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Interference Mitigation Proposals Exploiting Antenna Diversity using Space Time Block Codes for Bluetooth Enabled Devices

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Abstract* – *Previous research work has focused on residential coverage and achievable data rates using the Bluetooth Personal Area Network (PAN) standard. To meet the bit rate needs of future consumer electronic devices, M-PSK modulation schemes were proposed as likely candidates for high data rate Bluetooth extension. Frequency hopping statistics obtained for both the 79-hop and 23-hop systems in Bluetooth for data medium (DM) and data high (DH) packets in asynchronous mode show a clear need for mitigating interference. This can be achieved by employing synchronous transmissions in order to obtain reliable throughputs, particularly for time-bounded devices. This paper investigates the advantages of exploiting antenna diversity using space time block codes (STBC) with maximum likelihood decoding for high data rate Bluetooth enabled devices in synchronous and asynchronous transmissions. Results are presented for Bluetooth systems employing no antenna diversity and systems employing two transmit and two receive antennas using STBC. Results show that the reliability of both time-bounded and non-time bounded Bluetooth enabled devices can be enhanced by exploiting STBC coupled with suitable interference cancellation techniques.

INTRODUCTION

Bluetooth is a point-to-point universal radio interface for ubiquitous connectivity in the area of Personal Area Networks (PAN). The technology currently operates in the unlicensed 2.45GHz ISM band and utilises frequency hopping with terminals cycling through 79 1MHz hop channels (or 23 1MHz hop channels in Japan, France and Spain) at 1600 hops/s [1]. One of the drawbacks with the current standard is a restricted bit-rate of 1Mb/s. Although this may seem adequate for low bit rate applications, such as data modems, cordless telephones and low bit rate videophones, it is insufficient to support high bit rate VCR/TV quality digital video (2-12Mb/s).

Previous research [2] has shown that higher data rates can be achieved by employing coherent M-PSK modulation schemes in future Bluetooth evolutions instead of the current GFSK scheme. Although this enhances the data throughput performance, fundamentally it may still be limited due to the interference present in the 2.45GHz band. The majority of research interest has so far focussed on the impact of Bluetooth on Wireless LANs and vice-versa [3-5]. However, given the impending avalanche of Bluetooth enabled consumer electronic devices in the market, concern is being voiced over the interference between Bluetooth enabled devices themselves.

This paper investigates a scenario driven environment which allows a realistic projection of the behaviour of Bluetooth piconets. Two frequency hopping kernels [6] were implemented to investigate the frequency collision statistics for synchronous and asynchronous transmission modes in both 79-hop and 23-hop systems in Bluetooth utilising the DM1 and DH5 packet structure. Synchronous transmission as implied here means that all the piconets are time-synchronised with each other. These results were used in conjunction with a standard Bluetooth modem implemented in software to obtain the average data throughput that can be achieved for the test environment. Due to limited space, results are presented only for a QPSK modulation, although the investigations were carried out for BPSK and 8-PSK schemes as well. The investigation is extended to incorporate antenna diversity, using STBC and the maximum-likelihood (ML) decoding, for mitigating interference in order to achieve improved performance in high data rate Bluetooth enabled devices.

BLUETOOTH FREQUENCY COLLISION ANALYSIS

The Bluetooth communication structure is based on an ad-hoc network. A group of Bluetooth units sharing the same channel is known as a piconet. Each piconet contains a master and up to seven active slaves. All Bluetooth units within a piconet hop using the same hop pattern defined by the Bluetooth device address (BD_ADDR) and clock (CLK) of the master. Since each piconet contains a master with a unique BD_ADDR and a different CLK, the hop pattern is unique to each other. The initial investigation begins by implementing the 79-hop and 23-hop kernels in Bluetooth and calculating the number of frequency collisions that occur between a single

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wanted piconet (wanted Bluetooth user) and up to 4 unwanted piconets/interferers when they are in the connection state (i.e. during user data transmission). Figure 1 shows the test environment containing 5 piconets (1 wanted piconet and 4 interferers). Table 1 lists the devices selected for transmission in each piconet and their relative distance from the receiver of the wanted piconet. To obtain more information on the frequency hopping kernels implemented and collision statistics results, the reader is referred to [7].

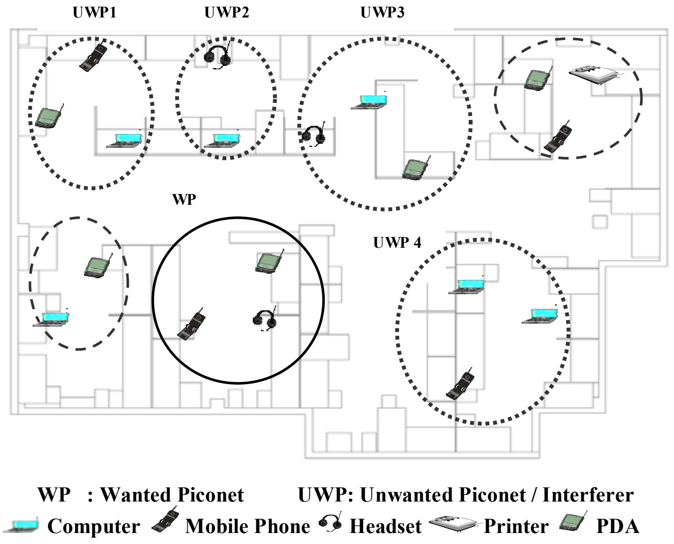


Figure 1: Plan view of a typical office environment (18.5m by 13.8m) containing 5 piconets (4 interferers and 1 wanted user) with distributed Bluetooth enabled consumer electronic devices

Table 1: Transmitter and receiver in each piconet and their relative distance from the receiver of the wanted piconet

Piconet	Master (TX)	Slave (RX)	Distance (TX_{UWP}-RX_{WP})	Distance (RX_{UWP}-RX_{WP})
WP	Mobile Phone	PDA	-	-
UWP1	PDA	Computer	8.64 m	6.17 m
UWP2	Headset	Computer	6.15 m	5.34 m
UWP3	Computer	PDA	7.30 m	4.40 m
UWP4	Mobile Phone	Computer	5.32 m	6.36 m

INDOOR PROPAGATION MODELLING TOOL

The frequency collision statistics obtained were used in conjunction with a Bluetooth software modem to obtain the average data throughput performance within the test environment. A state-of-the-art indoor space-time propagation model [8] based on ray launching [9-11] was used to predict the complex temporal and spatial characteristics of the radio channel for the test environment concerned.

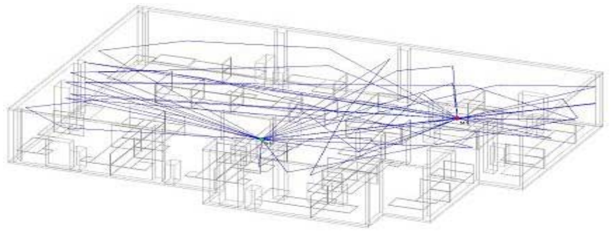


Figure 2: Ray geometry plot for the test indoor environment

Figure 2 shows a ray geometry plot for the indoor test environment studied. The received signal power of the interferers at the receiver of the wanted piconet was generated for a maximum of 6 orders of reflections and transmissions combined with a single order of diffraction. Half wavelength dipole antennas were used at each transceiver, located 0.8m above the floor (typical desk height).

The test environment is primarily a research office with partitioned workspaces containing mainly blocks with a plaster layer. It has a suspended floor that is made of high-density floorboards with an upper metal sheet. Such an environment is commonplace in UK office environments. The relative permittivity and conductivity of the materials are 6 and 0.05S/m respectively. The maximum transmit and receive gains of the antennas is 2.0dBi [12]. A peak transmit power of 0dBm (1mW) is assumed.

The model was used to calculate the signal power at the receiver of the wanted piconet due to transmissions from interfering piconets. In this investigation when a collision occurs, the received signal power from interfering piconets is assumed to be an AWGN noise source. As a result, the transmitted packet in the wanted piconet is subjected to a higher degree of noise (rise in the noise floor) and hence an increased chance of becoming corrupted. Packet Error Rate (PER) versus the ratio of energy per bit to noise power spectral density (E_b/N_o) plots were obtained using this approach. These results were used to compute the data throughput (DT) curves using the following relationship:

$$DT = (1 - PER) \times \log_2 M \times DR$$

where M is the constellation size (4 for QPSK) and DR is the maximum data rate (bits/s) for DM1 and DH5 packets.

SPACE TIME BLOCK CODES FOR BLUETOOTH

A simple space time block coding scheme was proposed by Alamouti in [13]. Figure 3 shows a block diagram of the baseband representation of space time block codes incorporated into the Bluetooth software modem. The transmitter and receiver are both equipped with two antennas each. In this simulation, a flat fading channel and perfect channel knowledge at the receiver is assumed. It has also been assumed that the Doppler frequency of the channel is small enough such that the channels between the two transmit antennas and the two receive antennas remain static over the time period of the data packets being transmitted. During the

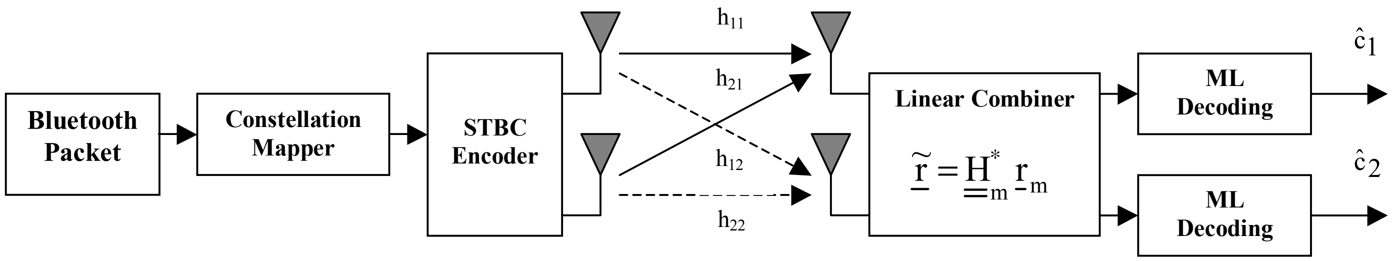


Figure 3: Transmitter and receiver baseband representation of space time block codes for 2 transmit and 2 receive antennas

first symbol transmission period, two symbols c_1 and c_2 are transmit simultaneously from the first and second antennas respectively. In the second transmission period, symbols $-c_2^*$ and c_1^* are transmit from the first and second antennas respectively. The received signal vector for receive antenna 1 and receive antenna 2 can thus be written as:

$$\underline{r}_1 = \underline{\underline{H}}_1 \underline{c} + \underline{\eta}_1 \qquad \text{and} \qquad \underline{r}_2 = \underline{\underline{H}}_2 \underline{c} + \underline{\eta}_2$$

$$\underline{\underline{H}}_1 = \begin{bmatrix} h_{11} & h_{21} \\ h^*_{21} & -h^*_{11} \end{bmatrix} \qquad \underline{\underline{H}}_2 = \begin{bmatrix} h_{12} & h_{22} \\ h^*_{22} & -h^*_{12} \end{bmatrix}$$

where $\underline{c} = [c_1 \quad c_2]^T$ represents the first two symbols, and $\underline{\eta}_1$ and $\underline{\eta}_2$ are vectors containing AWGN noise samples that are modelled as identically independently distributed Gaussian random variables with zero mean and power spectral density $N_o/2$ per dimension. The ML decoding rule is:

$$\hat{c} = \arg \min_{\hat{\underline{c}} \in C} \sum_{m=1}^{2} \left\| \underline{r}_m - \underline{\underline{H}}_m \hat{\underline{c}} \right\|^2$$

Since the channels are orthogonal to each other, the above decoding rule can be further simplified by premultiplying the received signal vector $\underline{r}_m$ by $\underline{\underline{H}}^*_m$ [14].

RESULTS AND DISCUSSION

Figures 4 (a)–(d) show the average data throughput curves for DM1 and DH5 packets using synchronous and asynchronous transmissions in both 79-hop and 23-hop systems in the presence of 1 and 4 interferers. The results primarily display the improvement in performance obtained when:

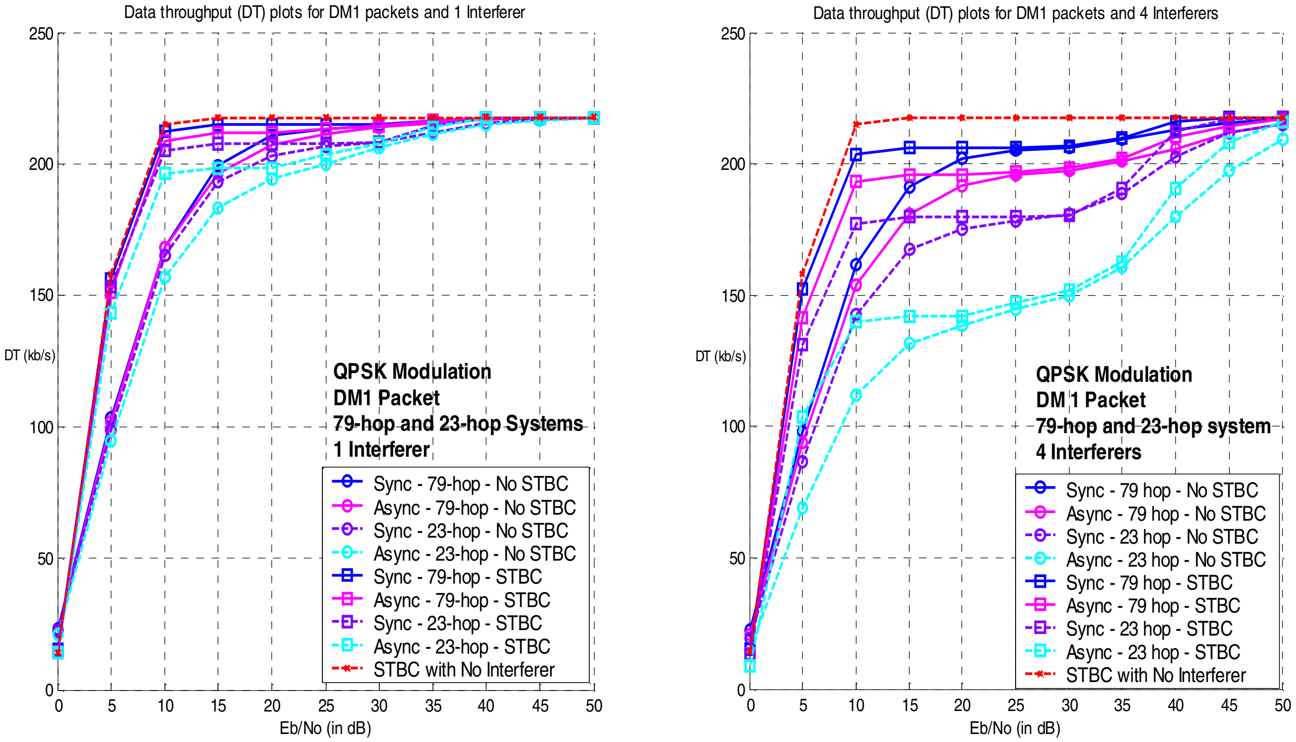
- synchronous transmission (when all the piconets are time synchronised to each other) as opposed to asynchronous transmission in Bluetooth is employed with no antenna diversity and
- STBC is employed in Bluetooth with ML decoding for DM1 and DH5 (as opposed to the use of forward error correcting mechanism i.e. 2/3rd rate shortened (15,10) Hamming binary block code followed by single error correcting decoding used only for DM1 [15]).

From the results, it can be seen that the diversity gain obtained from the use of STBC clearly improves the data throughput performance of high data rate Bluetooth systems. While the Bluetooth system with no antenna diversity is found to be noise limited at low Eb/No values and interference limited at high Eb/No values [7], the use of STBC improves the performance and becomes noise limited up to about 10dB and interference limited beyond that.

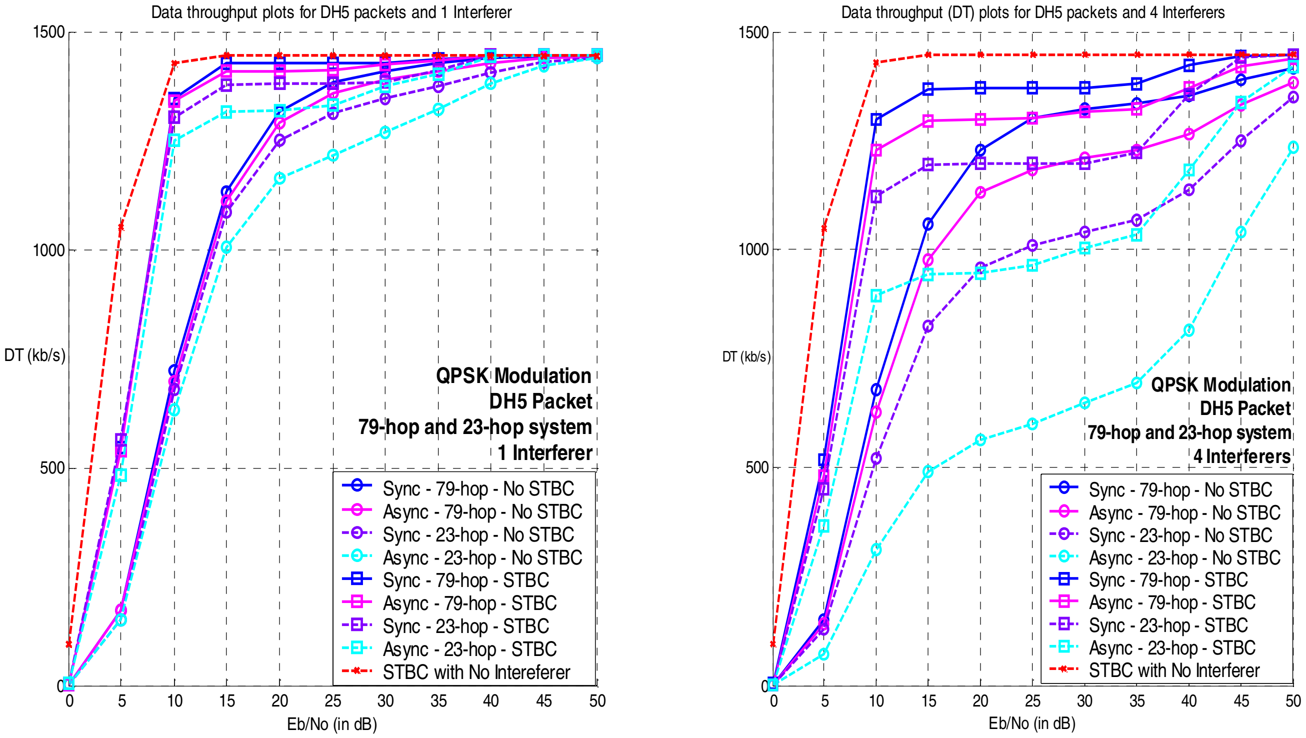
Table 2 summarises the results in Figures 4(a)-(b) for an Eb/No value of 10dB for STBC and no-STBC cases. This value was chosen because maximum data throughput is achieved at just over 10dB when STBC is used in an interference free environment. From Table 2 it can be seen that at 10dB, even without any interference cancellation techniques (such as Zero Forcing and Minimum Mean-Squared Error (MMSE)), the use of two transmit and two receive antenna diversity increases the data throughput performance by approximately two fold for DH5 packets. The use of STBC does not have such a large impact on medium rate packets. However, this improves quite significantly when higher modulation schemes are employed, especially in the presence of large numbers of interferers.

Table 2: Data throughput values for Bluetooth systems with and without STBC in the presence of 1 and 4 interferers at Eb/No = 10 dB using QPSK
[UWP: Unwanted Piconet WP: Wanted Piconet]

Packet Type	**Mode**	**Eb/ No (dB)**	**Data Throughput (kb/s)**			
			79-hop		**23-hop**	
			1 UWP	**4 UWP**	**1 UWP**	**4 UWP**
Bluetooth System (No Antenna Diversity)						
DM1	**Sync**	**10**	168	162	165	143
	Async	**10**	168	154	157	112
	No Interferer	**10**	190			
DH5	**Sync**	**10**	722	1060	680	830
	Async	**10**	798	970	632	490
	No Interferer	**10**	1100			
Bluetooth System (with STBC employing 2Tx and 2Rx antennas)						
DM1	**Sync**	**10**	213	204	205	177
	Async	**10**	218	193	196	140
	No Interferer	**10**	215			
DH5	**Sync**	**10**	1350	1300	1305	1130
	Async	**10**	1330	1230	1250	890
	No Interferer	**10**	1430			



Figures 4(a) – (b): Data throughput plots for data medium (DM1) packets using Bluetooth with no antenna diversity and Bluetooth using STBC (2Tx 2Rx diversity) schemes in synchronous and asynchronous modes for 79-hop and 23-hop sequence



Figures 4(c) – (d): Data throughput plots for data high (DH5) packets using Bluetooth with no antenna diversity and Bluetooth using STBC (2Tx 2Rx diversity) schemes in synchronous and asynchronous modes for 79-hop and 23-hop sequence

The results show that STBC would prove to be an attractive option for future high data rate Bluetooth applications. The performance of the Bluetooth system without antenna diversity may not seem catastrophic in the presence of interferers for non-time bounded applications. However, the performance is not attractive for time-bounded high quality cordless digital applications such as digital video and TV. In real time applications, packet reliability is important since packet retransmission is not practical. Thus the data throughput must be at an acceptable level such that the quality of performance is not degraded. The use of asynchronous mode in the 23-hop system is therefore not favourable. Hence, in 23-hop systems, synchronous transmission using DH5 packets with STBC is strongly recommended. The increased performance using STBC becomes more apparent when higher level modulation schemes (such as 8-PSK) are used in high data rate Bluetooth systems.

CONCLUSIONS AND FUTURE WORK

Based upon these results, the vast majority of non-time bounded applications such as good quality audio streaming over the Internet as well as web browsing, cordless telephones (DECT), videophones, modems and personal digital assistants (PDAs) are feasible in practise. Although this also applies to asynchronous systems, the trade-off between quality and performance is far more attractive in synchronous transmission. The performance of Bluetooth using the 23-hop system without STBC has highlighted a cause for concern, especially for time-bounded applications. In the presence of large number of interferers, the performance would prove to be unreliable. Hence the use of synchronous transmission is recommended. In order for this to be possible, a suitable means for channel access and channel control is needed.

The performance improvement obtained by using STBC shows promising scope for future high data rate Bluetooth devices. This is particularly the case for time-bounded applications and will improve the performance for non-time bounded applications. The use of synchronous transmission in comparison to asynchronous transmission is particularly attractive since antenna diversity can be exploited in order to be able to increase the capacity of the wireless channel. STBC as employed here does not require any explicit knowledge about the interferer. In addition, by employing synchronous transmissions as well as spatial and temporal techniques for interference mitigation, high data rate Bluetooth enabled devices can now coexist in harmony with other Bluetooth and non-Bluetooth devices using various wireless LAN standards such as those based on the IEEE 802.11b and Home RF standard. In practise, a two element antenna array in Bluetooth devices is a feasible and realistic option to make this proposal favourable in order to combat interference [16]. Future work will involve applying the Zero Forcing (ZF) and Minimum Mean-Squared Error (MMSE) techniques for interference rejection within a STBC architecture and comparing the relative performance to combat interferers to achieve further improvement in high data rate Bluetooth applications.

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