Mechanisms of Interference Reduction for Bluetooth

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Abstract—**Operating in an unlicensed frequency band involves interacting with other technologies, possibly hindering all wireless traffic involved. A relative newcomer to the 2.4 GHz spectrum, Bluetooth is negatively affected by higher power technologies such as wireless LANs, cordless phones, and microwave ovens. The problems introduced by the interference from these common devices are cause for concern, and even more problems arise when Bluetooth devices interfere with their own communication. One proposed method of handling these issues involves two separate mechanisms, specifically (1) power control and (2) adaptive frequency hopping. Listen-Before-Talk (LBT) can be used as both a power saving technique and a way to avoid packet loss by simply surveying each frequency band prior to transmitting. Adaptive frequency hopping (AFH), a modification of frequency hopping that is native to Bluetooth, is a more common field of study and less intrusive to other devices. This technique includes searching for a subset of channels with less noise and limiting the hopping pattern to that subset of channels. Both techniques suggest a solution to the interference problem that will grow with the proliferation of Bluetooth devices. This paper will analyze the interference with Bluetooth from microwaves, wireless LANs, and itself, and examine LBT and AFH along with other methods of adapting to this problem.**

I. INTRODUCTION

Bluetooth was designed as a low-cost, short range (less than 10 m), and low speed alternative to cables [1]. It operates in the unlicensed 2.4 to 2.483 GHz Industrial, Scientific and Medical (ISM) spectrum. Fast frequency hopping spread spectrum (FHSS) is used at a rate of 1600 hops/s, with Gaussian frequency shift keying (GFSK) modulation and forward error correction (FEC). Based on the applications of Bluetooth, transmission power is typically 1 mW, with a raw data rate of 1 Mbps. This includes an array of different forward and reverse link configurations, ranging from a symmetric link of 432.6 kbps to an asymmetric link of 721/57.6 kbps [2].

In a network of Bluetooth devices, up to eight mobile nodes such as a printer, notebook, desktop, and mobile phone can establish a communication link between themselves, called a piconet [3], which is arranged using one master and up to seven slaves. The devices in a piconet follow the same hopping sequence and operate in synchronization.

The 2.4 GHz spectrum used by Bluetooth is quickly becoming popular because of its worldwide availability and convenience. Some of the well-established technologies utilizing this frequency band are 802.11b (otherwise known as Wi-Fi), cordless phones, and two-way radios. Because they use the same spectrum, any one of these types of devices has the capacity to interfere with Bluetooth devices. The effects of interference will be discussed in Section II.

The types of interference can be separated into the categories of frequency static and frequency dynamic [4]. Cordless phones, 802.11b, two-way radios, and microwave ovens are all frequency static. In the eyes of a Bluetooth device, they occupy the same frequencies at the same power levels for long periods of time.

Another common source of interference is the interaction with other Bluetooth piconets. If one piconet comes into contact with another and neither recognizing the other's presence, the result is frequency dynamic noise.

Section III will discuss the many valid ideas on how to reduce the effects of interference, ranging from establishing protocols through a coexistence task force to implementing power management by changing the hardware. Some of more application specific solutions involve turning interfering devices on and off as needed, or specifying selected frequency bands for each network to use. Two of the most promising mechanisms are Listen-Before-Talk (LBT) and Adaptive Frequency Hopping (AFH). LBT utilizes empty cycles to check each channel before transmitting, assuring that the airwaves are free for use. AFH also checks channels before transmitting, and only operates on the channels that are not busy with other wireless traffic. Using both LBT and AFH together provide a better method of decreasing the effects of interference.

Section IV will cover the effectiveness of current Bluetooth standards, illustrating how the technology is already very usable.

II. EFFECTS OF INTERFERENCE

While cordless phones, 802.11b, two-way radios, microwaves, and Bluetooth devices can all interfere with proper operation of a Bluetooth piconet, some are greater threats than others. One standard that has claimed much of the airspace is 802.11b. It not only uses the same frequency, but transmits at approximately 30 times the power and is typically located within or near the same types of devices that utilize Bluetooth technology [5]. This is cause for concern for many Bluetooth chip manufacturers as well as device vendors who offer computers, PDAs, and other products that use both technologies. In addition, the goal of Bluetooth is to create a versatile, pervasive product that will be used everywhere and in everything, and with success comes more piconet to piconet noise. In this section, we will examine the in-band interference produced by both 802.11b and Bluetooth.

A packet is lost to noise when both the interfering and the Bluetooth packet overlap in the time and frequency domains. The Bluetooth receiver is able to detect this loss by examining the signal to interference ratio (SIR), and tallies the lost packets into a bit error rate (BER).

Packets from two piconets are transmitted with period T, packet sizes S_{Bi} and S_{Bj}, with C_B being the available number of channels. The number of channels is forced to 79 based on current regulation [5], but changing the regulation would be necessary to implement a method to decrease the probability of collision discussed in Section III. The probability of an asynchronous in-band Bluetooth packet collision, *p(i,j)* is

$$p(i,j) = \frac{S_{Bi} + S_{Bj}}{T} \frac{1}{C_B}. \tag{1}$$

In the same manner, the probability of an 802.11b packet interfering with a Bluetooth packet is

$$p(i,W) = \frac{S_{Bi} + S_W}{T} \frac{C_W}{C_B}, \tag{2}$$

where S_W is the 802.11b packet size, typically around 750 bytes. The frequency band of the 802.11b signal, C_W, occupies the whole ISM band [4,5].

We can also compute the degree of interference from other Bluetooth piconets based on distance and standard path loss models. As in all wireless communication, the distance between the transmitting and receiving devices will determine the number of other local piconets that can interfere with the signal. The distance between the transmitter and receiver is *d*, and the average Bluetooth piconet distribution density is D_{BT}. The energy threshold, $\gamma_{I/S}$ is fixed at 11 dB [1]. The probability of $p_r(\Omega_I(r)/\Omega_S(d) > \gamma_{I/S})$ is a measure of how the interference power, Ω_I, exceeds signal power, Ω_S, by $\gamma_{I/S}$. The expected number of interfering piconets is

$$N(\gamma) = D_{BT} \int_0^{2\pi}\int_0^{D} p_r(\Omega_I(r)/\Omega_S(d) > \gamma_{I/S}) r\,dr\,d\theta. \tag{3}$$

Using (3), the standard exponential delay path loss model, and log-normal shadowing with standard deviations of σ_I and σ_S, we can simplify this equation [6].

$$N(\gamma) = D_{BT}\pi(d)^2 \exp\left[\frac{2(\sigma_{I/S} - 10n\gamma\log_{10}(e))}{(10n\log_{10}(e))^2}\right], \tag{4}$$

where the radius of effective interference area → ∞.

From (1), (2), and (4), we can simulate a noisy environment that may be common to Bluetooth in a few years. Equation (5) illustrates the probability of at least one packet collision given N(γ) Bluetooth piconets and one 802.11b link.

$$\overline{p}_c(i) = 1 - (1 - p(i,W)) \prod_{j=1, j\neq i}^{N(\gamma)} (1 - p(i,j)), \tag{5}$$

Fig. 1 illustrates the probability of packet collision dependent on the number of interfering piconets N(γ) from (4) and the packet size. As shown in (5), one 802.11b interference source is present, adding a constant probability of collision to the varying probability of piconet collisions. Packets are sent using Data High (DH) rate, which does not utilize FEC. By transmitting with DH instead of Data Medium (DM) or Data/Voice (DV) there will be a larger effect due to 802.11b because it is frequency static noise. Conversely, there will be very little difference in the effect due to other piconets, because FEC does not help decrease frequency dynamic noise. The packet sizes are DH1, DH3, and DH5, which use 1, 3, and 5 time slots of the 1600 slots available per second. Intuitively, the larger packet sizes experience a higher probability of packet collision. Note that this diagram also includes one source of 802.11b interference.

From (5), the BER can be found using the packet error rate (PER) [7], which is the probability of a packet error $p_c(i)$ as calculated in (1) and (2) [8]. Equation (6) calculates the BER, where m is the number of bits in the Bluetooth packet, and can vary between 200 and 2400 bytes [1].

$$BER = 1 - \sqrt[m]{1 - \overline{p}_c(i)}, \tag{6}$$

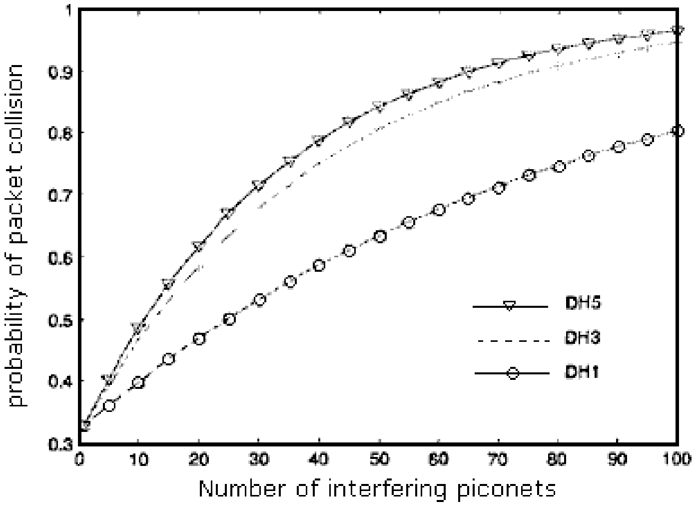

Fig. 1: The probability of packet collisions based on N(γ), the number of interfering piconets, and packet size. This simulation includes one source of 802.11b interference.

The total throughput of all N(γ) piconets, where s_a and s_d are the acknowledge and data packets, respectively, is

$$S = \rho N(\gamma)\left[1 - \frac{2(s_a + s_d)}{TC_B}\right]^{N(\gamma)}\left(1 - \frac{(s_a + s_d + s_W)C_W}{TC_B}\right) \quad (7)$$

where ρ is the payload information duty cycle.

Fig. 2 is a plot of the aggregate throughput of a system, dependent on the number of interfering piconets N(γ) from (4) and the packet size. As in Fig. 1, DH1, DH3, and DH5 are the packet sizes of lengths 1, 3, and 5 slots respectively. Included in this simulation is one source of 802.11b interference. Notice that the amount of transferred data is much higher for the larger packet sizes when there are a small number of interfering piconets. As the number of piconets grow, the probability of collisions in the larger packet sizes increases, as shown in Fig. 1. This in turn decreases the efficiency of large packet sizes, and demonstrates that the smallest possible packet size should be used in environments with more than 75 interfering piconets. It is important to remember that the benefit of being able to transmit larger packet sizes is not always as helpful as it may seem to be.

The analysis of (1-7) shows that the BER and the aggregate throughput, which are the main determinants of the performance and quality of the network, are dependent upon many factors. The distance separating the transmitter and receiver, signal power, environment, number of available channels, packet size, and piconet density all play a role in the quality of the connection.

III. INTERFERENCE REDUCTION TECHNIQUES

A. Coexistence Task Force

There are a number of proposed methods of reducing interference between devices utilizing the 2.4 GHz ISM spectrum, many of which are currently in use or being studied for use by various businesses and task forces. One task force in particular, the IEEE 802.15.2 (Coexistence Task Group 2), is working on a list of "Recommended Practices" for wireless personal area networks (WPANs), which applies mainly to Bluetooth. In this section, we will cover some of the promising methods of dealing with the co-channel interference.

B. Industry Standards

There are two paths to take when developing industry standards. One is to simply force all devices to talk to each other to determine which network is allowed to talk on what frequency and on what channel. This is called collaborative coexistence, and while it seems to be a simple way to avoid the interference problem, there are a few hazards to this method. A collaborative solution would require Bluetooth piconets to talk to each other, which may or may not be feasible depending on the density of Bluetooth devices in the area. This is similar to the Bluetooth Scatternet solution, where a master of one piconet might act as a slave in another piconet, providing a link enabling all local Bluetooth devices to exchange information, in spite of the eight node limit [9]. For example, a city street with many people carrying Bluetooth enabled mobile phones might unnecessarily wear down a user's battery, simply by causing a large volume of constant chatter about which phone can have which frequencies. In a more problematic scenario, enabling Bluetooth chips to converse with everything from garage door openers to 2-way radios would not only be unpractical, but in most instances impossible. Because of these issues, the IEEE 802.15.2 task group will only published one collaborative coexistence mechanism [10].

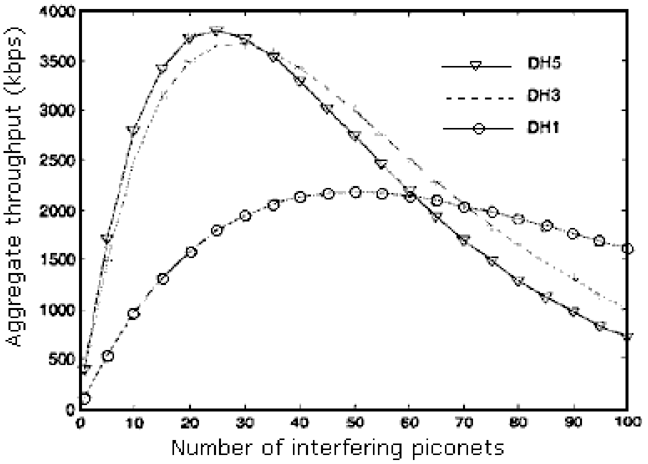

Fig. 2: The aggregate throughput of all piconets based on N(γ), the number of piconets, and packet size. This simulation includes one source of 802.11b interference.

The second path is noncollaborative coexistence, which is the last avenue for improving the Bluetooth standard, making it more impervious to interference. However, within this category are a host of possibilities, which will be the focus of the remainder of this section.

C. On/Off Usage

The simplest way to keep your Bluetooth device running quickly and smoothly is to ban the use of all other wireless traffic in the immediate area [5]. This may be useful in some mission-critical applications, such as a hospital, but in most areas it would be more than a minor inconvenience (Fig. 3). This is not an easy way to manage connectivity, and the reasons for Bluetooth is to decrease the problems associated with remembering to plug-in or unplug, be tethered to, or worry about compatibility between devices. The effort to investigate every source of interference would not be worth the convenience of a wireless connection. Especially considering how the usage of both Bluetooth and 802.11b

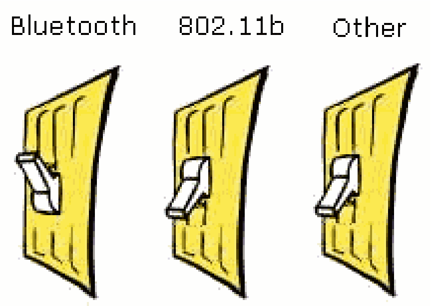

Fig. 3: In most scenarios, on/off usage is not worth the effort.

devices continues to grow, the degree of user awareness required to make this method succeed is not worth the time.

D. Alternate Frequency Bands

The same method used in countless other cases, from military to television to mobile phones, is to request a specific frequency band from the Federal Communications Commission (FCC). This may or may not be likely, but in either case it is not an immediate solution to the problem.

Another proposed method to avoid all of the wireless traffic in the unlicensed 2.4 GHz range is to move some of the technologies to the 5 GHz band [5]. This has been more of a discussion for technologies like 802.11b, where one convincing reason would be the increased transfer speeds. Bluetooth, on the other hand, is not as speed-hungry as other technologies are, and there are many reasons to avoid the jump to 5 GHz. Specifically, there is a 6.9 dB path loss penalty in moving from 2.4 GHz to 5.3 GHz. The required power to overcome this path loss and still retain the same range is about five times the current output. As mentioned in [9], Bluetooth should not noticeably increase the physical size or power consumption of the device in which it is embedded. At this frequency, barriers like walls and trees provide higher attenuation, degrading the signal and increasing the power consumption even more [11]. Looking to the future, the FCC has not restricted the 5 GHz range any more than it has the 2.4 GHz range, and wireless local area networks (WLANs) and microwaves are already being developed for that spectrum. Unless there is a drastic change in the applications Bluetooth was designed for, the move to another frequency band is a concept that is unlikely to succeed.

E. Power Adaptation

One of the more technical approaches to reducing interference is to monitor and control transmission power [5]. This idea has been in practice for many years, a staple for improving the quality of mobile phones [12]. Many Bluetooth devices require short-range interaction, much less than the 10 m specification. By monitoring the power received from a device and adjusting power transmission accordingly, a piconet could not only save on power consumption, but cause less interference to the devices around it. This method has many positive aspects which could easily outweigh the effort to design additional hardware. Unfortunately, this is also a passive way to help the interference problem, and only assists other devices. Expecting the same treatment in return may not be enough.

F. Listen-Before-Talk

While AFH uses frequency selection to identify opportune ways of transmitting and receiving data, Listen-Before-Talk (LBT) relies on timing. This technique is especially useful given Bluetooth's slotted structure, where each packet is sent in a series of bursts. LBT involves "listening" to the channel before blindly shooting data into the air. By either waiting for transmissions from other sources to finish, or realizing that the channel is free to use, LBT can wisely avoid a wasteful transmission. This method is beneficial because there is already dead time built into each cycle (Fig. 4), so it can perform the check without effecting normal data flow. The down side to BLT is that it cannot predict the future. For example, a Bluetooth device checks a channel, determines that it is safe, sends a packet, and that packet collides with another signal sent slightly afterwards. In this case, there was no way to determine when the other signal was going to be sent, and how to avoid it (Fig. 5). Unfortunately, direct sequence spread spectrum (DSSS) devices like 802.11b lack the ability to check the

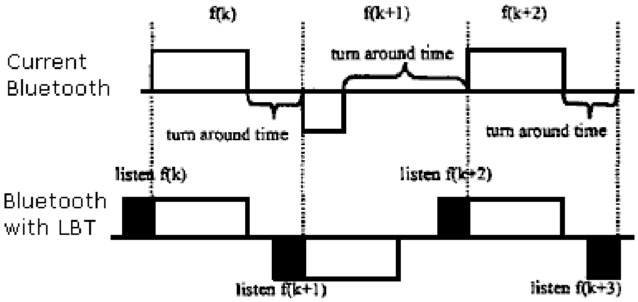

Fig. 4: The spare time in each Bluetooth cycle can be used to "listen" for other packets that might interfere with the transmission.

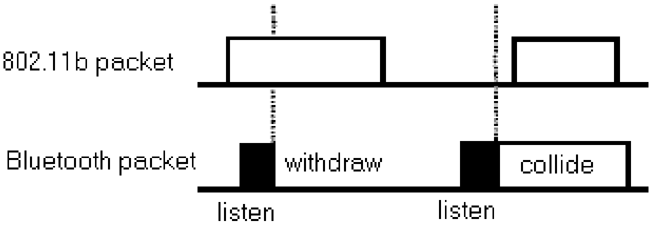

Fig. 5: A Bluetooth and an 802.11b packet vying for the same channel at the same time, 802.11b arriving first, Bluetooth's LBT recognizes the transmission and withdraws until the next slot; with Bluetooth arriving first, a collision.

whole spectrum every time a packet is sent, so reciprocity is not an option with this method.

G. Adaptive Frequency Hopping

Frequency hopping is the method Bluetooth devices use to spread their signals across a wide spectrum, which allows the device to handle noisy frequencies. Frequency hopping also permits other devices to use the same frequency band for communication because it dilutes a single transmission across a wide range of frequencies. Equations (1) and (2) claim that by increasing the number of channels used, you can decrease the probability of a packet collision. This is true in a random environment, but Bluetooth devices do not always operate in a random environment. By the nature of an unlicensed spectrum, there will always be frequencies that are noisier than others. Adaptive Frequency Hopping (AFH) makes use of this fact by monitoring the channels and labeling them as “bad” or “good”. Then the “bad” channels are mapped to “good” channels, creating a much better pattern of frequency hops. AFH regularly surveys the channels to keep the best possible pattern [13]. By using AFH, the probability of a packet loss is much less than reflected in (1) and (2), having virtually eliminated other sources of collision. The problem with this method is that it increases frequency dynamic interference by limiting its hops to select frequencies. This is one of the reasons why the FCC imposed regulations that enforce the use of all 79 available channels. AFH works extremely well in low-density environments, but when the number of other piconet interference communications rise above 40, the AFH method drops below standard Bluetooth performance [4].

H. Combinations of Interference Reduction Techniques

When learning about each of these techniques, the tendency might be to focus on the “best” one, and focus solely on it. As powerful as some of these methods may be, combining 2 or more mechanisms into one method for improving communication could result in a better solution. One method composed of LBT and AFH shows that combining the two mechanisms will result in the high throughput of AFH around low numbers of piconets, and the high throughput of LBT with high numbers of piconets. This is because LBT is designed to minimize frequency dynamic interference, while AHF is designed to minimize frequency static interference. Fig. 6 shows how AFH by itself will drop below normal Bluetooth when more than 40 piconets and one 802.11b source are interfering. It also shows the large benefits of LBT in this environment, but the most beneficial arrangement of any is the AFH + LBT combination interference reduction method [4].

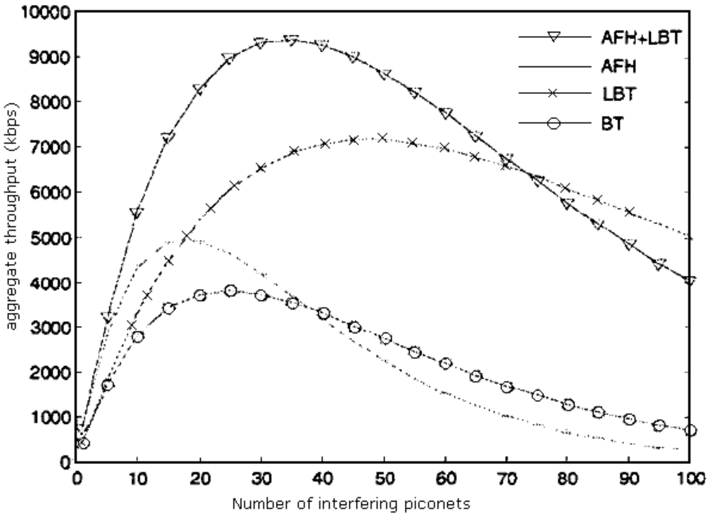

Fig. 6: The aggregate throughput of all piconets based on N(γ), the number of piconets, using the common Bluetooth configuration, LBT, AHF, and a combination of LBT and AHF. This figure includes one 802.11b interferer as well as the interfering piconets.

IV. CURRENT BLUETOOTH FUNCTIONALITY

In spite of all the research that has been and continues to be published concerning Bluetooth and the interference in the 2.4 GHz spectrum, Bluetooth devices are already on the market [2]. This is because the Bluetooth standard works, and continues to be improved by countless researchers. One company, Xilinx, has extensive Bluetooth information and tutorials [14]. In their experiments, they show how well Bluetooth can handle the increase in other Bluetooth piconet traffic nearby.

There is signal degradation as the number of piconets increases, but the loss is graceful. Fig. 7 illustrates how many piconets can coexist with each other and still function at a usable rate. The dark circles around packet transmissions indicate two packets colliding. The three parts of this figure show how the presence of 4 piconets degrades the net efficiency to 95%, 10 piconets degrades efficiency to 89%, and 20 piconets degrades efficiency to 79%. Even though this is only in the presence of Bluetooth devices, the BER is not only acceptable, but also very promising.

V. CONCLUSION

Bluetooth is a definite contender for air space in the 2.4 GHz unlicensed spectrum. However, “contending” for space is not a viable solution, therefore coexistence is the key to success. In this paper, both the effects of interference and the methods to counteract these effects were explored. The IEEE 802.15.2 task force and other researchers are considering methods of aiding coexistence by reducing interference. Reducing interference is the key to high-

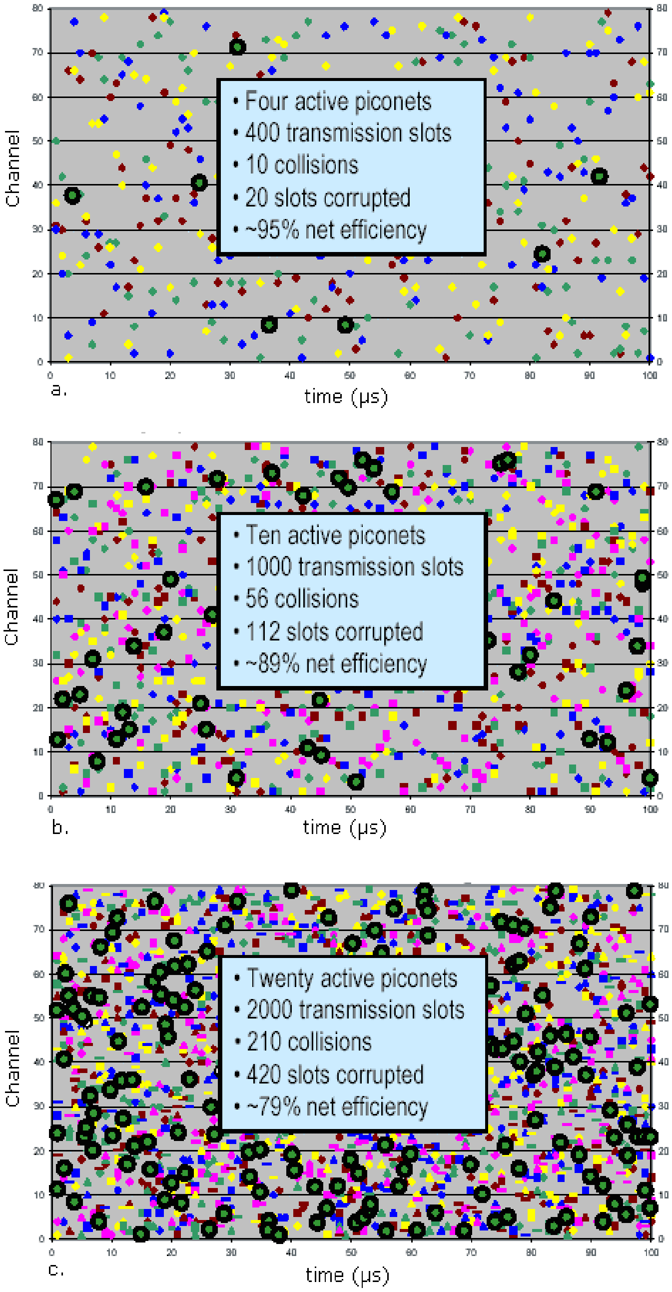

Fig. 7: The net efficiency of piconets in a pure Bluetooth environment degrades gracefully as more piconets are added. The dark circles indicate two packets colliding.

throughput, reliable communication. Some of the more promising methods are power adaptation, Listen-Before-Talk, adaptive frequency hopping, and a combination of LBT and AFH. Not only to many of these methods decrease interference, but power adaptation and LBT also decrease power consumption. As Bluetooth technology grows more pervasive, methods of decreasing interference will need to become proficient, or the users and eventually the standard will suffer.

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