Arumugam, AK., Armour, SMD., Lee, BS., Tariq, MF., & Nix, AR. (2001). Consumer electronics application and coverage constraints using Bluetooth and proposed Bluetooth evolution technologies. *IEEE Transactions on Consumer Electronics*, 47(3), 283 - 293. [Issue 3]. <https://doi.org/10.1109/30.964111>

Peer reviewed version

Link to published version (if available):
[10.1109/30.964111](https://doi.org/10.1109/30.964111)

[Link to publication record in Explore Bristol Research](#)
PDF-document

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CONSUMER ELECTRONICS APPLICATION AND COVERAGE CONSTRAINTS USING BLUETOOTH AND PROPOSED BLUETOOTH EVOLUTION TECHNOLOGIES

A. K. Arumugam, S. M. D. Armour, B. S. Lee, M. F. Tariq and A. R. Nix
University of Bristol, Centre for Communications Research, Merchant Venturer's Building
Woodland Road, Bristol, BS8 1UB, UK

ABSTRACT

This paper considers issues such as residential coverage and achievable bit rate using the Bluetooth Personal Area Network (PAN) standard. Link budget analysis is performed by combining detailed link level physical layer simulations with site specific power predictions from a state-of-the-art indoor propagation model. Assuming a 1mW transmit unit, coverage plots are generated at 2.4 GHz for an example single and multi-storey residential environment. The investigation considers Bluetooth data medium (DM) and data high (DH) packet types. Results for the transmission of symmetric asynchronous data link (ACL) packets are used to discuss the bit rate capabilities of various time-bounded and non-time bounded Bluetooth enabled consumer electronic devices. To meet the bit rate needs of future consumer electronic devices, QPSK, 16-QAM and 64-QAM are proposed as possible enhancements to the current GFSK mode. Using physical layer simulations, the coverage and data rate performance of these new modes are analysed and compared with those of standard Bluetooth. The use of linear receive architectures and coherent modulation, although adding significantly to the unit cost, is shown to significantly improve radio sensitivity. Results indicate that high bit rate QAM operation is now possible over an extended coverage area.

INTRODUCTION

In recent years, the radio communications industry has moved rapidly towards the development of a universal radio interface for ubiquitous radio connectivity. In the area of Personal Area Networks (PAN), this has led to the development of the Bluetooth radio standard. PAN devices can be classified into one of three major categories – mobile, stationary or consumer electronic [1]. 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 [2]. 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-bit period (BT) product of 0.5 [3].

One of the drawbacks with 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 1 lists typical bit rate requirements for commonly used consumer electronics 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]

Table 1: Typical bit rate requirements for today's consumer electronic devices

This paper aims to increase the data rate capability of Bluetooth to extend its application to a wider range of devices. Packet Error Rate (PER) and Data Throughput (DT) performance is analysed for standard Bluetooth devices and enhanced units employing higher-level modulation schemes such as QPSK, 16-QAM and 64-QAM. The peak data rate for the aforementioned schemes is 2, 4 and 6Mbit/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 outlines the development of the indoor propagation-modelling tool and presents the resulting coverage maps. Section V considers the suitability of the proposed techniques in terms of time bounded and non-time bounded consumer electronics devices.

Figure1: Block diagram of the Bluetooth transmitter and receiver simulated in Matlab

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.

1 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, 4 and 6 times when QPSK, 16-QAM and 64-QAM modulation schemes are employed respectively.

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

Table 2. DM and DH packets for ACL link

The ACL packets have the general structure shown in Figure 2. Each packet occupies a time slot of 625 μ s. When multiple time slot transmission is used, the total number of payload bits is either 3 or 5 times the value listed in Table 2 depending on whether DM/DH 3 or 5 is used.

Figure 2. Structure of ACL Packets

Although each packet has a duration of 625 μ s, the duty cycle of a standard DM1 packet is just 366 μ s. 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. The CRC is derived from the Upper Address Part (UAP) of the 48-bit device address assigned to each Bluetooth unit by the manufacturer.

2 Coding Scheme

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.

3 Interleaver

After the encoding process, block interleaving is applied to the entire packet. This step is implemented to further protect the transmitted data from error bursts due to large delay spreads, which in turn cause inter-symbol-interference (ISI) when the operating range increases from 10m to 100m.

4 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, the simplicity of the resulting design enables low cost implementation.

The remaining three modes utilise QPSK, 16-QAM and 64-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 and 64-QAM require fully coherent detection, the performance of differentially detected QPSK has not been simulated. If differential detection is desired (to reduce cost) then operation using BPSK, QPSK and 8-PSK modes is recommended although not studied further in this paper.

5 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:

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

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:

$$g(t) = h(t) \otimes \text{rect}(t/T) \quad (2)$$

where $\text{rect}(t/T) = 1/T$ for $|t| = T/2$ and zero otherwise. The transmitted signal, S_T can be represented by the following relationship:

$$S_T(t) = A_m \exp(j\phi_m(t)) \quad (3)$$

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

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

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 QPSK, 16-QAM and 64-QAM, the mapped signal is passed through a root-raised cosine (RRC) filter with a roll-off factor, α of 0.35.

For the QAM schemes, the amplitude and phase of the transmit symbols can be calculated by the following two

Figures 3(a) and 3(b): PER versus E_b/N_0 for GFSK and QPSK Modulations

Figures 3(c) and 3(d): PER vs. E_b/N_0 for 16QAM and 64QAM Modulations

equations:

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

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

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 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:

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

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.

6 Packet Error Rate (PER) and Data Throughput (DT) Calculation

Once the packet is received and coherently detected, a CRC is performed on the payload 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 the simulation. Instead, the user data PER is calculated by comparing the transmitted and received data.

The data throughput (DT) is calculated using the following relationship:

$$DT = (1 - PER) \times M \times DR \quad (8)$$

where M represents the number of bits/symbol (1 for GFSK, 2 for QPSK, 4 for 16-QAM and 6 for 64-QAM) and DR is the maximum data rate (listed in Table 2) for the corresponding packet.

SOFTWARE SIMULATION

Figures 3(a)-(d) show the packet error rate (PER) versus the ratio of energy per bit to noise power spectral density (E_b/N_0) 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)).

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

Figures 4(c) and (d): Data throughput plots for 16QAM and 64QAM modulations

IV. PROPAGATION MODEL

A state-of-the-art indoor space-time propagation model [12] based on ray launching [13-15] is used to predict the complex temporal and spatial characteristics of the radio channel. This model is used to provide information on the received signal power in an indoor single and multi-storey building. The results are generated for a maximum of 6 orders of reflection and transmission combined with a single order of diffraction. Short dipole antennas are used at the basestation and terminal, located approximately 0.8m above the floor (typical desk height). The maximum transmit and receive gain of the antennas is 1.5dBi [16]. A peak transmit power of 0dBm (1mW) is assumed.

Figures 5(a) and 5(b) respectively show a typical point-to-point indoor prediction within a single and multi-storey environment. The test area is constructed predominantly from brick and has a concrete floor. The dimension of the test area is 16x11m² with 3m high ceilings. The relative permittivity and conductivity of the material are 3 and 0.005 S/m respectively [16].

Figures 6(a) and 6(b) show coverage plots of the received signal power on the ground and first floors respectively. The noise power spectral density generated at the receiver is given by the following equation [17]:

$$N_o = 10 \log_{10} kT + 10 \log_{10} (BW) + NF \quad (9)$$

where $k = 1.38 \times 10^{-20}$ (mW/Hz/K) represents Boltzmann's constant and $T = 300K$ is the temperature in Kelvin. NF is

the noise figure of the RF amplifier which is taken to be 20dB for the GFSK system [1]. For the QAM schemes, a NF of 10dB is assumed (this superior value resulting from the more expensive radio front-end). The operating bandwidth, BW is 1MHz. Thus, $N_o = -94$ dBm for the GFSK system and -104 dBm for the QAM schemes. The received E_b / N_o is calculated for every point in the test area (with a grid spacing of 0.2m). The E_b / N_o is calculated using the following expression:

$$(E_b / N_o)_{dB} = P_R - N_o + 10 \log_{10} ((1 - \alpha) / k) - \langle \text{peak} / \text{mean} \rangle_{dB} \quad (10)$$

where P_R is the received power, N_o is the noise power spectral density, α is the roll off factor of the RRC filter and k is the number of bits/symbol. Since the transmit power is assumed to be 1mW peak, the peak-to-mean ratio $\langle \text{peak} / \text{mean} \rangle$ of the QAM schemes is subtracted from the expression. Table 3 lists key parameters for each of the four modulation schemes investigated.

Modulation Scheme	NF (dBm)	N _o (dBm)	k (bits/symb)	<peak / mean> (dB)
GFSK	-20	-94	1	1
QPSK	-10	-104	2	3.4
16-QAM	-10	-104	4	5.0
64-QAM	-10	-104	6	5.6

Table 3: Key Modulation Parameters

Figures 5(a) and (b): Received signal strength in a single and double storey indoor environment

Figures 6(a) and (b): Coverage plots for the received signal strength (in dBm) for the ground and first floors

Figure 7(a) and (b): Ground floor data throughput and packet coverage for GFSK modulation

Figure 7(c) and (d): Ground floor data throughput and packet coverage for QPSK modulation

Figure 7(e) and (f): Ground floor data throughput and packet coverage for 16-QAM modulation

Figure 7(g) and (h): Ground floor data throughput and packet coverage for 64-QAM modulation

Figure 8(a) and (b): First floor data throughput and packet coverage for GFSK modulation

Figure 8(c) and (d): First floor data throughput and packet coverage for QPSK modulation

Figure 8(e) and (f): First floor data throughput and packet coverage for 16-QAM modulation

Figure 8(g) and (h): First floor data throughput and packet coverage for 64-QAM modulation

V. RESULTS AND DISCUSSION

The results presented in Figures 6(a) and (b) assume a ground floor Bluetooth transmitter placed in the point marked 'TX' in the plots. An important observation from Figures 6(a) and (b) is that the maximum received signal strength on the first floor of the building is nearly 16 dB lower than that on the ground floor. Consequently, the maximum data link achievable on the first floor is expected to be less than that on the ground floor. Figures 7(a)–(h) show the data link and the packet type coverage plots using GFSK, QPSK, 16-QAM and 64-QAM modulation formats for the ground floor of the test area concerned. The data link plots are obtained by finding the maximum data throughput achievable based on the received E_b/N_0 value (calculated from the signal to noise ratio as discussed in section IV). Figures 4(a)–(d) are used as the reference E_b/N_0 plots. Similar plots were generated for the first floor of the test area and are shown in Figures 8(a)–(h). Coverage analysis is summarised in the following section.

The PER versus E_b/N_0 plots shown in Figures 3(a)–(d) show that the E_b/N_0 required to achieve a PER of 1% increases as higher-level modulation schemes are employed. This is 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) thus resulting in higher PER. Table 4 lists the E_b/N_0 required to achieve a PER of 1%.

Modulation Scheme	Eb/No required for 1% PER (dB)					
	DM1	DH1	DM3	DH3	DM5	DH5
GFSK	32	36	33	37	39	40
QPSK	24	26	25	28	26	30
16-QAM	26	33	27	34	29	37
64-QAM	36	40	36	41	38	43

Table 4: E_b/N_0 required for 1% PER

Table 5 lists the maximum data throughput of the DM1 and DH5 packet types at E_b/N_0 values of 20dB and 35dB (see Figures 4(a)–(d)). The data throughput is significantly increased as higher-level modulation schemes are employed. This suggests that the proposal for using QAM schemes is an attractive option for increasing the data throughput.

Packet Type	Data throughput (kb/s)				
	Eb/No (dB)	GFSK	QPSK	16-QAM	64-QAM
DM1	20	90	217	400	390
	35	108	217	435	652
DH5	20	190	800	1400	350
	35	410	867	1700	2400

Table 5: Data throughput for DM1 and DH5 packets

It can be observed from Figures 7 and 8 that the data throughput is much higher for the QAM schemes compared to that achievable by the currently specified GFSK scheme. However, the distance from the transmitter at which maximum data throughput can be achieved decreases as higher-level modulation schemes are employed. 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 adaption would be required.

The coverage plots shown in Figures 7 and 8 assume no clutter in the indoor environment. This accounts for the impressive coverage using a 1mW transmitter. Figures 9(a) and (b) show the data throughput plots for the GFSK system on the ground floor and first floor respectively, assuming an additional clutter loss of 10dB. It can be seen that the data throughput now degrades (comparing Figures 9(a) and (b) with Figures 7(a) and 8(a)) due to the presence of such clutter. For the GFSK, QPSK and 16-QAM modulation schemes, the packet type coverage plots in Figures 7 and 8 show that the DM5 and DH5 type packets are predominantly responsible for providing the maximum data throughput within the indoor environment on both the ground and first floors. However, the DM1 packet is used for the 64-QAM mode since the maximum data throughput achievable with this mode is comparatively low due to the transmit power level used.

Figure 9(a): GFSK Ground Floor Throughput (clutter)

Figure 9(b): GFSK First Floor Throughput (clutter)

VI. CONCLUSION AND FUTURE WORK

From the results obtained it is possible to determine the feasibility of the proposed higher-level modulation schemes. Figures 10(a) and (b) show the percentage of ground and first floor locations in the right hand side of the building that achieve a given data throughput. The indoor environment is modelled as two homes situated back to back. The percentage coverage is only calculated within the home where the transmitter is located. In our investigation, this corresponds to the right-hand side of the building (see Figures 6(a) and (b)). Power levels in the left-hand building are considered as unwanted interference.

The feasibility of 64-QAM is questionable based on Figures 10(a) and (b), which suggests a strong need for power control (to increase the maximum transmit power). 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.

From Figures 7 and 8, it can be concluded that the 64-QAM modulation scheme is certainly not favourable although video data rates are achievable over a very small coverage area. QPSK and 16-QAM are certainly more attractive schemes although the former does not achieve data rates high enough for high quality cordless VCR applications. The QPSK mode has the advantage that it can be differentially detected, thus reducing the potential cost of the receiver when compared to higher level QAM schemes. Given that QAM introduces considerable complexity, it appears that much higher bit rates 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. This appears to offer a good trade-off between bandwidth efficiency, power requirements and achievable data rate. From the above it can be concluded that PSK schemes are more likely candidates for a low cost high data rate Bluetooth extension.

From Figures 10(a) and (b) it can be seen that the introduction of clutter has a significant impact on the overall coverage. At 80% coverage on the ground floor, the achievable data rate is 400 kb/s with clutter and 433 kb/s without clutter. However, on the first floor, at 80% coverage, the achievable data rates are 100 kb/s and 360 kb/s respectively with and without clutter.

Table 6 summarises the possible applications for each of the modulation schemes investigated here. The proposed evolution technologies enable consumer electronics devices using Bluetooth to be more applicable to time bounded applications.

Figure 10(a): Data Coverage (Ground Floor)

Figure 10(b): Data Coverage (First Floor)

The need for more accurate propagation data has been identified, particularly the modelling and measurement of in-building clutter. In this analysis, the impact of clutter was evaluated using a bulk loss of 10dB. Given the use of ray tracing, the results obtained are unique to the particular environment considered. The results depend very heavily on the geometry of the indoor environment as well as the thickness of the walls and ceilings and the materials used to construct the building.

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 there are regulations to avoid interference in many radio communications systems, 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.

	Applications using GFSK	Applications using QPSK	Applications using 16QAM	Applications using 64QAM
	400 kb/s	830 kb/s	880 kb/s	20 kb/s
GROUND FLOOR	Non-time bounded applications such as web browsing, cordless telephones (DECT) and videophones, cordless modems and PDAs	Time-bounded applications such as moderately good digital quality video and non-time bounded applications	Time-bounded applications such as moderately good digital quality video and non-time bounded applications	Low data rate non-time bounded applications.
	360 kb/s	820 kb/s	360 kb/s	10 kb/s
FIRST FLOOR	Non-time bounded applications such as web browsing, cordless telephones (DECT) and videophones, cordless modems and PDAs	Time-bounded applications such as moderately good digital quality video and non-time bounded applications	Non-time bounded applications such as web browsing, cordless telephones (DECT) and videophones, cordless modems and PDAs	Low data rate non-time bounded applications.

Table 6: Consumer electronics application using the present and proposed Bluetooth evolution technologies

ACKNOWLEDGEMENTS

A.K. Arumugam and B.S. Lee wishes to thank the Overseas Research Scholarship (ORS), UK for the financial support provided in funding this work. In addition, A.K. Arumugam also wishes thank the Institution of Electrical Engineers (IEE), UK for the financial support provided by the Robinson Research Fellowship fund.

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BIOGRAPHIES

Arun Kumar Arumugam was born in Malaysia in 1977. He obtained a BEng in Electronic and Communications Engineering in 1999 from the University of Bristol. He is currently studying for a PhD at the University of Bristol. He was awarded the Robinson Research Fellowship by the Institution of Electrical Engineers (IEE) UK in November 2000. His research interests are in enhancements of the Bluetooth technology and interference suppression techniques exploiting space-time block codes and antenna diversity for Bluetooth enabled devices.

Simon Armour received his BEng degree from the University of Bath (UK) in 1996. He has subsequently undertaken study for a PhD at the University of Bristol (UK) on the subject of Combined OFDM-Equalisation Strategies. Following a period of post-doctoral research in the area of advanced Wireless LAN technologies, he was appointed to the position of Lecturer in Software Radio in 2001. His research interests include Software Radio, Wireless LANs/PANs, Wireless Home Networks and Multicarrier Modulation. He is a member of the IEE and IEEE.

Beng-Sin Lee was born in Singapore in 1971. He received a BEng in Electronic Engineering in 1998 from the University of Bristol. He is currently studying for a PhD in Electronic Engineering at the University of Bristol. His main research interests are in the area of radio propagation, namely site specific wireless channel modelling in indoor and outdoor environments.

M. Fahim Tariq obtained a B.Sc. in Electrical and Electronic Engineering in 1994 from the Eastern Mediterranean University in Turkey. He joined the Centre for Communications Research, University of Bristol, UK in 1995, where he received PhD in the area of Channel Adaptive Modem Design in Jan 2001. Dr Tariq is currently a Research Associate working in the digital communications group. His research interests include advanced modulation and coding techniques, adaptive equalisation, channel modelling and capacity evaluation techniques. He is a

member of IEEE.

Andrew Nix received BEng and PhD degrees from the University of Bristol (UK) in 1989 and 1993 respectively. He joined the lecturing staff at the University of Bristol in 1992 and was promoted to Professor of Wireless Communication Systems in 2001. His main research interests include radiowave propagation modelling, cellular optimisation and advanced digital modulation/reception techniques. At present he leads the propagation modelling and wireless Local Area Network groups in the Centre for Communications Research (CCR). He has published in excess of 160 Journal and Conference papers, in addition to contributions to three related textbooks. In the area of propagation modelling, his group has developed state of the art deterministic propagation models for indoor, microcellular and macrocellular scenarios. He is an active member of ETSI BRAN (Broadband Radio Access Networks) and a member of the IEEE.