Quantifying Bluetooth Piconet Mutual Interference

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Abstract

Bluetooth^{TM} is a promising short-range radio network technology. The goal of Bluetooth networking is to allow small (10m), high-speed (1Mb/s) networks to be established around a user at very low cost (less than $5 per device). The Personal Area Network (PAN) provided among Bluetooth-enabled devices can be used to eliminate inter-device cabling and support data/service sharing between devices, including extensions of LAN and 3G cellular services. Operating via frequency hopping in the unlicensed 2.4 GHZ Industrial, Scientific, and Medical (ISM) frequency band, there is significant potential for mutual interference among co-located Bluetooth piconets (as they are called) in high-density applications. This study describes a simulation framework for quantifying Bluetooth piconet mutual interference and provides simulation results that refute the Rule of Ten, a common performance assumption regarding Bluetooth mutual interference.

1 Introduction

Mutual interference is a potential problem for Bluetooth applications in large office settings. Consider the case where Bluetooth is used as a cable replacement technology: each personal computer may have a piconet consisting of at least three nodes – a Bluetooth enabled mouse, keyboard, and personal computer. Some users may have additional Bluetooth-enabled devices including printers, PDAs, and mobile phones. Given that a typical cubicle is approximately 2 meters across, it is easy to envision densities of 20 piconets supporting up to 100 devices in a 100 square meter area.

A rule of thumb known as the "Rule of Ten" has been generally assumed regarding expected Bluetooth mutual interference: 10 piconets operating in a 10-meter square area can be expected to exhibit a 10% performance degradation. We believe this estimate to be highly optimistic. Many factors, especially the distance separating communicating nodes in any Bluetooth piconet, may contribute to performance degradations that are significantly higher.

2 Bluetooth Technology Standards

The Bluetooth protocol stack is illustrated in Figure 1[1]. The Bluetooth-specific protocols are SDP, L2CAP, Link Manager, Baseband, and the Bluetooth Radio. Our primary modeling focus is on the characteristics of the RF, Baseband, and L2CAP elements of the stack. Assuming maximum traffic density, it is the characteristics of these sub-layers that dictate network performance in the presence of mutual interference.

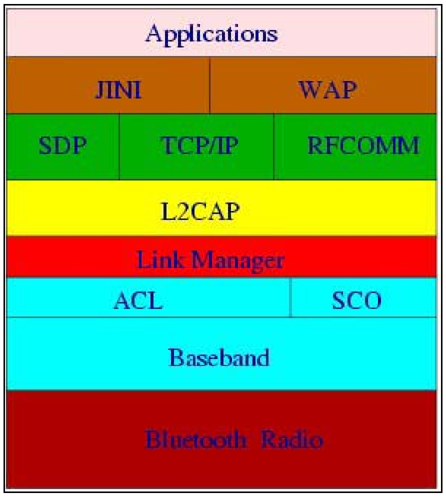

Figure 1: Bluetooth Protocol Stack.

The Bluetooth Radio (RF) sub-layer operates in the 2.4 GHZ ISM-band on a Time Division Duplex (TDD) channel consisting of 625µs timeslots -- implying 1600 slots/second. Bluetooth RF utilizes frequency hopping among 79 one-MHz wide frequencies bands in order to comply with FCC regulations regarding radiated energy. Standard transmit power is 1 mW (0 dBm). Node separation is typically less than 10 m, but may be up to 100 m at optional higher transmit power settings. The

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signal is modulated by binary Gaussian Frequency Shift Keying (GFSK). Packets may be sent of varying lengths, representing 1, 3, or 5 timeslots. Each successive transmission occurs on a different frequency.

The network unit in Bluetooth is called a piconet. A piconet consists of at least two nodes: a master and anywhere from one to seven slaves. The master defines the piconet's pseudo-random frequency hopping sequence and transmission timing, derived from the master's 48-bit address and clock value. The master controls the channel by polling the slave/s and is always the first to transmit in the TDD cycle. Each slave may only transmit after successful reception from the master.

The Bluetooth Baseband sub-layer offers two data link layer transmission services, Asynchronous ConnectionLess (ACL) and Synchronous Connection Oriented (SCO). SCO is a symmetric point-to-point service in which the master transmits on reserved slots. The slave transmits in the following slot. This service was designed to support real-time applications, especially voice. The ACL service utilizes a link-level ARQ algorithm in which packets are retransmitted until a positive acknowledgement is received by the sender, insuring that ACL frames are not dropped in the physical channel.

Bluetooth Baseband utilizes optional Forward Error Correction for certain packet types. SCO supports 1/3 and 2/3 FEC, while ACL allows for 2/3 FEC only. Tables 1 and 2 illustrate the packet types defined and their respective maximum throughput.

Table 1: Baseband ACL Packet Types

Type	Payload (bytes)	FEC	Symmetric Max Rate (Kb/s)	Asymmetric Max Rate (Kb/s)	
				Fwd	Rev
DM1	0-17	2/3	108.8	108.8	108.8
DH1	0-27	NO	172.8	172.8	172.2
DM3	0-121	2/3	258.1	387.2	54.4
DH3	0-183	NO	390.4	585.6	86.4
DM5	0-224	2/3	286.7	477.8	36.3
DH5	0-339	NO	433.9	723.2	57.6

Table 2: Baseband SCO Packet Types

Type	Payload (bytes)	FEC	Symmetric Max Rate (Kb/s)
HV1	10	1/3	64
HV2	20	2/3	64
HV3	30	NO	64

The Logical Link Control and Adaptation Protocol (L2CAP) handles application multiplexing, segmentation and reassembly (SAR), and group abstractions.

The Link Manager (LM), also called Link Management Protocol (LMP), is responsible for connection establishment, security, and control. LM messages are filtered out at the receiving node and are not sent up the protocol stack.

The Service Discovery Protocol (SDP) identifies services available by or through a Bluetooth device.

3 SuiteTooth: Bluetooth model for OPNET

The complexity of the Bluetooth protocol and the fact that it operates in an unlicensed frequency band with other technologies (including the 802.11b, or "WiFi", wireless LANs) dictate the consideration of high-fidelity, discrete-event simulation models to facilitate network performance engineering. The authors have developed such a model suite that enables a wide range of simulation studies, including:

- Application performance
- Protocol stack integration
- Link layer framing and scheduling
- Radio performance
- Channel access and utilization
- RF interference effects
- Adaptive feedback mechanisms

Our Bluetooth Simulation Model Suite (Suitetooth) is an open, modular framework for advanced PAN network performance engineering. Built for the OPNET™ simulation environment, Suitetooth models allow users to predict performance characteristics and study behavioral interaction for personal area network applications that use both existing and emerging wireless technologies. The suite includes component models for RF, Baseband, and L2CAP sub-layers, with additional provisions for LMP, ISM-band coexistence, and traffic source modeling.

Bluetooth Radio

The core of the physical channel model is a complete representation of the RF spectrum. Timing, frequency, bandwidth, modulation, and radiated power are explicitly modeled for all transmissions. The impact of radio performance and dynamic interference in the RF channel account for data corruption and losses that impact higher-layer processes.

Baseband

The Baseband model supports both ACL and SCO services to the densities allowed by the specification (up to seven connections per master for ACL and three connections per master for SCO). All framing formats and packet types identified in Tables 1 and 2 are included. A modular scheduling algorithm allows that framing be fixed, variable, or user-defined. Scheduling logic may be modified at the slave nodes and master nodes independently. Standard polling behavior, including NULL response frames, is also included, as is automatic retransmission of un-acknowledged ACL frames.

L2CAP

L2CAP logic is included in the same OPNET process model as the Baseband functionality and extends the model to include application multiplexing and segmentation/reassembly services.

LMP

A source/sink process for LMP traffic is provided. The standard model allows LMP traffic volume to be modeled and may be extended to support dynamic reconfiguration of the node characteristics.

ISM Band Coexistence

Suitetooth includes a generic ISM-band jammer as well as an adaptation of the standard OPNET 802.11b wireless LAN model. These models allow the effects of ISM band coexistence between the two systems to be quantified within the context of free space, indoor, and user-defined path loss models. The custom RF pipeline models may be adapted to other ISM-band technologies.

Traffic Sources

Independent, renewal-process based traffic sources create a tightly controlled experimental environment for exercising the Data Link Layer and Physical Layer models. For these sources, system behavior above Bluetooth is abstracted into simple stochastic traffic sources and sinks. Traffic flows between Bluetooth nodes are specified using packet interarrival time and packet size probability distribution functions (PDFs) for each user-defined flow. Constant bit rate (CBR) sources have been used in this study.

Although they were not enabled for this analysis, standard OPNET Client/Server traffic sources have also been integrated into the model. For these applications, a modified Address Resolution Protocol (ARP) process maps IP addresses to Bluetooth active member address/piconet combinations.

The Bluetooth master node model shown in Figure 2 depicts the resulting node model architecture.

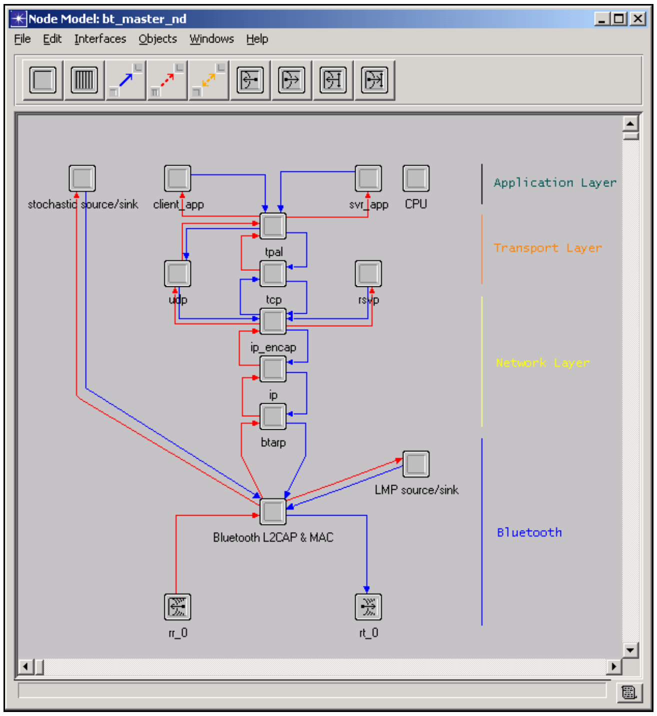

Figure 2: Bluetooth Master Node Model

4 Mutual Interference

Recall that the RF uses a TDM framing geometry. A minimum of 259µs is unused at the end of the final slot of each transmission to allow for TX/RX synchronization. Furthermore, each piconet's channel is defined by its master. Thus, multiple piconets transmit/receive timing cycles will offset by some random, but constant, time value (neglecting clock drifts).

Analytical relationships for the probabilities of collisions among co-located piconets have been derived [2].

$$P_s^s(n) = (1-GP_1)^{n-1} \qquad (1)$$

$$P_s^d(n) = (1-GP_1)^{2(n-1)} \qquad (2)$$

Equation (1) relates the probability of collisions between two co-located piconets whose geometry is such that the competing piconet's transmissions overlap by only one packet. G is a measure of utilization of the channel, a value between 0 and 1. P_1 is 1/79, the probability of overlapping frequencies. Equation (2) relates the probability of collisions between two co-located piconets whose geometry is such that the competing piconet's transmissions overlap two packets.

Equations (1) and (2) can be used to estimate the packet loss rates for the worst case (depending on relative synchronization) to fall in the region:

$$.108 <= \text{packet loss rate} <= .205 \qquad (3)$$

when n = 10 and G = 1 (10 piconets running at maximum traffic capacity). It is assumed that a packet collision will cause a packet to be dropped. This is a good assumption for DH5 packets, since a single bit error in the payload leads to packet failure. Note that in reality, the DH packet headers are protected by 1/3 FEC, which is included in the simulation model, but neglected in the analytic approximation.

5 Simulation Scenarios

Higher received powers will result in improved SNR and ultimately better network performance. The primary determinant of received power in this study is the master-slave physical separation.

Seven scenarios were generated, each includes ten master nodes fixed in a 10 x 10m square. Master-slave separation was constant for each scenario, and varied: 0.1, 0.3, 0.5, 1.0, 1.5, 2, 5, and 10 meters.

Figure 3 illustrates a typical scenario with 1.5 m master-slave separation.

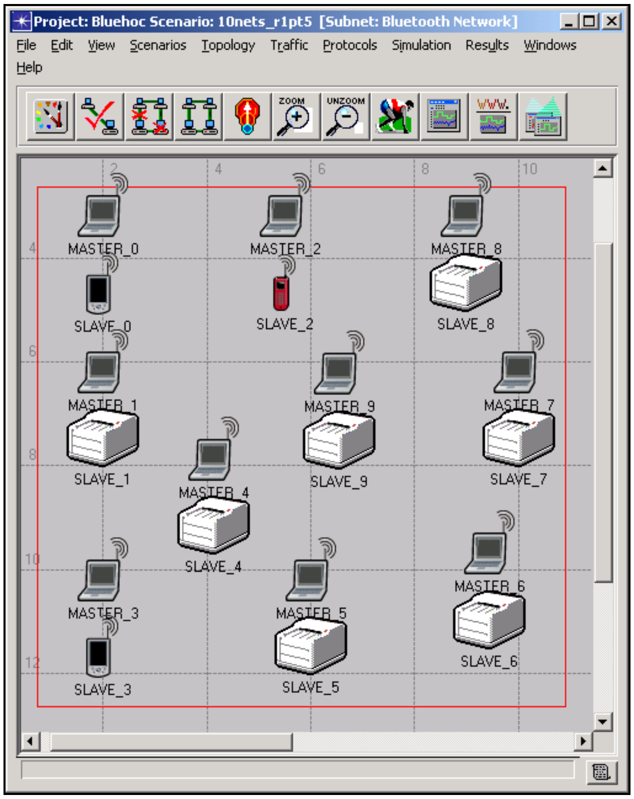

Figure 3: Typical 10x10 Mutual Interference Scenario

All scenarios were configured with symmetric ACL links running full capacity DH5 traffic generated by the stochastic source/sink processes. Two performance metrics were observed, aggregate throughput and aggregate packet loss.

Bluetooth RF performance in these models is highly dependent on the modulation models used in the radio pipeline. This study employed radio performance data available on IBM's Bluehoc website [3].

6 Simulation Results

Figures 4 and 5 depict measured packet loss rates and the resulting impact on throughput, respectively.

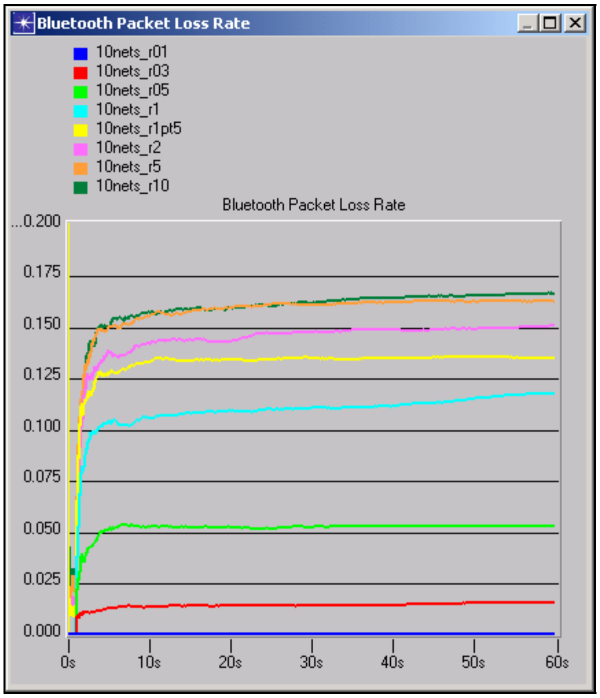

Figure 4: Packet Loss Rate for Mutually Interfering Piconets

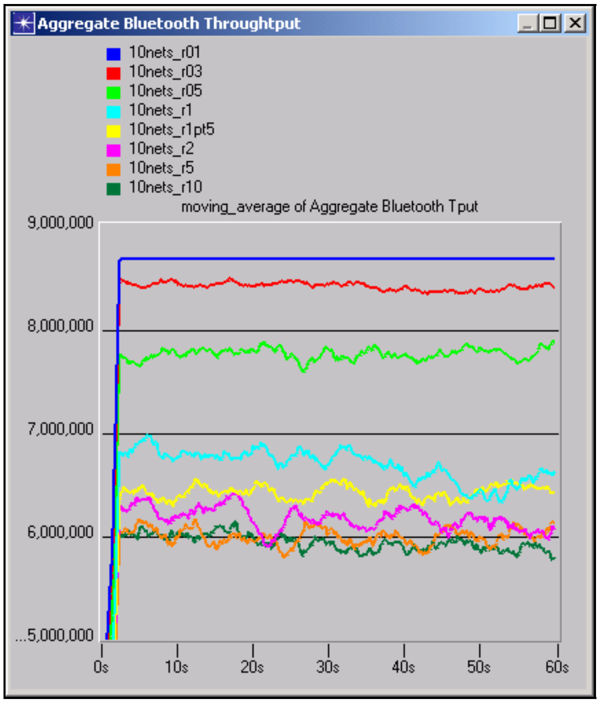

Figure 5: Aggregate Bluetooth Throughput for Mutually Interfering Piconets

Packet loss rates (Figure 4) reach nearly 17% as master-slave separation approaches 10 meters. Marginal increases in packet loss are quite a bit higher per unit distance within the first 1.5 meters.

Aggregate Network Throughput (Figure 5) drops in proportion to the packet loss rates in Figure 4. It also shows little ultimate performance loss from a 5 to 10 meter separation.

7 Analysis

Figure 6 clearly shows exponential throughput degradation as a function of node separation, which is characteristic of many RF networks. A 24% reduction occurs at a distance of only 1 meter.

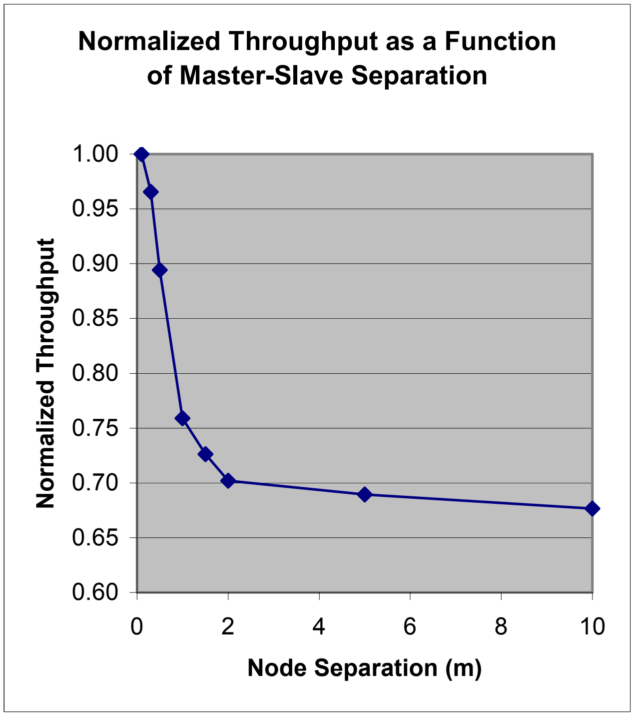

Figure 6: Normalized Throughput as a Function of Node Separation

The maximum packet error rate of 17% falls within the range predicted in (3). The throughput, however, falls at a rate nearly twice the associated packet loss rate. This relationship is essentially linear over typical Bluetooth network geometries and is illustrated in Figure 7.

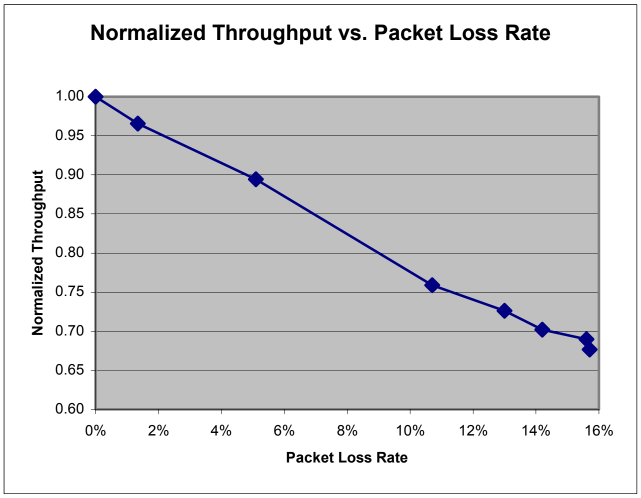

Figure 7: Normalized Throughput as a Function of Node Separation

The "2x" effect is due to the control of the channel by the master: when a slave misses a packet, it has necessarily missed a poll and cannot transmit in the following slot. Thus, when a packet is dropped at the slave, two packets are lost – one in the forward channel and one in the return channel.

Finally, the "rule of thumb" that 10 piconets in a 10 x 10 space will encounter 10% performance degradation only holds true for specific network configurations. In this study, the configuration that leads to a 10% throughput degradation is a master-slave separation of 1 meter. However, the degradations ranged from 0% to 32% over the set of geographic distributions of interest.

8 Topics for Further Study

The models used to execute this study are currently suitable for a number of interesting extensions:

Piconet Density: The number and location of the Bluetooth master nodes was held constant in this study. A more comprehensive treatment would consider a range of possibilities for piconet geographic distribution including regular and irregular configurations.

Slave Distribution: This study contemplated only single slave nodes within each piconet. Up to seven slaves are supported in Bluetooth piconets which may also be distributed in regular or irregular patterns.

Traffic Configuration: This study used constant bit rate sources running directly over the Bluetooth protocol. Actual traffic over ACL links is likely to be highly bursty and may show interesting interdependencies with higher layer control protocols, notably the TCP/IP stack.

Bluetooth Service: ACL traffic was modeled and measured here. Similar exercises with SCO sources are expected to differ substantially due to the fact that the SCO specifications attempt to trade packet error rate for reduced jitter in the reception of Layer 2 frames.

Forward Error Correction (FEC): Both ACL and SCO services allow for the selection of frames that protect the frame payload with forward error correction, but with a consequential loss in maximum throughput capacity.

Frame Selection and Scheduling: In this study, framing was fixed, but the specification (and the models) incorporate an option for versatile frame selection that can be used to optimize network performance for variable bit rate applications.

Additional Extensions: The model suite employed in this study has been used for proprietary research within other organizations. It has formed the basis of studies concerning dynamic Bluetooth network control that employ adaptive FEC, adaptive frequency hopping, and power modulation via receive signal strength indication. It is currently being modified to support scatternet formation and operation modeling (scatternets are arbitrary internetworks of Bluetooth piconets that support larger network topologies).

References

[1] The Bluetooth Specification. http://www.bluetooth.org/specifications.htm

[2] Amre El-Hoiydi, "Packet Error Rate due to Interference between Bluetooth Networks – Probabilistic Upper Bound and Simulation Results", http://www.home.ch/~spaw2031/amre/publications/2001MPRG_Bluetooth.pdf

[3] Bluetooth radio performance analysis on IBM's Bluehoc website: http://oss.software.ibm.com/bluehoc/pres/pres2/index.htm