*, pp. 211-215, Tokyo, Nov. 1995.

[17] W. Xu, A. Chockalingam, and L. Milstein, “Performance analysis of multichannel wireless access protocol in the presence of bursty packet losses”, *Proc. MILCOM’98*, vol. 1, pp. 233-237, Boston, Oct. 1998.

[18] M. Zorzi and R. Rao, “Throughput analysis of Go-Back-N ARQ in Markov channels with unreliable feedback”, *Proc. ICC’95*, vol. 2, pp. 1232-1237, Seattle, June 1995.

[19] M. Zorzi, A. Chockalingam, and R. R. Rao, ``Performance Analysis of TCP on Channels with Memory," *Tech. Report, Center for Wireless Communications, UCSD, La Jolla*, Sep. 1998.

[20] N. Chaskar, T. Lakshman, and U. Madhow, “TCP over wireless with link level error control: analysis and design methodology”, *IEEE/ACM Transactions on Networking*, vol. 7, no. 5, pp. 605-615, 1999.

[21] http://oss.software.ibm.com/bluehoc/, 2002.

[22] http://www.isi.edu/nsnam/ns/, 2002.

[23] L.N. Kanal, and A. Sastry, "Models for Channels with Memory and Their Applications to Error Control," *Proc. IEEE*, vol. 66, no. 6, July, 1978, pp. 724-744.

[24] W. Turin, and R. van Nobelen, "Hidden Markov Modelling of Fading Channels," VTC 98, pp. 1234-1238.

[25] F. Babich, and G. Lombardi, "A Markov Model for the Mobile Propagation Channel," *IEEE Trans. Vehic. Tech.*, vol. 49, no. 1, January, 2000, pp. 63-73.

[26] C. Pimentel, and I. Blake, "Enumeration of Markov Chain and Burst Error Statistics for Finite State Channel Models," *IEEE Trans, Vech. Tech.*, vol. 48, no. 2, March, 1999, pp. 415-427.

[27] S. Sivaprakasam, and K.S. Shanmugaan, "An Equivalent Markov Model for Burst Errors in Digital Channels," *IEEE Trans. Communications*, vol. 43, April, 1995, pp. 1347-1355.

[28] J. Nakayama, "Generation of Stationary Random Signals with Arbitrary probability Distribution and Exponential Correlation," *IEICE Trans. Fundamentals*, Vol. E77-A, no. 5, May, 1994, pp. 917-921.

[29] C. Snow, and S. Primak, “Performance Evaluation of TCP/IP in Bluetooth Based Systems”, *Proc. IEEE VTC Spring’02*, in press.