MODELLING FOR BLUETOOTH PAN RELIABILITY

Xiao Xiong
John Pollard
University College London
Department of Electronic and Electrical Engineering
Torrington Place, London, WC1E7JE, UK
Email: jp@ee.ucl.ac.uk

KEYWORDS

Bluetooth, Personal Area Networks, communication reliability, redundant links, sensors.

ABSTRACT

Bluetooth-enabled sensors may be used for monitoring personal health but there is considerable interference in the received signal due to multi-path reflections. It is important that communication reliability should be improved in safety-critical data-acquisition applications.

A new topology of the Bluetooth radio system is presented using *cloned* transmitting devices to enhance signals in particular directions. The multi-path interference at the receiver was reduced and this enabled improved signal quality (lower Bit Error Rates) to be achieved. Computer modelling was conducted to evaluate the magnitude of improvement by using *Space/Time/Frequency* redundancy in indoor wireless communications.

INTRODUCTION

Communication reliability is very important for sets of wireless-enabled sensors that monitor the health of people in their home. Personal safety may be at stake.

A suitable technology is a Bluetooth Personal Area Network (PAN). This is a set of low power, inexpensive, short-range (10-100m) radio transceivers that operate at 2.45 GHz (Bluetooth SIG 2003). A single Master controls no more than seven Slaves in a Piconet and a PAN comprises several communicating Piconets.

Packets of information are transmitted over radio channels that suffer co-channel interference. This is due to multiple paths between source and sink because of the many irregular scatterers (walls or furniture) in an indoor environment. Time-dependent errors appear at the receiver because the communicating devices hop from frequency to frequency with time. Frequency transitions are chosen to change multi-path interference in a non-coherent manner.

The aim of the present work is to reduce the communication errors by adding redundancy in connectivity for the channel. Bluetooth *clones* allow two links between Master (+ Master-Clone) and Slave.

Computer modelling has been used to confirm the observed performance of a single Bluetooth radio link (Pollard and Kontakos 2001). This work is extended to examine the cloned communication system and to determine its improvement in terms of Bit Error Rate.

CLONE TOPOLOGY

The topology of a cloned Bluetooth system is presented in Figure 1. Master1 and Master2 (Master + Clone) are synchronized by a common clock and communicate with a Slave. Phase shifters are used in order to set different delays of the transmitted signals at the Master end (Brabant 2003).

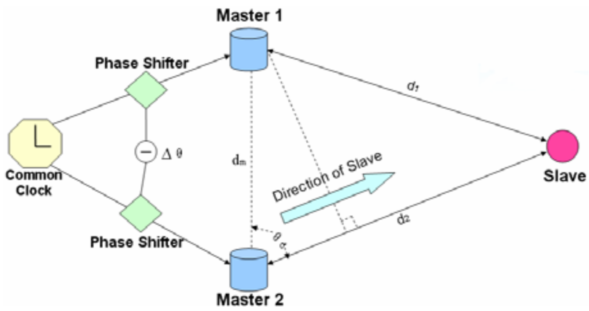

Figure 1: Schematic of Cloned Bluetooth System

The idea of this design is to reduce the effect of reflection in fading channel. In this topology, the original signal is transmitted by two identical Masters and reaches the Slave with varied phase shift as the frequency hops. As the two frequency-hopping signals meet with different reflections while passing through the indoor channels, they do not suffer constant destructive interference. After being received and added at the Slave, the quality of the time-averaged received signal improves.

Proceedings 19th European Conference on Modelling and Simulation
Yuri Merkuryev, Richard Zobel, Eugène Kerckhoffs © ECMS, 2005
ISBN 1-84233-112-4 (Set) / ISBN 1-84233-113-2 (CD)

MODELLING PROCESS

Overview

For verifying above proposal, the characteristics of baseband signal throughout the entire transmission process are examined by using computer modelling. A general model is illustrated in Figure 2.

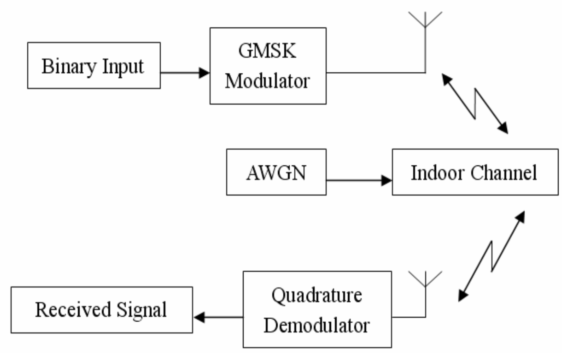

Figure 2: General Communication Model

Maximal length shift-register binary data are up-converted by a Gaussian Minimum-Shift-Key (GMSK) modulator at a prescribed carrier frequency. The pass-band signal then passes through the multi-path indoor channel with Added White Gaussian Noise (AWGN). At the receiver end, a quadrature demodulator is adopted to recover the original baseband signal.

Modulation

Figure 3 shows a simulation model of GMSK modulator. A Gaussian filter shapes sampled binary data. Samples are fed to Voltage Controlled Oscillator (VCO) where they are integrated and up converted to high frequency band.

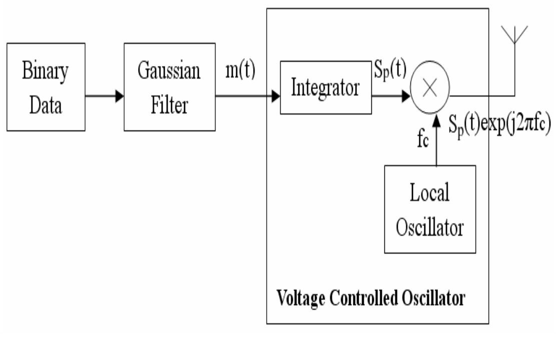

Figure 3: GMSK Modulator

The two signals $s_1(t)$ and $s_2(t)$ transmitted from two Masters that are subject to different phase delay can be expressed as $\mathrm{Re}[\hat{S}(t)\exp(j2\pi f_c t+\varphi 1)]$ and $\mathrm{Re}[\hat{S}(t)\exp(j2\pi f_c t+\varphi 2)]$, respectively.

Continuous-Phase Frequency-Shift Keying (CPFSK) is used as the modulation scheme. The pass-band CPFSK signal, $S_p(t)$ of a constant envelope modulated signal of carrier frequency, f_c (2.45 GHz) is:

$$S_p(t) = \mathrm{Re}[S_b(t)\exp(j2\pi f_c t)] \quad \textbf{(1)}$$

Re[] is the real part of the complex number, and

$S_b(t)$ is the baseband modulated signal:

$$S_b(t) = \cos[\theta(t)] + j\sin[\theta(t)] \quad \textbf{(2)}$$

Here, $\theta(t)$ is the phase of the signal:

$$\theta(t) = \int m(t)dt \quad \textbf{(3)}$$

where m(t) is the Gaussian-shaped sampled binary data signal to be transmitted over the channel (Haykin 2000).

Indoor Channel

Figure 4 shows a statistical model for indoor multi-path propagation (Saleh and Valenzuela 1987). There are three clusters of waves which follow different reflection paths (*multi-path*) illustrated in this figure. These clusters are delayed with respect to the Line-of-Sight (LOS) wave by several nanoseconds.

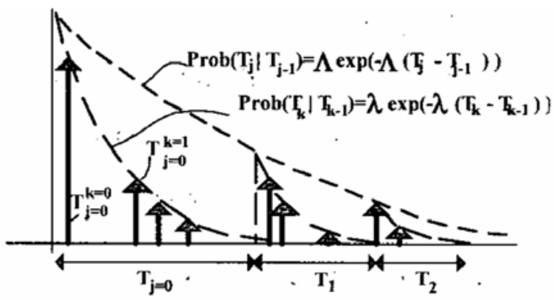

Figure 4: Double-Poisson Arrival Channel Model

The simulation is of the propagation of two signals $S_{p1}(t)$ and $S_{p2}(t)$ through two different indoor channels which are based on the model shown in Figure 4. Additionally, AWGN samples are generated using the Box-Muller method (Press et al. 1988).

Figures 5 and 6 are the impulse responses of the two example indoor channels by using an ideal input pulse with unit amplitude. The figures show that the clusters of reflected waves in channel 1 are delayed by a different amount from those of channel 2. This indicates that a large interference does not occur at the same time in the two channels. The channels are de-correlated.

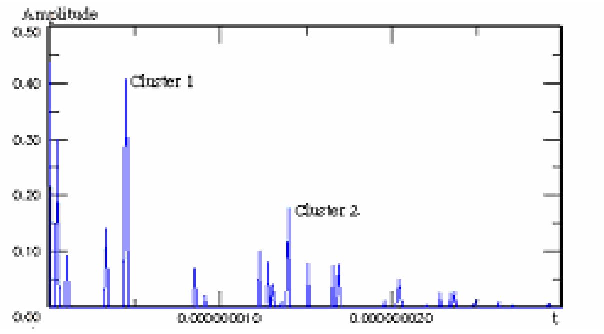

Figure 5: Channel 1 Impulse Response

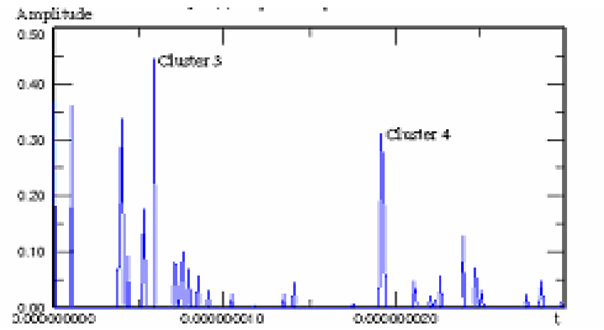

Figure 6: Channel 2 Impulse Response

Demodulation

Figure 7 is a demodulator that consists of an adder, a quadrature demodulator and a differentiator. The recovered baseband signal m(t) can be used to examine the transmission characteristics.

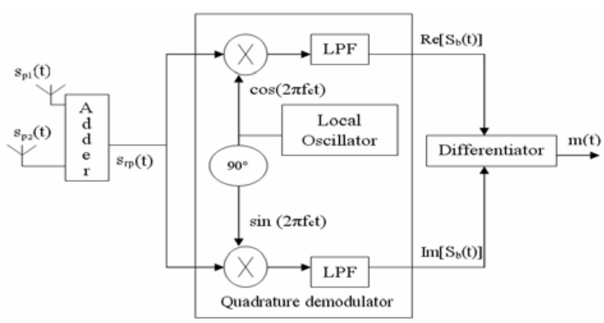

Figure 7: Demodulator Model

Quadrature demodulation is employed to down-convert the pass-band signal to baseband. The baseband signal may be recovered by multiplying the carrier signal and removing the high frequency component. A differentiation with respect to time is then required for recovering the Gaussian-shaped sampled binary signal, m(t) (see Equation 3).

MODELLING RESULTS

Figure 8 is input phase data filtered by Gaussian filter:

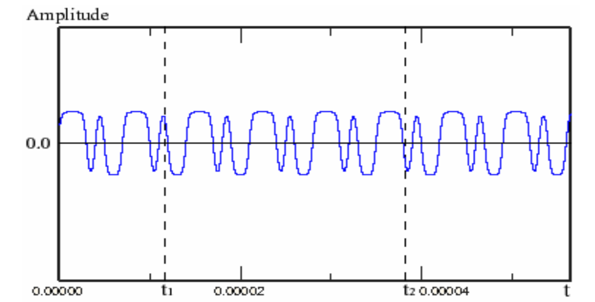

Figure 8: Original Data after Gaussian Filter

After the above simulation procedure, the integrated phase output was obtained that had a similar shape to the input. This is shown in Figures 9 and 10:

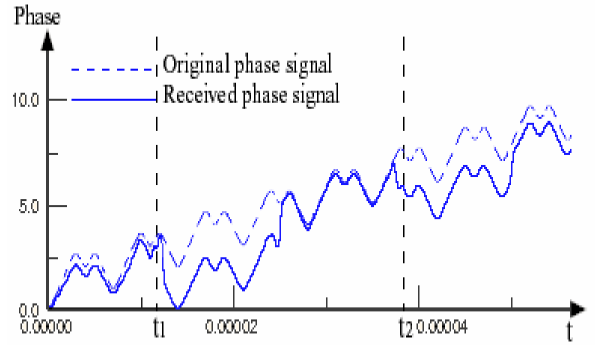

Figure 9: Phase vs. Time for Master Only Data

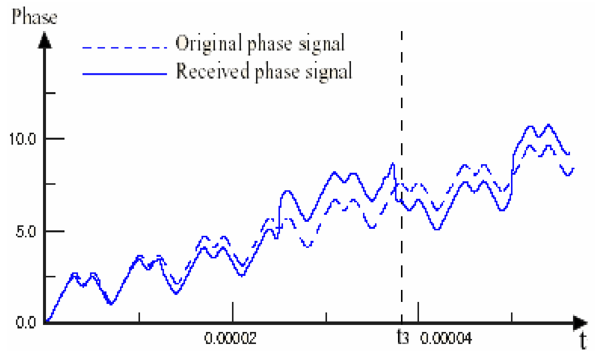

Figure 10: Phase vs. Time for Master+Clone Data

The mean (broken-line) phase signal increases with time as shown and represents the integrated phase signal expected with no effects of the channel. The continuous line is the integrated phase signal after being passed through the indoor channel in each case. Distortion can be seen. This is due to the multi-path reflected waves and causes errors in received data.

The wave form of the single Master signal in Figure 9 has severe distortion points at time t_1 and t_2. In comparison, the (Master + Clone) signal in Figure 10 is more smooth and more nearly approximates the expected phase signal except for time t_3.

Figure 11 and Figure 12 show the recovered Gaussian filtered sampled signal after differentiating the waveforms shown above.

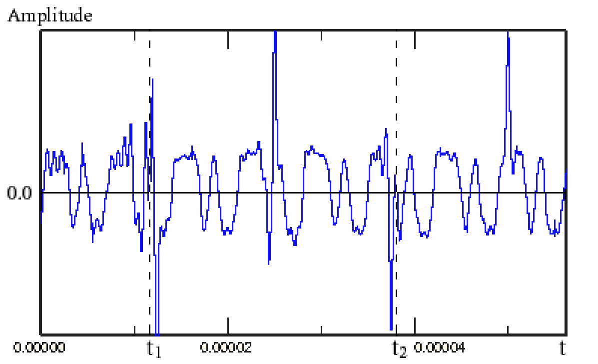

Figure 11: Recovered Signal for Master Only Data

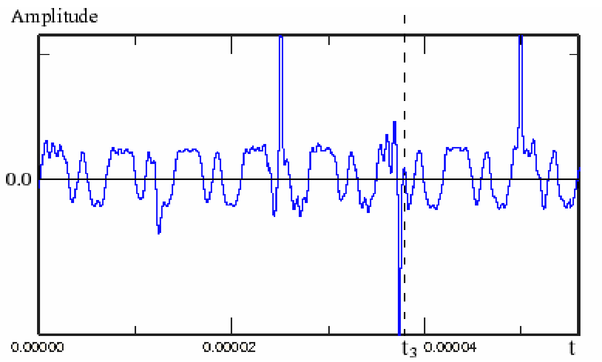

Figure 12: Recovered Signal for Master+Clone Data

The broken line indicates the times (t_1, t_2, t_3) where an error in the output was observed in comparison to the original input data.

The time frame for simulation of the results allowed a very limited snapshot of the phase vs. time. Nevertheless, it can be seen in Figure 12 that only one error is produced in detection at time t_3 within the same measurement period as in Figure 11. It can be inferred that lower Bit Error Rate, BER can be achieved under the (Master + Clone) topology.

The results below further demonstrate the above statement. Figure 13 shows the simulated Bit Error Rate (BER) performance of the single Master topology as the carrier frequency was changed for a constant channel model. It can be seen that the multi-path interference that caused errors was critical in the determination of channel reliability and this was a strong function of frequency. Between 2.413 and 2.417 GHz (a frequency change of 4 MHz), the BER decreased by nearly an order of magnitude. The reliability of communication had BER > 10^{-2} for the whole frequency-hopping spectrum for this physical channel. This is satisfactory for speech but barely satisfactory for data transfer for wireless health monitoring.

It can be seen that at carrier frequencies near 2.417 GHz and 2.439 GHz, BERs are as high as 10^{-1}. This means that these frequencies are not available for use in reliable communication systems and an Adaptive Frequency Hop table would be parameterised to preclude them.

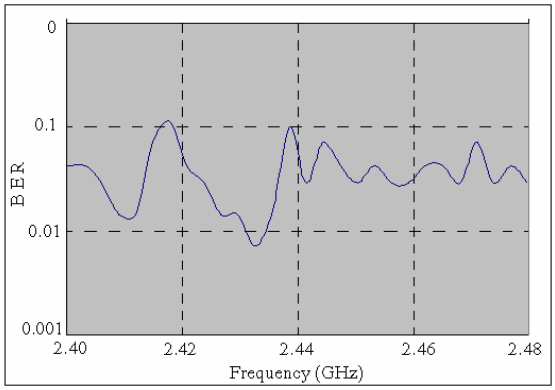

Figure 13: BER vs. Frequency for Single Master

The measured Received Signal Strength Intensity (RSSI) vs. frequency is shown for a single Master topology in Figure 14. There is an inverse relation between RSSI and BER and the measured results bear out the sensitivity of BER simulated results vs. frequency.

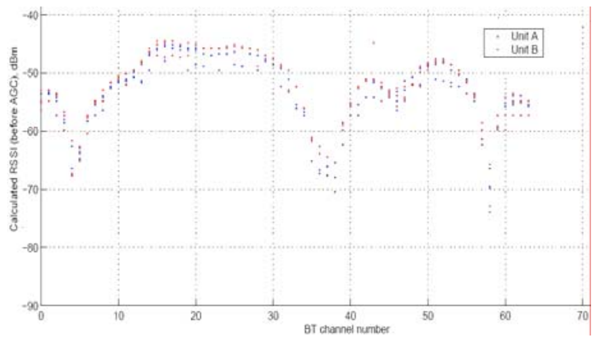

Figure 14: Received Signal Strength vs. Frequency [CSR]

The results from the Bit Error Rate simulation of Single and (Master + Clone) topology are tabulated in Table 1.

Table 1: Comparison of BER Performance in Single and Master + Clone Topology

Hopping Frequency (GHz)	BER			
	Single Master Topology	Cloned Masters Topology		
		Phase Shift		
		0°	90°	180°
2.400	4.29 X10^{-2}	4.29 X10^{-2}	1.43 X10^{-2}	4.29 X10^{-2}
2.418	1.14X10^{-1}	1.43 X10^{-2}	4.29 X10^{-2}	2.86 X10^{-2}
2.439	1X10^{-1}	5.71 X10^{-2}	7.14 X10^{-2}	5.71 X10^{-2}

It can be seen that the BER at frequency 2.400 GHz has been improved from $4.3 x 10^{-2}$ for a Single Master topology to $1.4 x 10^{-2}$ for a phase difference of 90^o between Master and Clone. In addition, the error rates at frequencies: 2.418 GHz and 2.439 GHz are significantly improved for all phase differences and these two frequencies become usable for speech communication.

Table 1 therefore indicates that more hopping frequencies are available and the communication reliability could be enhanced by using the Master + Clone topology in Bluetooth radio systems.

SUMMARY

A (Master + Clone) Bluetooth topology was proposed and this has been simulated using a realistic model of the Bluetooth radio system. The characteristics of base-band signal were examined. The initial theory of this topology was verified to be feasible and useful. Improved signal quality (reduced error rate) was capable of being achieved.

REFERENCES

Bluetooth SIG. 2003. *Specifications of the Bluetooth System. V1.2,* http://www.bluetooth.com,

Brabant, G. 2003. *Bluetooth in Space*, MSc. in Space Technology. & Satellite Communications, UCL.

Haykin, S. 2000. *Communication Systems*, John Wiley.

Pollard, J.K. and N.P. Kontakos. 2001. *Bluetooth RF layer performance evaluation*, London Communications. Symposium, UCL, 155-158.

Press, W.H. et al.. 1988. *Numerical Recipes in C*, Cambridge University Press.

Saleh, A.A.M. and R.A. Valenzuela. 1987 *A Statistical Model for Indoor Multipath Propagation*, IEEE Journal of Selected Areas of Communications, **SAC-5(2)**, 128-137.

AUTHOR BIOGRAPHIES

XIAO XIONG was born in Wuhan, Hubei province in China. He graduated in Communication Engineering from Huazhong University of Science and Technology, which is one of the best-regarded universities in the country.

He completed a Masters Degree by Research in Telecommunication Engineering at UCL in 2004.

JOHN K. POLLARD is in the Department of Electronics and Electrical Engineering at UCL. His background is in the design of Integrated Circuits, communication systems and software systems.

In recent years, he has been interested in the use of the World-Wide Web as an enabling technology for teaching and for distributed software simulation. An integrated combination of hardware and software is necessary to connect a distributed system of computers and mobile input/output electronics (such as mobile telephones and Bluetooth-enabled devices) with databases and real, physical apparatus.