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Proposed Evolution Technologies for Bluetooth

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***Abstract* – This paper begins by highlighting key features of the Bluetooth baseband standard. Software simulated results for the transmission of symmetric asynchronous data link (ACL) packets are used to discuss bit rate capabilities of various time-bounded and non-time bounded Bluetooth enabled consumer electronic devices. The investigation considers Bluetooth data medium (DM) and data high (DH) packet types. To meet the bit rate needs of future consumer electronic devices, BPSK, QPSK and 16-QAM are proposed as possible enhancements to the current GFSK modulation. The relative merits and demerits of using coherent modulation and linear receive architectures versus non-linear differential detection are discussed. Although adding considerably to the unit cost, the former is shown to significantly improve radio sensitivity. Results indicate that although the use of QAM modulation facilitates higher data rates, PSK schemes are more likely candidates for a low cost, high data rate Bluetooth extension due to the fact that they have less demanding hardware requirements.**

I. INTRODUCTION

The Bluetooth radio standard is an example of a universal radio interface for ubiquitous radio connectivity in the area of Personal Area Networks (PANs). Bluetooth represents a technology specification that aims to provide robust short range radio communication with low terminal cost, complexity and power consumption. Although this technology is targeted towards electronic devices within the home or office, it also covers consumer electronic devices such as portable computers, Personal Digital Assistants (PDAs), cordless telephones, videophones, televisions and Video Cassette Recorders (VCR).

The Bluetooth radio interface operates in the unlicensed 2.45GHz Industrial, Scientific and Medical (ISM) band. Frequency hopping is used with terminals cycling through 79 1MHz hop channels at 1600 hops/s [1]. The current technology is capable of transmitting data and/or voice at raw half-duplex rates of up to 1Mb/s without the use of cables between portable and fixed electronic devices. Asymmetric and symmetric systems provide maximum half-duplex user data rates of 725kb/s and 433kb/s respectively. Gaussian Frequency Shift Keying (GFSK) modulation is used with a bandwidth-symbol period (BT) product of 0.5 [2][3].

One of the drawbacks with the current Bluetooth technology is its restricted bit rate. Although it is highly desirable for low bit rate applications such as data modems, cordless telephones and low bit rate videophones, it is unable to transport high bit rate VCR / TV quality digital video. TABLE I lists typical bit rate requirements for commonly used consumer electronics devices.

This paper investigates the possibility of increasing the data rate capability of Bluetooth by employing higher level modulation schemes and thereby extending its application to a wider range of devices.

Packet Error Rate (PER) and Data Throughput (DT) performances are analysed for a standard Bluetooth device and enhanced units employing higher-level modulation schemes such as QPSK and 16-QAM. The peak data rates for the aforementioned schemes are 2 and 4 Mb/s respectively.

Section II outlines the structure of the baseband modem shown in Figure 1. In Section III, the software-simulated physical layer performance results are presented. Section IV discusses the suitability of the proposed techniques in terms of time bounded and non-time bounded consumer electronics applications.

TABLE I
TYPICAL BIT RATE REQUIREMENTS FOR TODAY'S CONSUMER ELECTRONIC DEVICES

Applications	Required Bit Rates
Cordless Telephones using DECT	9.6kb/s – 552kb/s [4]
Cordless Videophone using MPEG4	9.6kb/s – 64kb/s [5]
Cordless TV	4 – 9 Mb/s [6]
Cordless VCR	Up to 2Mb/s [6]
Cordless Data Modems	9.6kb/s – 56kb/s [7]
Personal Digital Assistants (PDAs)	9.6kb/s – 128kb/s [7]

II. BLUETOOTH BASEBAND STRUCTURE

Figure 1 shows the baseband block diagram of the simulated Bluetooth system. Only symmetric asynchronous data link (ACL) packets are investigated in this study.

A. Packet Structure

Table 2 lists the 6 symmetric ACL packet types investigated in this simulation. The figures correspond to a maximum data rate of 1Mb/s using GFSK modulation as specified in the current Bluetooth standard. These values increase by 2 and 4 times when QPSK and 16-QAM modulation are employed respectively.

The ACL packets have the general structure shown in Figure 2. Each packet occupies a time slot of 625µs. When multiple time slot transmission is used, the total number of

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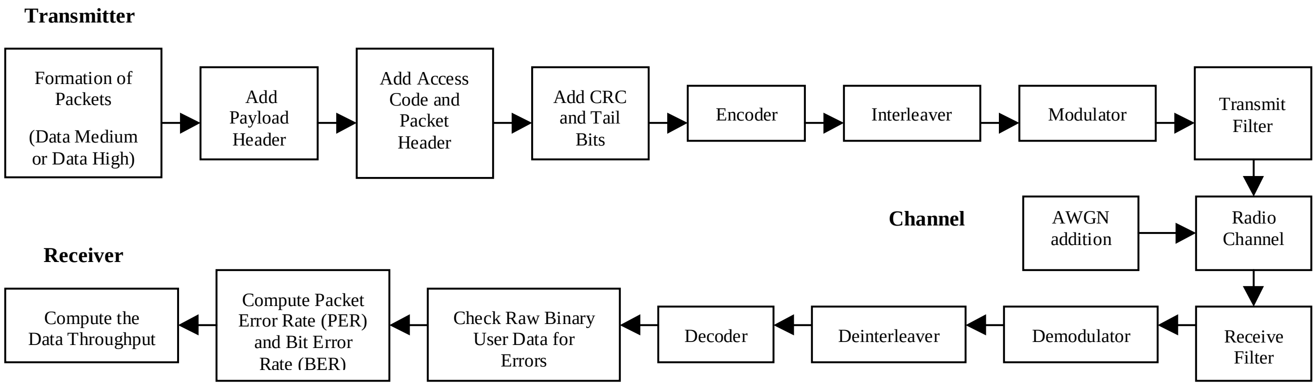

Figure 1: Block diagram of the Bluetooth transmitter and receiver implemented in Matlab

payload bits is either 3 or 5 times the value listed in Table II depending on whether DM/DH 3 or 5 is used.

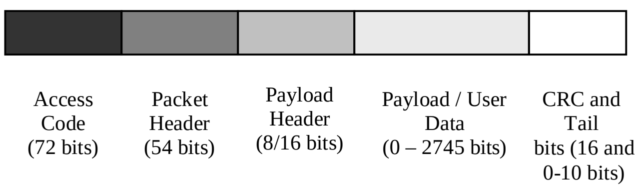

Figure 2: Structure of an ACL packet

Although each packet has a duration of 625μs, the duty cycle of a standard DM1 packet is just 366μs. The remaining time is used for frequency hopping. The access code is derived from the master's identity [8,9]. Apart from the DM1 and DH1 packets, all others contain a 16-bit payload header. The 16-bit cyclic redundancy check (CRC) is calculated only for the payload header and payload.

TABLE II
DM AND DH PACKETS FOR ACL LINK

Packet Type	Number of User Data / Payload Bits per time slot	Symmetric Maximum Rate (kb/s)
DM1	136	108.8
DM3	323	258.1
DM5	358	286.7
DH1	216	172.8
DH3	488	390.4
DH5	542	433.9

B. *Coding and Interleaving*

Two Forward Error Correction (FEC) schemes are employed in Bluetooth. The first is a 1/3-rate repetition code applied to the packet header. Each of the 18 bits in the packet header is repeated 3 times, thus producing 54 encoded bits. The packet header is then decoded at the receiver using the maximal polling method. The second coding scheme is a 2/3-rate shortened (15,10) Hamming binary block code that is applied to the payload header, payload and CRC as well as the tail bits. The tail bits are appended at the end of the CRC to ensure that the sum of bits in the payload header, payload and CRC is a multiple of 10. Decoding at the receiver is performed using the single error correcting decoding algorithm using a predefined parity check matrix [10]. This decoding algorithm corrects all single errors and detects all double errors within each block of 15 bits. With the exception of the packet header, the DH packets are not encoded.

After the encoding process, block interleaving is applied to the entire packet. This step is implemented to mitigate against error bursts which may otherwise have a severe impact on the performance of the FEC code.

C. *Modulation*

The investigation in this paper considers four modulation schemes. The GFSK scheme is implemented based on the current Bluetooth standard. At the receiver, non-linear differential phase detection is applied. This form of detection does not require knowledge of the amplitude or the absolute phase of the transmitted signal. Although radio performance is poor compared with coherent detection, the simplicity of the resulting design enables low cost implementation.

The remaining three modes utilise BPSK, QPSK and 16-QAM modulation with coherent detection. This type of detection requires a far more complex and expensive radio design - requiring automatic gain and phase control in addition to linear up and down conversion and power amplification. The advantage of such schemes is their greater bandwidth efficiency and (relative to discriminator detection) improved radio sensitivity [11]. Given that 16-QAM requires fully coherent detection, the performance of differentially detected BPSK and QPSK has not been simulated. If differential detection is desired (to reduce cost) then the use of higher level PSK modulation schemes (8-PSK for example) should be considered. However, this is not studied further in this paper.

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E. *Filtering and Radio Channel*

In the GFSK system, the mapped signal is passed through a 24-tap Gaussian filter with a *BT* product of 0.5, where *B* represents the 3dB bandwidth of the filter and *T* the symbol period. A modulation index, *h* of 0.28 is used [11]. The impulse response of the Gaussian filter is given as:

$$h(t)=\frac{1}{\sqrt{2\pi}sT}exp(-t^2/2s^2T^2) \qquad (1)$$

where s is given by $s=\sqrt{\ln(2)}/2\pi BT$.

The convolution between the Gaussian filter and the rectangular pulse is given by the expression:

$$g(t) = h(t) \otimes rect(t/T) \qquad (2)$$

where $rect(t/T)=1/T$ for $|t|=T/2$ and zero otherwise.

The transmitted signal, S_T can be represented by the following relationship:

$$S_T(t) = A_m exp^{j\phi_m(t)} \qquad (3)$$

where A_m represents the amplitude of the transmitted signal and $\phi_m(t)$ the integrated phase given by:

$$\phi_m(t) = \pi h \sum_{-\infty}^{t} I_n g(\tau - nT) d\tau + \phi_o \qquad (4)$$

where I_n is mapped to ± 1 according to the binary data and ϕ_o is the initial phase of the carrier. In the case of BPSK, QPSK and 16-QAM the mapped signal is passed through a root-raised cosine (RRC) filter with a roll-of factor, α of 0.35. For the QAM scheme, the amplitude and phase of the transmit symbols can be calculated by the following two equations:

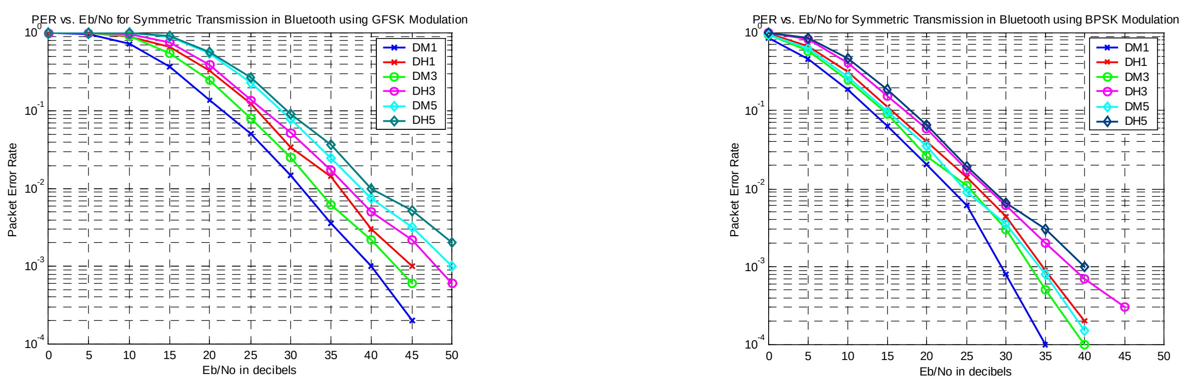
$$A_m(t)=\sqrt{I_{ch}(t)^2+Q_{ch}(t)^2} \qquad (5)$$

$$\phi(t)=arctan(Q_{ch}(t)/I_{ch}(t)) \qquad (6)$$

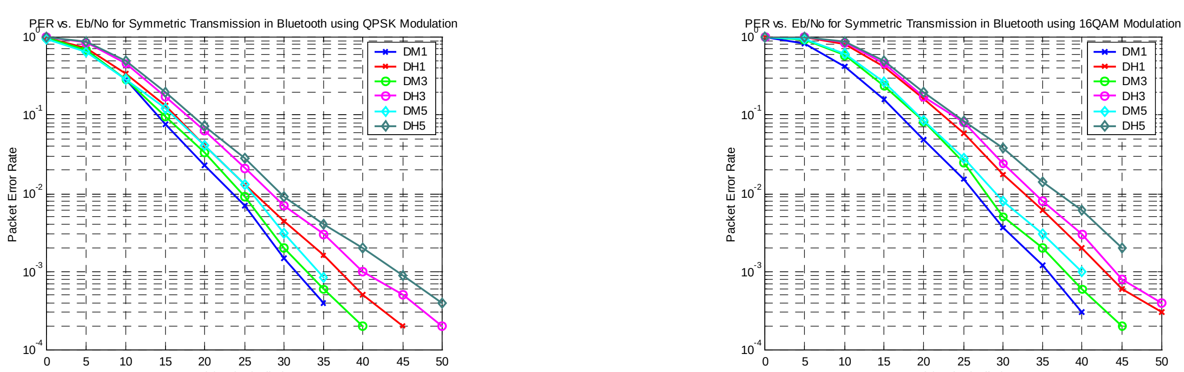
where I_{ch} and Q_{ch} are the RRC filtered baseband I and Q samples. The Bluetooth radio system makes use of frequency hopping, where each Bluetooth packet is sent over a different quasi-static uncorrelated Rayleigh fading channel. For multi-slot transmissions, the entire 3 or 5 slot transmission is sent on the same hop frequency. A narrowband Rayleigh fading channel is used to represent the worst possible multipath scenario.

Assuming the channel amplitude and phase is represented by A_c and ϕ_C respectively, the signal arriving at the receiver can be represented by the following equation:

$$S_R(t) = A_c A_m exp\{ j[\phi_m(t)+\phi_c]\}+A_n exp\{ j\phi_n \} \qquad (7)$$



Figures 3(a) and 3(b): PER versus Eb/No for GFSK and BPSK Modulations



Figures 3(c) and 3(d): PER versus Eb/No for QPSK and 16-QAM Modulations

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where A_n and ϕ_n are the amplitude and phase of the additive noise term. For the GFSK system, the RRC filter is also applied at the receiver. The signal is then passed through a phase detector and differentiator in order to recover the Gaussian filtered waveform. In order to improve the signal to noise ratio, an integrate and dump filter is used prior to the decision device.

F. *Packet Error Rate (PER) and Data Throughput (DT)*

Once the packet is received and coherently detected, a CRC is performed on the packet header and payload. Although the current Bluetooth standard specifies the CRC as a measure of determining if a retransmission is required, automatic repeat request (ARQ) itself is not employed in this simulation. Instead, the user data PER is calculated by comparing the transmitted and received data packets. The data throughput (*DT)* is calculated using the following relationship:

$$DT = (1 - PER) \times M \times DR \tag{8}$$

where M represents the number of bits/symbol (1 for GFSK and BPSK, 2 for QPSK and 4 for 16-QAM) and DR is the maximum data rate (listed in Table 2) for the corresponding packet.

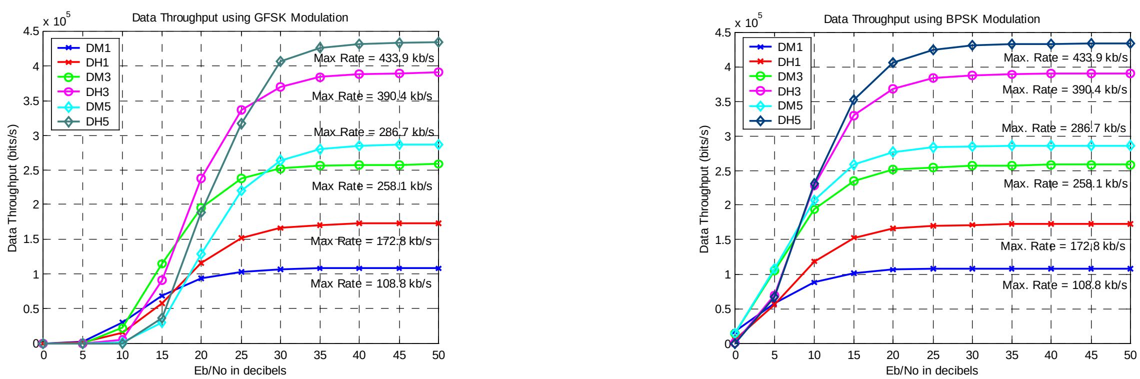
III. Software Simulation

Figures 3(a)-(d) show the packet error rate (PER) versus the ratio of energy per bit to noise power spectral density (Eb/No) for the six different ACL packets in Bluetooth using the four different modulation schemes. These results are used to obtain the data throughput curves for each packet type (see Figures 4(a) – (d)).

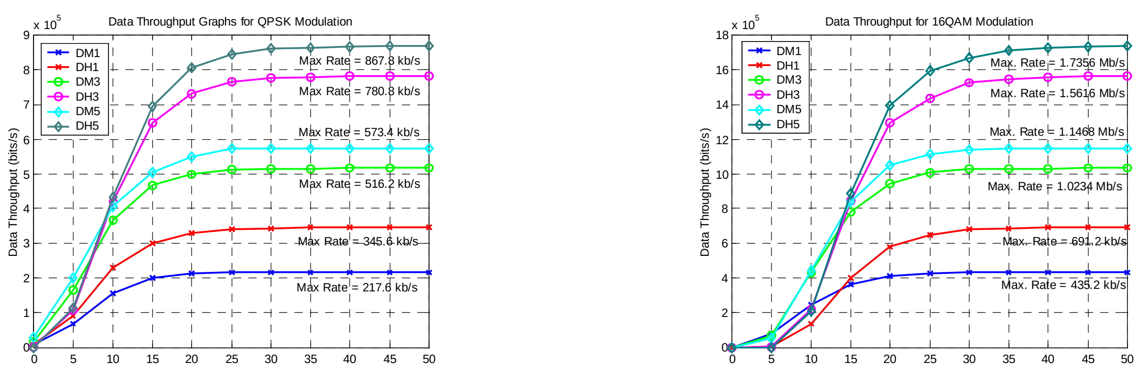
IV. Results and Discussion

The PER versus Eb/No plots shown in Figures 3(a)-(d) show that the Eb/No required to achieve a PER of 1% increases as higher-level modulation schemes are employed. This is, of course, expected since as higher-level modes are used, symbols are more susceptible to noise (since the Euclidean distance is reduced for a given average energy per bit). The use of a more complex receiver architecture for the BPSK scheme offers between 9-12dB gain over the GFSK scheme. TABLE III lists the Eb/No required to achieve a PER of 1%.

TABLE IV lists the maximum data throughput of the DM1 and DH5 packet types at Eb/No values of 20dB and 35dB (see Figures 4(a)-(d)). The data throughput is



Figures 4(a) and (b): Data throughput plots for GFSK and BPSK modulations



Figures 4(c) and (d): Data throughput plots for QPSK and 16-QAM modulations significantly increased as higher-level modulation schemes are employed. This suggests that the proposal for using PSK and QAM schemes are attractive future options in Bluetooth.

At 20dB for the DH5 packet, greater than 92% of the maximum achievable data rate for the BPSK (433.9kb/s) and QPSK (867.8kb/s) schemes can be supported. However, at the same Eb/No value, the GFSK scheme only achieves 44% of the maximum 433.9 kb/s data rate.

Similarly, at 20dB for the DM1 packet, greater than 98% of the maximum achievable data rate for the BPSK (108.8kb/s) and QPSK (217.6kb/s) schemes can be supported compared to only 83% of 108.8kb/s for the GFSK scheme. Although both the GFSK and BPSK schemes achieve a raw data rate of 1Mb/s, the use of more complex linear receive architectures for PSK has the advantage of increasing the overall data throughput to facilitate higher bit rate consumer electronics applications.

TABLE III
Eb/No REQUIRED FOR 1% PER

Modulation Scheme	Eb/No required for 1% PER (dB)					
	DM1	DH1	DM3	DH3	DM5	DH5
GFSK	32	36	33	37	39	40
BPSK	23	26	25	28	26	29
QPSK	23	26	25	28	26	29
16-QAM	26	33	27	34	29	37

TABLE IV
DATA THROUGHPUT FOR DM1 AND DH5 PACKETS

Packet Type	Data throughput (kb/s)				
	Eb/No (dB)	GFSK	BPSK	QPSK	16-QAM
DM1	20	90	107	217	400
	35	108	108	217	435
DH5	20	190	406	800	1400
	35	410	432	867	1700

Results obtained for data link coverage over an indoor home environment [12] have shown that in the presence of interference, the performance of higher-level modulation schemes would degrade rapidly. In a practical system, a combination of power control and link adaptation would therefore be required.

V. CONCLUSIONS AND FUTURE WORK

BPSK, QPSK and 16-QAM are certainly attractive schemes for facilitating high data rate applications using Bluetooth. Although a linear receiver architecture is more costly, the advantages of achieving data rates in excess of 2Mb/s is attractive for Bluetooth enabled cordless TV and VCR applications. The PSK schemes have the advantage of possible simple differential detection, thus reducing the potential cost of the receiver when compared to higher level QAM scheme. Given that QAM introduces considerable complexity, it appears that the higher bit rate requirements of video applications would be more readily achieved by increasing the operating bandwidth beyond the current 1MHz. To achieve useable VCR/TV video rates with QPSK modulation, the bandwidth would need to be increased by a factor of 5-10 times. This appears to offer a good trade-off between bandwidth efficiency, power requirements and achievable data rate. Thus it can be concluded that a combination of the use of PSK modulation schemes and greater bandwidth is a more likely candidate for a low cost, high data rate Bluetooth extension.

The ISM band is prone to interference from other Bluetooth enabled devices as well as Wireless Local Area Network (WLAN) products such as those based on the IEEE 802.11 standard. Although regulations to avoid interference in many radio communications systems exist, no such regulations govern the 2.45GHz ISM band. Possible solutions exploiting spatio-temporal geometry are now being analysed to minimise the interference that exists within a Bluetooth operating environment.

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