IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Interference with Bluetooth Device

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Abstract

The Bluetooth and microwave ovens operate in the same frequency band which resulted in the study of interference of these two devices. Though Bluetooth devices use frequency hopping spread spectrum (FHSS), but the microwave oven have high power output which may result in the interference of the Bluetooth networks. In an experimental setup it is seen that the Bluetooth devices tolerate a high level of interference. In the experimental setup as the distance is increased between the Bluetooth device and the oven there is little degradation in the throughput due to interference. The experimental results us to conclude that the interference caused by the microwave ovens is not fatal, on the contrary we do notice the interference which is being caused and hence studied here.

Keywords: Bluetooth, interference, ISM band, microwave oven.

Introduction

The 2.400 – 2.4835 GHz band hosts a wide range of licensed ISM (Industrial, Scientific and Medical) products, unlicensed communications devices such as Bluetooth WPANs (wireless personal area networks), IEEE 802.11b's Ethernet WLANs (wireless local area networks). While broadband modulation techniques and low power generally ensure that these devices do not interfere with one another, interference may become a problem as the volume of users increases. A number of microwave devices operate in the ISM band. The primary occupants of this spectrum are non-communications devices such as microwave ovens and RF-excited lighting. The power leakage from these devices is limited by concerns about user safety rather limiting interference to unlicensed devices. The relatively large leakage power of microwave ovens is a potent source of interference to unlicensed Federal Communications Commission (FCC) Part 15 [1] communications devices.

The Bluetooth short-range radio specification is proposed as a standard that will make wireless networking ubiquitous. However, like any other wireless technology, it will undoubtedly run into interference problems from other 2.4 GHz devices. While microwave ovens are not the only ISM band application, they represent one of the most common applications and are some of the most powerful interference sources. This thesis investigates the interference potential of microwave ovens operating in the ISM band to Bluetooth communication.

Section 2 of this paper describes the power and frequency characteristics of Bluetooth devices and microwave ovens. Section 3 discusses the experimental setup and measurements and the tools used to conduct the experiments. Section 4 discusses the results from the experiments, and Section 5 concludes the study with our observations on Bluetooth operations in the presence of microwave ovens.

Bluetooth and Microwave Oven Operations

Bluetooth Operation

Bluetooth is a well-defined open standard maintained by the Bluetooth Special Interest Group (SIG). Bluetooth operates in the ISM band with data being transmitted in the range of 2.402 GHz to 2.480 GHz. It is a FHSS device where each packet is transmitted or received on a different channel. The FHSS is pseudorandom, there is no intelligence in the FHSS to avoid hopping onto certain channels. Even with the pseudorandom FHSS sequence, interference from devices such as microwave ovens may still produce significant packet errors and reduce throughput. The most important aspects of a Bluetooth device for an interference study are its frequency and power output. The FHSS employed by Bluetooth uses 79 channels 1 MHz wide with a hopping rate of 1600 channels per second. Bluetooth communication is also time division duplex (TDD) where, between two entities on the same Bluetooth piconet (a network of two or more Bluetooth devices), one device transmits in a period followed by another device's transmission. Bluetooth operates under FCC Part 15 rules, which stipulate that it must not give interference, and it must take any inference it receives. The FHSS reduces Bluetooth's ability to produce interference to other ISM band devices by spreading the power throughout the spectrum. The FHSS has the added benefit of being able to reduce the effects of interference sources: if another device is using a portion of the ISM band, the Bluetooth device will retransmit on another channel unacknowledged packets lost to interference on a particular channel. With more than two members of a piconet, the master controls the transmission sequence by polling each slave sequentially to indicate when it may transmit.

Frequency hop spread spectrum*:* Bluetooth transmits data by employing frequency-hopped spread spectrum. Using this technology, the available 79 MHz ISM bandwidth is subdivided into non-overlapping, one MHz channels, as shown in Figure 1 below.

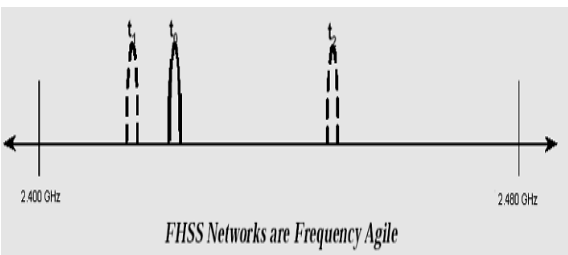

Figure 1

The transmitting radio transmits a data packet on one of these 79 frequencies (channels) and rapidly hops to another frequency to transmit the next packet, and so on. The sequence of frequencies to which the transmitting radio hops is predetermined, and is generated by a frequency selection kernel in the master radio unit. The technology employs a time division duplex scheme where data is transmitted at a rate of 1600 hops/sec. Thus, time periods are divided into 1/1600 = 625 µsec slots. Transmission from the master to the slaves begins with the even numbered slots and the slaves respond in the odd numbered slots.

The co-existence problem: Part 18, of the FCC Code of Federal Regulations describes a wide range of low power radio devices for communications, sensing, and other applications operating in the ISM band. Bluetooth is one of the "Part 15" devices which does not require a license for operation. The penalty that all unlicensed Part 15 devices must bear is that they may not give interference to licensed users of the operating band or to other Part 15 devices, and must accept any interference to which they are subjected. Thus, the transmitter power and the antennas of Part 15 devices are limited to prevent interference. Bluetooth transmission power levels range from 0 dBm (1 milliwatt) up to a maximum of 20 dBm (.1 watt). Microwave ovens, on the other hand, are extremely powerful emitters that have effective isotropic radiated powers (EIRP) on the order of 16-33 dBm. Since ovens are Part 18 devices licensed for operation in the ISM band, their power emissions are not regulated by the FCC. Oven emissions are regulated more by safety standards concerned with health hazards of emissions rather than their effect on unlicensed communication devices. Therefore, the high-power emissions of ovens make them a major source of interference to Bluetooth communication.

Microwave Oven Operation

A microwave oven is basically a metal cavity provided with a source of microwave energy and equipped with a door and door seal to prevent microwave energy from escaping the cavity. The source that produces the microwave energy is a magnetron tube.

Residential Microwave oven**:** The typical residential microwave uses a single magnetron tube. Static stable standing wave patterns inside the cavity of the oven would produce an uneven heating effect. Microwaves often employ a mechanical "stirrer" to distribute the microwave energy more uniformly in the oven. In this manner, the food or drink placed on the rotating table is "illuminated" on all sides and is cooked more evenly. This heating process effects the magnetron loading and thus its frequency. The type and size of the food load also effects the operating frequency as do changes in the food load as it cooks. In addition, most residential ovens operate in a half wave mode. They employ half wave rectifiers and sometimes use the magnetron itself as the rectifier.

Commercial microwave Oven*:* Commercial microwave ovens display somewhat worse spectral characteristics. These ovens employ magnetron pairs that operate on alternate half cycles. Stirrers are used to distribute the energy uniformly in the cooking chamber. The commercial oven occupies considerably more spectrum than the residential oven.

Measurements

Spectrum Capture

To capture the oven spectrum a computer-controlled spectrum analyser is used over a period of time. Here a real-time spectrum analyser is approximated by programming a computer interface to capture data from the spectrum analyzer at a rate of approximately 2 sweeps per second. Each sweep captured the signal power levels over the entire 79 MHz spectrum occupied by Bluetooth transmissions.

The major relevance of this technique to capture the spectrum over a period of time is to improve upon the standard peak-hold measurements used to classify microwave oven outputs. Unlike the spectrum plots shown in Figs. 2 and 3, a peak-hold plot gives no indication of power fluctuations or frequency wander that occurs during the oven's operation. Fig. 2 gives a clear indication that the output power levels are not constant, and Fig. 3 shows that while this oven is fairly narrowband, the power densities do move around the center frequency of 2.53 GHz.

The spectrum analyzer used to capture the Power SpectralDensity (PSD) data swept the 79 MHz ISM band for 33 ms twice a second. During the 33 ms sweep, the oven completed 2 full periods of operation to produce the resulting spectrum of Figs. 2 and 3. The sweep was triggered from the AC line to ensure that the sweep would coincide with the oven output.

The received power recorded in Figs. 2 and 3 peaked around –25 dBm at about 2.455 GHz, which is about 30 dB higher than the upper limit of the received power range of Bluetooth, and even the most significant sideband (at approximately 2.433 GHz) peaked around –61 dBm, which is in the range of the Bluetooth's minimum received power. While looking at the microwave oven output power characteristics, we used a number of different ovens, each of which had widely varying spectrums. The microwave oven used for the interference tests was chosen because of its high power output; it should represent a worst-case situation for residential microwave oven interference. However, the exact effects of any given microwave oven on a Bluetooth network will inevitably vary from the data collected in our experiments. Our data should provide an upper bound on the interference problems a Bluetooth network will have in the presence of any microwave oven.

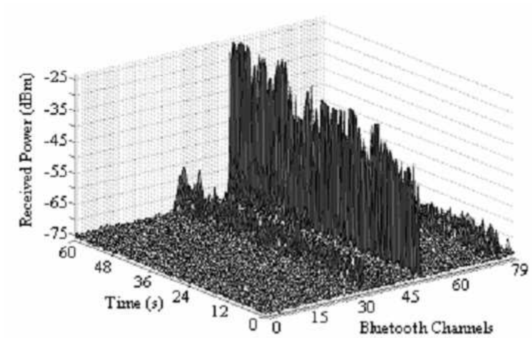

Figure 2

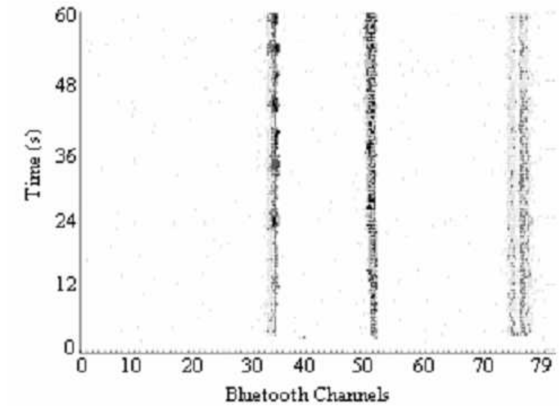

Figure 3

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Bluetooth Devices and Control Software

The configuration of theBluetooth devices was set to limit the maximum transmitpower to 12 dBm even though they were capable of a maximum power of 20 dBm.

The devices are controlled via a USB bus by two separate computers running Center for Wireless Telecommunications' (CWT) Bluetooth Protocol Stack. The protocol stack is written at the CWT and handles all layers above and including

the Host Controller Interface (HCI). To utilize the protocol stack, an application called Bluetooth Test Program is created that allows any computer to interface with any Bluetooth device over a serial or USB line. From the interface, any command available through the HCI stack can be issued such as reading or writing hardware registers, performing inquiries, creating and destroying connections, and transmitting data.

For our experiments, we are interested in the maximum data throughput. A packet must fill every time slot in order to achieve maximum throughput and for us to accurately observe the entire hopping sequence and the effect of the microwave oven on each timeslot. The Bluetooth Test Program is programmed in order to ensure that the Bluetooth device transmitted a data stream with a full payload during every timeslot. The program ensured that, under optimal conditions of no interference or packet errors, maximum data throughput was always achieved. By the careful tuning of the program, we guaranteed that any reduction in throughput was caused by bit errors and interference.

Data Collection Techniques

To analyze the interference effects on the Bluetooth network, we wanted to know the contents of every data packet on the link. By knowing the data packets, we can calculate the data throughput of the link and observe lost data packets or any errors in the data packets. Errors could occur either from the interference source or through routine errors introduced by the radio channel, and a lost packet is a packet with so many bit errors that it can no longer be recognized as a Bluetooth packet. Because the Bluetooth Test Program ensured all time slots were filled with a data packet, any empty time slot observed at the receiver corresponded to a lost packet.

We used a Bluetooth protocol analyzer to capture all data packets. The protocol analyzer captures all packets including the frequency of the transmission, time slot of the transmission based on the master's clock, packet payload, and whether the packet had a recoverable error (errors correctable by the FEC information) or a non-recoverable error (the FEC could not correct the errors or no FEC was present).

A histogram is used to analyze the interference. It shows the number of packets of each type on all 79 channels as captured by the protocol analyzer. The histogram gives a visual representation of the Bluetooth network transmissions. For all tests, the master transmitted a single type of data packet (DM1, DH1, DM3, or DH3) and, according to the acknowledgement system in the Bluetooth protocol, the slave acknowledged with a NULL packet. The histogram displays recoverable error packets, non-recoverable error packets, and lost packets. Fig. 4 shows the configuration of a bar in the histograms, segmented by the type of packet. A channel with a high-powered interferer will have fewer usable data packets and more lost and erroneous packets.

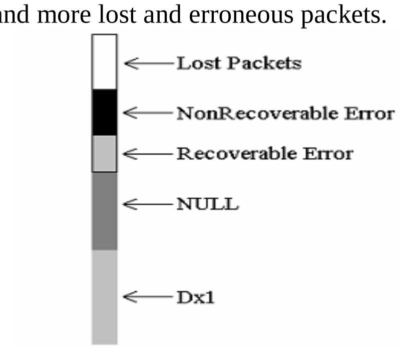

Figure 4

Experimental Setup

During all the experiments, the slave unit was connected to the spectrum analyzer through a power splitter fed by a printed dipole antenna with 0 dB gain, and the protocol analyzer sat as close to the antenna as physically possible as shown in Fig. 5.Unfortunately, there was no access to the antenna port of the protocol analyzer, and so there was no way to connect the protocol analyzer to the slave antenna. The spectrum analyzer, protocol analyzer, and slave Bluetooth device were all controlled by a laptop while a separate computer controlled the master Bluetooth device. Each of the test setups used for the experiment can be found in Fig. 6.The setups include the slave configuration of Fig. 5 as well as the master Bluetooth device, the controlling computer, and the distances separating the two Bluetooth devices from each other and the oven along with any obstacles in the environment.

The first test we performed was to generate a CW signal in the ISM band with enough power to interfere with Bluetooth transmissions. This test was used as a check to verify the Bluetooth devices' reaction to an interferer.

Fig. 6a was used as the experimental setup for the CW interference test. The CW signal generator replaced the oven as the interference source. Fig. 7a shows the histogram generated by the protocol analyzer information for a non-interfering case and Fig. 7b shows the histogram for the network with a 5 dBm CW tone at 2.440 GHz.

As expected, there were few errors in the non-interfering environment and all errors were uniformly distributed across the channels. Given 50000 packets over 79 channels, there should be about 632 packets per channel, as Fig. 7a confirms. In the CW interference environment, all packets transmitted on frequency 2.440 GHz were lost due to the extremely high interfering tone. Furthermore, the adjacent channels showed lost packets due to adjacent channel interference. All the packets lost on frequencies 2.439, 2.440, and 2.441 GHz would then have to be retransmitted, which causes the increase in the number of packets on the other channels.

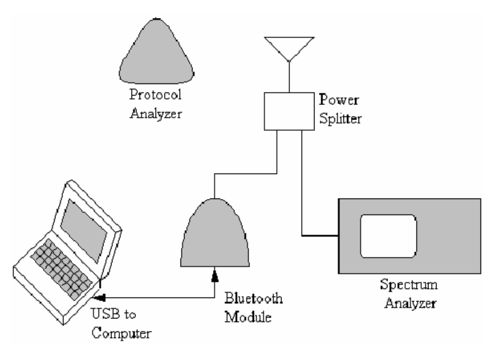

Figure 5

After the CW tests confirmed the operation of our test setup, we ran tests using the microwave oven as the interference source in a number of different setups. We used three basic environments for tests with different setups in each environment. The first environment is a modular building, where the CWT Bluetooth Lab is located, the second environment is an office setting, and the third environment is an outdoor line-of-sight path, each of which is shown in Fig. 6.

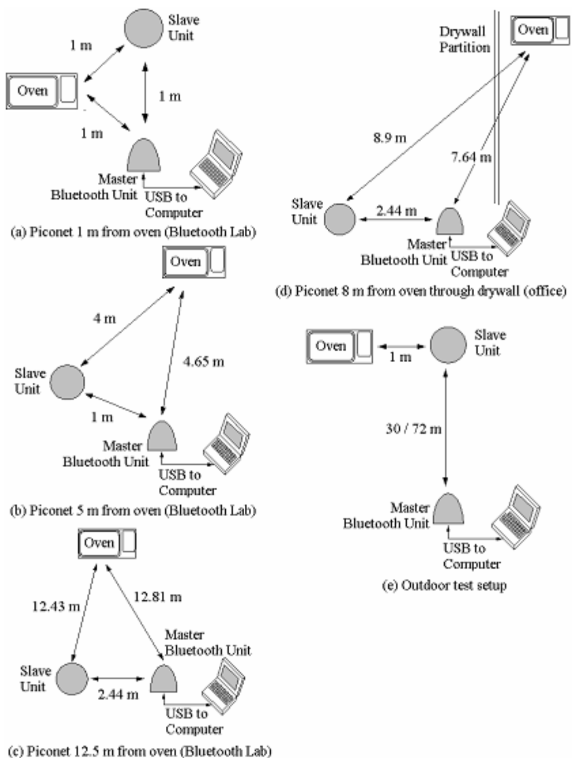

Figure 6

Each test consisted of a 30 second transmission where a total of 24000 packets were transmitted by both the master (data packets) and the slave (NULL packets). All setups were run for both DM1 packets, which contain 2/3 rate FEC, and DH1 packets which contain no FEC. The different packet types provide insight into the value of the FEC.

All tests followed the same procedure. To start each test, the oven was warmed up for 30 seconds, and then the computer controlled spectrum analyzer captured the oven spectrum for 30 seconds. After the spectrum capture was completed, the Bluetooth devices were connected and the protocol analyzer began to capture all the traffic. Upon connection, data transmission began and the master transmitted 24000 data packets to the slave.

To illustrate the results, the experimental setup of Fig. 6a will be used as an example. Following our experimental procedure, the spectrum of the oven was captured for 30 seconds and can be seen in Fig. 8. DM1 packets were then transmitted and captured by the protocol analyzer, and then the test was repeated with DH1 Packets. The histograms for the DM1 and DH1 packets are shown in Fig. 9a and 9b.

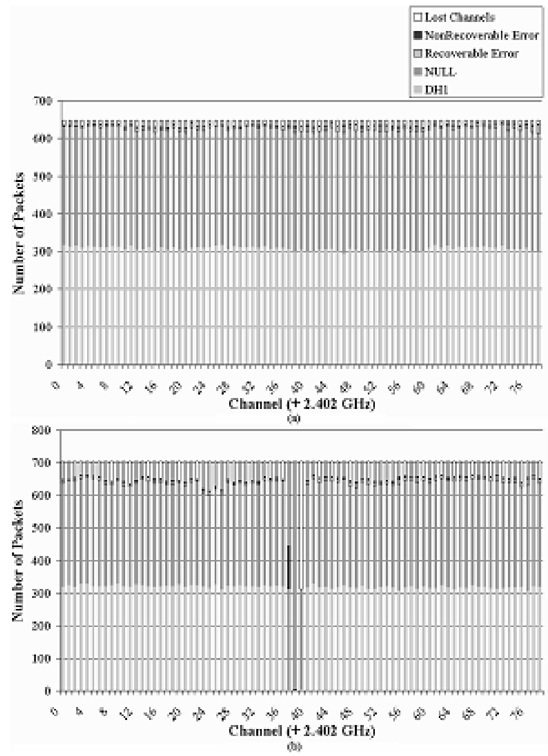

Figure 7

The PSD plot of Fig. 7 shows the oven output at the time of the test, which exhibits widely varying signal powers over the capture period. The operating frequencies of the microwave oven correspond to the frequencies where the most number of lost packets occurred. The histograms of Fig. 9 show a wide range of channels being affected by the oven. The most notable areas are the frequencies around 2.453 GHz and the wide range of effected channels from roughly 2.430 to 2.450 GHz. Moving in frequency away from the oven's center frequencies of operation shows a decrease in the number of lost packets, although significant error packets still occur.

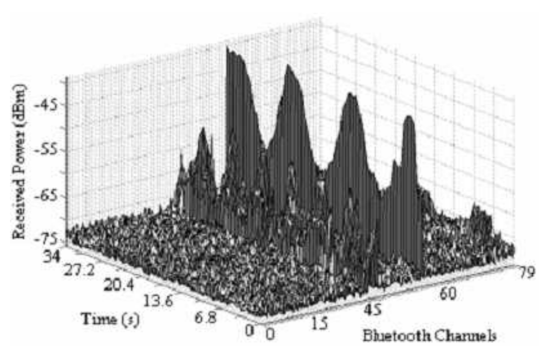

Figure 8

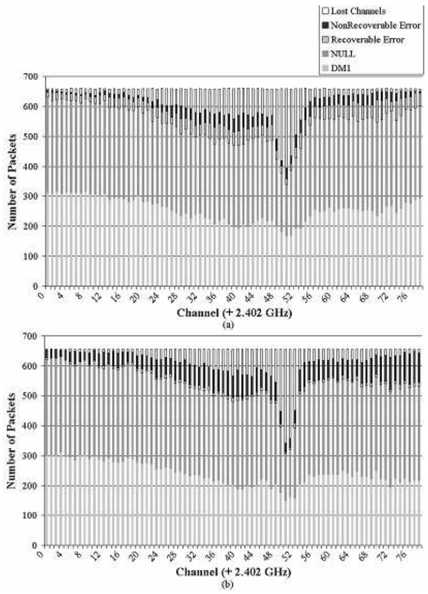

Figure 9

The large number of channels affected by the oven output is due to both the bandwidth of the output spectrum of the oven as well as the adjacent channel interference. The CW tests show that adjacent channels are susceptible to high-power transmitters, and the histograms of Fig. 9 reiterate the issue of adjacent channel interference and how high power interferers pose a larger threat than to just a single channel.

While we have seen the correlation between the microwave output and the Bluetooth piconet packet performance, we used a qualitative metric to provide a measure of the damage caused by microwave ovens. The metric used was the effective data rate of the piconet during the test period. The data rate can be calculated using the information from the protocol analyzer data in the following formula:

$$R = \frac{(Num\ Packets) \times (Bytes / Packet) \times (Bits / Byte)}{(End\ Time) - (Start\ Time)}$$

This is the maximum data rate possible for a DM1 packet. Each DM1 packet contains a maximum of 17 bytes per packet, and a DH1 packet contains a maximum of 27 bytes per packet, which gives the DH1 packets a maximum data rate of 172.8 kbps.

Result

Several different experimental setups were used to develop trends in the microwave oven interference environment. Table I summarizes the data rates calculated for the different experimental scenarios for both DM1 and DH1 packet transmissions. The letter marking each scenario in Table I directly matches the setups in Fig. 6.

With no oven interference, the piconet approached the maximum transmission speed. The worst scenarios were the outside measurements where the radio link was pushed to extreme limits while the microwave oven sat just 1 m away from the slave. The results show that at this distance a majority of packets were lost due to the interference. The general trend was that the closer the Bluetooth slave was to the oven, the worse the performance became due to the higher interference power of the oven output, but moving the master closer to the slave improved the throughput.

TABLE I: BLUETOOTH DATA RATES IN INTERFERENCE ENVIRONMENT

Experimental Scenario (from Fig. 6)	DM1 packet transmission (kbps)	Percent of Max	DH1 packet transmission (kbps)	Percent of Max
Maximum Data Rate	108.8	100	172.8	100
a. Piconet 1 m from oven - Without oven on	108.4	99.6	166.3	96.2
a. Piconet 1 m from oven - With oven on	75.3	69.2	99.9	57.8
b. Piconet 5 m from oven	85.2	78.3	149.6	86.6
c. Piconet 12.5 m from oven	105.4	96.9	163.7	94.7
d. Piconet 8 m from oven through drywall	103.9	95.5	160.7	93.0
e. Outside - 30 m master/slave separation	25.1	23.1	68.4	39.6
e. Outside - 72 m master/slave separation	38.5	35.4	38.4	22.2

Conclusions

The distance between the piconet members and the distance to the microwave determines the extent to which the microwave ovens affect Bluetooth networks. The weaker the Bluetooth signal and the closer the oven was, the greater the effect of the interference. This result is no surprise; however, the Bluetooth devices maintained connection and usable throughput even in the extreme situation where the oven was very close. If a more reasonable distance of 10 m is maintained between the oven and any member of a Bluetooth piconet, the effects of interference will be minimal, and if closer, the interference does not significantly degrade the performance until within about 5 m of the oven. Placing obstructions in the path between the piconet and oven such as a drywall can also improve performance at closer distances. This study also found the lack of throughput improvement due to the FEC coding used on some data packets. The overhead required for the FEC is not worth the small coding gains in almost any situation.

References

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