Improving Wireless Link Throughput via Interleaved FEC

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Abstract

Wireless communication is inherently vulnerable to errors from the dynamic wireless environment. Link layer packets discarded due to these errors impose a serious limitation on the maximum achievable throughput in the wireless channel. To enhance the overall throughput of wireless communication, it is necessary to have a link layer transmission scheme that is robust to the errors intrinsic to the wireless channel. To this end, we present Interleaved-Forward Error Correction (I-FEC), a clever link layer coding scheme that protects link layer data against random and busty errors. We examine the level of data protection provided by I-FEC against other popular schemes. We also simulate I-FEC in Bluetooth, and compare the TCP throughput result with Bluetooth's integrated FEC coding feature. We show that I-FEC consistently and significantly outperforms other link layer coding schemes by providing an impressive amount of protection against heavy channel burst errors.

1. Introduction

With the increasing utilization and the consumption of digital information through wireless devices, maximizing the available wireless channel bandwidth becomes essential in maintaining quality services to the wireless users. Since a wireless communication channel typically exhibits higher error rates due to attenuation, fading, scattering, or interference from other active sources, a challenging problem is to provide the wireless applications with the best possible data throughput in the presence of wireless channel errors.

As most wireless channel errors are discovered and discarded at the link layer, link layer retransmission triggered by corrupted data decreases the effective channel bandwidth. This results in inferior performance from higher network layers such as TCP and video streaming applications. Therefore, if the number of retransmissions can be reduced with a robust link layer error controlling scheme, the performance of wireless communication would dramatically improve against channel errors.

Traditionally, one of three techniques is used for error-control: 1) Retransmission which uses acknowledgements, and time-outs; 2) Redundancy, and 3) Interleaving [6] [13]. Retransmitting lost packets is an obvious means by which error may be repaired, and it is typically performed at either the link layer with Automatic Repeat reQuest (ARQ) or at the end-to-end layers with protocols like TCP. When data is exchanged through a relatively error-free communication medium, retransmission is clearly a good tactic. However, retransmission is not the best strategy in an error-prone communication channel, where high latency and bandwidth overhead are believed to make retransmission a less than ideal error controlling technique.

Redundancy is the means by which repair data is added along with the original data, such that corrupted packets can be repaired at the receiver without any additional transmission from the sender. A number of redundancy techniques have been developed in both the application and link layers to combat the effect of errors [11] [14]. Some popular link layer protocols, such as Bluetooth [15] and 802.11a [9] have implemented some variations of data redundancy techniques such as Forward Error Correction (FEC), which is well recognized for its robustness against random data losses, to enhance their throughput performance. However, redundancy comes at the cost of reduced bandwidth, since these schemes incur error correction overhead.

As an error concealment scheme, Interleaving is a useful technique for reducing the effects of losses. The basic idea behind interleaving is to first re-sequence the data before transmission, so that originally adjacent units of data are separated by a predetermined distance while in flight from source to destination, and return to their original order at the receiver. Since interleaving reduces the damage from loss by dispersing the occurrence of errors in the original stream, [3] [4] [16] have deployed interleaving techniques to real-time video streaming applications to obtain better performance. On the other hand, even though interleaving doesn't impose any extra bandwidth overhead, it can potentially increase the processing latency, as the receiver requires that all the necessary transmitted data packets be in its buffers before it can reconstruct the original data packets.

Unfortunately, wireless channel errors are bursty in occurrences. A pure retransmission strategy is too costly for the error-prone wireless communication channel. Redundancy and interleaving techniques are not enough by themselves to safeguard data transmissions from burst errors. Redundancy methods such as FEC coding are only effective in counteracting random losses, but the connection is still vulnerable to burst channel errors. Interleaving is capable of minimizing the effect of burst errors, but it can not recover from the errors introduced into the data packets. Besides, typical packet level interleaving methods, such as [4] [16], costs extra latency to the connection.

In this paper, we focus on the problem of protecting link layer data against the random errors and burst errors that characterizes the wireless channel. By combining the robustness of FEC against random errors and the survivability of Interleaving against burst channel errors, we show that applying bit level interleaving to FEC coded packets is an effective method to combat wireless channel burst errors. The tactic we deployed is I-FEC, which stands for Interleaved-Forward Error Correction.

We compare the data retransmission rate of I-FEC under different burst error rates against the other schemes, and compare the TCP throughput result of I-FEC to Bluetooth's built-in FEC coding scheme under different topologies and channel conditions. Without costing any additional overhead or latency, we show that I-FEC consistently and significantly outperforms FEC by achieving an unparalleled amount of protection against heavy channel burst errors.

The rest of this paper is organized as follows. In section 2, we describe the channel error model, and the current implementation of the Bluetooth technology. In section 3, we present Interleaved FEC and related analysis. In section 4, we compare the effectiveness of different error controlling schemes through simulation. Section 5 concludes the paper.

2. Overview

In section 2.1, we explain the Gilbert-Elliott model used to capture the bursty and dependent nature of wireless link errors. In section 2.2, we briefly describe the Bluetooth technology, which is used to perform the simulation and analysis of our proposed design.

2.1. Error Model

In reality, wireless channel errors are usually bursty and dependent in occurrences, rather than uniformly and independently distributed. To capture such behavior in the wireless channel, a discrete time Markov Chain (DTMC) model depicted in Figure 1, commonly known as the Gilbert-Elliott model [5] [8], is used to model the true nature of wireless channel errors. The Gilbert-Elliott model consists of two states, namely the *Good* state and the *Bad* state. Events originate from these states are denoted as g and b respectively. Four transition probabilities, P_{gg}, P_{gb}, P_{bg}, and P_{bb}, are then given and they specify the state transition probabilities. For example, P_{gb} defines the probability of transition from the good state to bad state, and P_{bb} defines the probability of remaining in bad state, which actually reflects the degree of burst errors. The Markov chain is ergodic with stationary probabilities $P_g = \frac{1-P_{bb}}{1-P_{bb}+P_{gb}}$ and $P_b = \frac{P_{gb}}{1-P_{bb}+P_{gb}}$, and P_b is the average bit error rate (BER) [17].

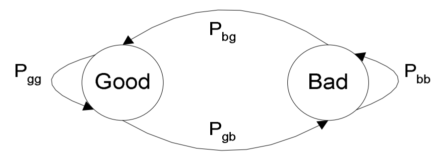

Figure 1: Markov Model for Wireless Link

Packet Size	FEC Level	P_{bb} = 0.1	P_{bb} = 0.3	P_{bb} = 0.5	P_{bb} = 0.7	P_{bb} = 0.9
100 bytes	(15,10)	3.25 %	9.42 %	15.44 %	21.47 %	28.61 %
	(7,4)	3.39 %	10.24 %	16.92 %	23.45 %	30.18 %
	None	32.92 %	32.93 %	32.94 %	32.98 %	33.23 %
200 bytes	(15,10)	7.40 %	20.48 %	31.84 %	42.00 %	51.16 %
	(7,4)	6.76 %	19.39 %	30.79 %	41.28 %	50.91 %
	None	55.09 %	55.10 %	55.11 %	55.13 %	55.29 %
500 bytes	(15,10)	16.86 %	42.59 %	60.57 %	73.33 %	82.68 %
	(7,4)	16.09 %	41.90 %	60.51 %	73.76 %	83.15 %
	None	86.49 %	86.49 %	86.49 %	86.50 %	86.55 %

Table 1: Packet error rates evaluated against different FEC schemes, link layer packet sizes, and P_{bb}, given that P_{gb} = 0.0005 and the initial channel state is *Good*

Given P_{gb} = 0.0005 and initial channel state is *Good*, Table 1 shows the packet error rates under different degrees of burst error. The packet error rate was conjointly evaluated against the different packet sizes (100, 200, and 500 bytes), and different FEC coding schemes ((15,10), and (7,4) Hamming code). The (m, n) Hamming coding means n bits data are coded into a m bits codeword with the ability to correct single bit error in each codeword.

Table 1 clearly shows that data packet coded by FEC scheme outperforms data packets without FEC coding when P_{bb} (degree of burst error) is small. However, when P_{bb} increases, we note that FEC coding schemes cease to make a significant difference in the packet error rate. We also observe that smaller packet sizes reduce the packet error rate in the link layer, but it degrades effective bandwidth as more packets, packet overhead, and communication overhead need to be transmitted.

2.2. Bluetooth Technology

Bluetooth is a short-range, low cost, and low power consumption radio technology operating in the unlicensed 2.4GHz ISM (Industrial-Scientific-Medical) frequency band. It employs FHSS (Frequency Hopping Spread Spectrum) technique and implements stop and wait ARQ (Automatic Repeat reQuest), CRC (Cyclic Redundancy Check), and FEC (Forward Error Correction) to achieve high reliability on the wireless links and to alleviate the interferences cause by other radio technologies, such as 802.11b [15], cordless phones, and microwave ovens. The FEC scheme used in Bluetooth is a (15, 10) shortened Hamming code, in which each block of 10 information bits is encoded into a 15 bit codeword, and it is capable of correcting single bit error in each block.

Bluetooth units can be connected to other Bluetooth units to form a piconet, which can support up to eight active units. One of the units in a piconet acts as a master and the other units act as slaves. All the data/control packet transmissions are coordinated by the master. Slave units can only send in the slave-to-master slot after being addressed in the preceding master-to-slave slot. Each slot lasts for 625 microseconds.

Mode	FEC	Packet		Symmetric Throughput (kbps)	Asymmetric Throughput (kbps)	
		Size (bytes)	Length (slots)			
DM1	Yes	17	1	108.8	108.8	108.8
DM3	Yes	121	3	258.1	387.2	54.4
DM5	Yes	227	5	286.7	477.8	36.3
DH1	No	27	1	172.8	172.8	172.8
DH3	No	183	3	390.4	585.6	86.4
DH5	No	339	5	433.9	723.2	57.6

Table 2: Different Bluetooth ACL connection modes

For real-time data such as voice, Synchronous Connection Oriented (SCO) links are used, while for data transmission, Asynchronous Connectionless Link (ACL) links are used. There are several ACL packet types, differing in packet length (and consequently, data transmission rate) and whether they are FEC coded or not. Table 2 shows the different ACL packet types and their properties.

Note that, in the symmetric connection mode, both master and slave nodes will occupy the same amount of Bluetooth time slots (625 microseconds in each time slot); whereas in the asymmetric connection mode, the Bluetooth link will occupy 1/3/5 time slots (for DM1/DM3/DM5 or DH1/DH3/DH5 mode) in one direction of this link and only one time slot in the opposite direction.

Due to the built-in support of FEC coding in Bluetooth, Bluetooth technology will be used to validate our proposed approach in the sections that follows. Performance comparison will then be made between the proposed approach and the current Bluetooth FEC implementation.

3. Interleaved FEC (I-FEC)

FEC coding has been well studied [1][2][7], and it is the preferred error-control scheme to fight random losses, even though perfect recovery cannot be guaranteed. The main drawback of FEC technique is the overhead incurred due to the redundancy information. Although the extra overhead of FEC decreases the maximum achievable throughput, its ability to correct minor data losses makes FEC a desirable link layer coding scheme in error-prone environments, such as in the wireless medium.

Bluetooth's link layer implements both DH and DM connection modes, differing in their usage of FEC coding. In DH mode, Bluetooth sends packets without FEC coding in order to maximize the achievable throughput; whereas in DM mode, it uses a (15, 10) shortened Hamming code to protect the packets from transmission errors. In DM mode, each block of 10 information bits is encoded into a 15 bit codeword, and it is capable of correcting single bit error in each block. Analysis has shown that the deployment of FEC coding in DM mode enhances the transmission performance when the bit error rate surpasses a certain threshold [10].

However, the majority of the existing FEC implementations, including DM mode in Bluetooth, operate on a continuous block basis; thus, it only performs well when the number of errors are small, the amount of burst errors are rare, and the occurrences of errors are independent to each other. But those assumptions are not valid for the wireless environment, because once the wireless channel turns bad, the errors will happen in bursts and becomes dependent on each other, as reflected by the Gilbert-Elliott model in the previous section.

Interleaving is the preferred solution to alleviate the effects of burst errors and has been popularly employed in end-to-end multimedia applications [3][4][16]. A sender interleaves the data packets before sending them out, and the receiver reconstructs the data packets after a certain amount of latency. Latency is determined by the level of interleaving, since reconstructing interleaved data packets would require the correct delivery of all packets involved in the interleaving.

I-FEC joins together the strengths of both the FEC and interleaving techniques. It aims to incorporate the robustness of FEC against random errors, as well as the interleaving's ability, to alleviate the effects of burst errors. We took advantage of the built-in FEC support in Bluetooth technology, and applied I-FEC to its link layer. Since Bluetooth is a popular personal area network technology suffering from constant interferences from other radio based network equipment, I-FEC is expected to alleviate the packet loss rate of Bluetooth networks and improve effective bandwidth.

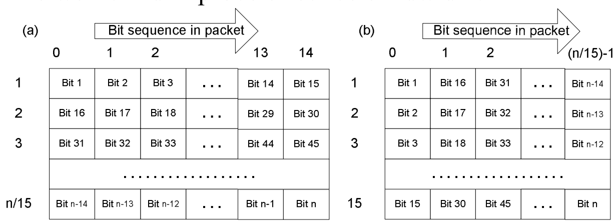

Figure 2: (a) Bluetooth DM mode; (b) I-FEC coding

In Bluetooth DM mode, a packet of size *n* bits is divided into several *n/15* bits blocks. Each block is a FEC codeword consisting 10 data bits and 5 redundancy bits. Unsurprisingly, FEC codeword used in DM mode remains vulnerable to burst errors because consecutive bits are still continuous in a FEC codeword. Instead of using the same design approach as the Bluetooth DM mode, I-FEC divides each packet into *15* blocks with *n/15* bits each. It then constructs the first 15-bit codeword by applying FEC to the first bit of each block, the second 15-bit codeword is constructed by applying FEC to the second bit of each block, and so on and so forth. Therefore, each codeword inherits the ability to correct single bit error like it was in the DM mode without having any continuous consecutive bits. The difference between I-FEC and Bluetooth DM mode is illustrated in Figure 2.

3.1. Analysis

Since I-FEC uses the same (15, 10) Hamming code for FEC coding as Bluetooth DM mode, the overhead used by I-FEC is the exact same amount used in the original DM mode, which implies that I-FEC will have the same maximum throughput as DM mode in a perfect wireless channel. Moreover, I-FEC resolves the latency problem associated with interleaving by applying *bit level interleaving* instead of packet level interleaving. The latency from interleaving becomes negligible since data is interleaved within a single link layer packet instead of being interleaved across different packets.

As a result, I-FEC inherits both the robustness of FEC coding against random errors, and the survivability of interleaving against burst errors. For instance, suppose bit sequence number one of the data packet is corrupted in Figure 2; both FEC and I-FEC coding schemes are capable of correcting that error. However, when burst error corrupts the first two bits of the data packet, the original FEC scheme will fail to recover the intended data; whereas I-FEC can successfully recover the original packet by distributing contiguous bit errors to different FEC codewords. In Figure 3 and 4, we capture the retransmission rate of 1) I-FEC, 2) The original FEC scheme (DM5 mode), and 3) without any FEC support (DH5 mode) under various channel conditions.

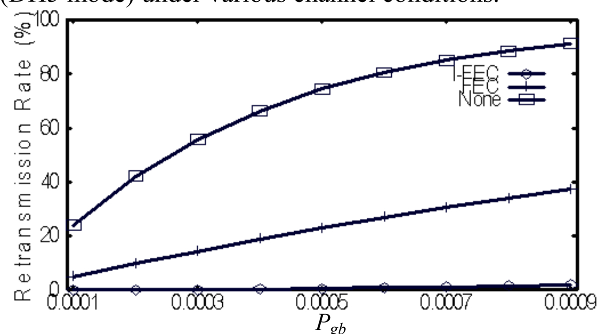

Figure 3: Retransmission Rates of different schemes evaluated at different Pgb, given Pbb = 0.2

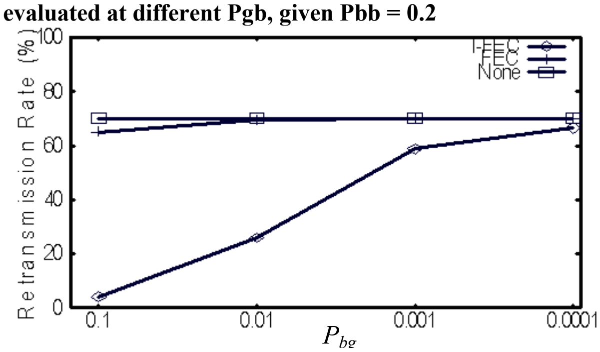

Figure 4: Retransmission Rates of different schemes evaluated at different P_{bg}, given P_{gb} = 0.0003

When the burst error rate is fixed at 0.2 (P_{bb} = 0.2), Figure 3 shows that I-FEC consistently achieves a lower retransmission rate than FEC. It is also observed that FEC coded transmission is consistently better in retransmission rate compare to transmission without FEC coding scheme. In Figure 4, with P_{gb} fixed as 0.0003, I-FEC again outperforms FEC by achieving a smaller retransmission rate. However, FEC coded transmission begin to perform as poorly as regular transmission when P_{bg} decreases due to increasing degree of burst error ($P_{bb} = 1 - P_{bg}$). When P_{bb} is greater than 0.999 (P_{bg} less than 0.001), it is observed that I-FEC results in a high retransmission rate as well. The reason behind the decrease in performance is the dramatic increase in length of burst errors when P_{bb} increases. When P_{bb} increases beyond 0.999, none of the available schemes can really make a difference in the retransmission rate. The relationship between the length of burst errors and P_{bb} is depicted in Figure 5.

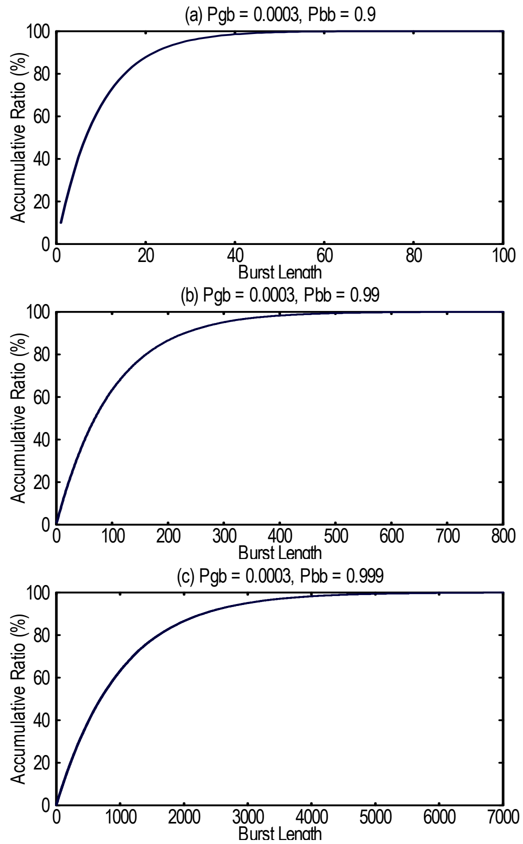

Figure 5: The accumulative ratio of burst length under different wireless channel conditions given P_{gb} =.0003; a) P_{bb} =.9 (b) P_{bb} = .99 (c) P_{bb} = .999.

4. Simulation

In this section, we present simulation results demonstrating the performance improvement by applying I-FEC to Bluetooth's link layer. The Bluetooth extension of NS-2 (Network Simulator) [12] was used for simulations. The extension implemented frequency hopping, time division duplexing, multi-slot packets, fragmentation and reassembly of packets in the Bluetooth baseband layer, and it supports scatternets and inter-piconet communication by defining gateway nodes to forward packets between piconets. We implemented a bit level burst error channel model and I-FEC to the link layer of the Bluetooth NS-2 extension.

The Bluetooth topologies used for the simulations are shown in Figure 6. Black circles are the master nodes, while white circles represent the slave (or gateway slave) nodes. Each simulation ran for 600 seconds. We used 5 time-slots packet in Bluetooth link layer, which means for transmission without using a FEC scheme, the DH5 packet type is chosen; whereas for the built-in FEC scheme, the DM5 mode is chosen. I-FEC is also designed as a 5 time-slots packet type, but it interleaves the FEC coded transmission from the DM5 mode. We evaluated the performance of these three schemes at different error rates, different degrees of burst error conditions, and different number of hops.

Note that in the 2-hop case, the capacity of the master (black node) will be shared between the two slaves. Thus, the maximum throughput in is just half of the maximum throughput of the 1-hop case.

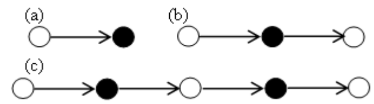

Figure 6: (a) 1 hop (b) 2 hop (c) 4 hop situation

4.1. TCP with different P_{gb}

TCP NewReno was used for the first set of simulation, and Figure 7 illustrates the performance of TCP NewReno evaluated under different link layer schemes, number of connections, and P_{gb} probabilities. Size of the TCP packet was set at 500 bytes, and the buffer size on each Bluetooth node was 9000 bytes. The channel condition of every hop is configured the same for every run, P_{bb} is always fixed as 0.2 and P_{gb} varies from 0.0001 to 0.001 for each series of experiment.

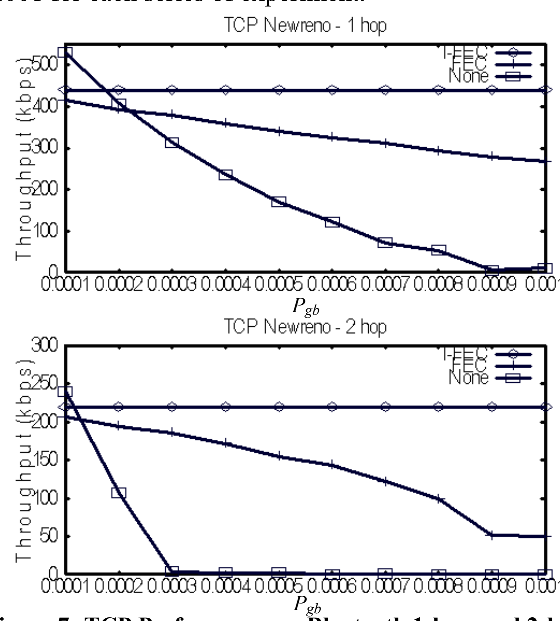

Figure 7: TCP Performance on Bluetooth 1-hop, and 2-hop connections with P_{bb} *=0.2*

The simulation result shows that TCP throughput decreases considerably when P_{gb} increases for FEC coded transmission (DM mode) and regular transmission (DH mode). On the other hand, I-FEC was able to maintain a very consistent throughput regardless of the changes in P_{gb}. The improvement on throughput becomes even more obvious whenever the error rate increases or when the hop number increases. Transmission without any coding scheme does outperform FEC and I-FEC coded transmission when the error rate is very small, this is due to the redundant error-correction code carried by FEC and I-FEC.

4.2. TCP with different P_{bb}

The second simulation is to compare the performance of TCP NewReno under different link layer schemes, number of connections, and varying burst error probabilities. The TCP connection and the Bluetooth configuration is the same as the previous section, except P_{gb} is now fixed at 0.0003 and P_{bb} varies from 0 to 0.9999 for each series of experiment.

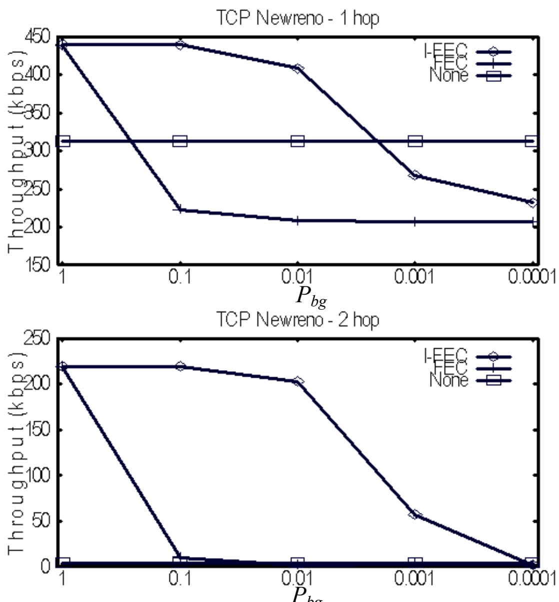

Figure 8: TCP Performance on Bluetooth 1-hop, and 2-hop connections with P_{gb} =0.0003

From Figure 8, I-FEC clearly outperforms the FEC coded transmission and regular transmission in most of the test cases regardless of the degree of burst error P_{bb} (P_{bb} =1- P_{bg}). The throughput performance of FEC coded transmission decreases dramatically when P_{bb} increases. This is due to the fact the FEC coding is designed to work on consecutive bits, which is proven to be quite vulnerable to burst errors. It is also observed that regular transmission actually performs well under the 1-hop scenario when P_{bb} is large, because the high error rate and the extra redundancy packets depreciate the FEC and I-FEC coding schemes. Nonetheless, this is a tradeoff in link later design, and it is possible to make the coding scheme adaptive to optimize the overall throughput performance.

5. Conclusions

We propose Interleaved Forward Error Correction (I-FEC), a hybrid approach incorporating the robustness of FEC coding to random errors and the survivability of interleaving to burst errors We analyzed various link layer coding schemes under different wireless channel configurations, and observed the different level of protection (retransmission rate) provided by each scheme. We also simulated I-FEC in Bluetooth, and evaluated its performance against the FEC scheme in Bluetooth, and observed that I-FEC displayed significant improvement in terms of TCP throughput in the presence of random wireless burst errors, especially when the degree of burst error is high. Additionally, the *bit-level* interleaving approach was effective in eliminate the latency usually associated with packet level interleaving. Therefore, we have demonstrated that I-FEC has much to contribute in providing higher performance and more reliable services in the wireless environment.

6. References

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