Chapter 2

Bluetooth Transmission Technology

2.1 Introduction

Recent technological innovations and declining prices for personal computers (PCs) and wireless phones are resulting in an emerging trend coined “pervasive computing”, which is defined as having access to information anytime and anywhere. The three complimentary wireless technologies that provide the means for pervasive computing are Wireless Wide Area Networks (WWAN), Wireless Local Area Networks (WLANs) and Bluetooth Personal Area Networks (PANS).

The research focus of this thesis is directed toward Bluetooth Personal Area Networks. Driven by the boom in Internet usage, on-line trading, banking and shopping, mobile and home offices, and corporate employees with multiple offices the convergence of the wireless radio and computer are a reality. Mobility is at the center of this marriage, bridging the gap between computing and communications for a wide range of computing devices such as notebook computers, pagers, cellular phones, and Personal Digital Assistants (PDAs). Connectivity among these devises will become a necessity to share resources, printing, transferring e-mail, Internet access and video data exchange among wired and wireless devices. Connectivity must incorporate the mobility of pagers, wireless and cordless phones, as well as the immobility of PCs and the portability of laptop computers. In a mobile work environment, communicating with office equipment without the burden of cables is not only convient and inexpensive it is also faster than serial or Irda and requires no line-line-of sight. The alternative to wired connectivity is the wireless short-range connectivity offered by Bluetooth technology at 2.4 GHz.

2.2 Bluetooth Transmission Technology

The dream for true, seamless, mobile data and voice communications that enables constant connectivity anywhere is quickly becoming a reality. Wireless and computer industries are clearly leading the way with revolutionary components that will shape our lives in the next century. In 1994, Ericsson Mobile Communications initiated a study to investigate the feasibility of a low power, low cost radio interface between mobile phones and their accessories. The aim of this study was to eliminate cables between mobile phones and PC Cards used to connect the phones to a computer for dial up networks (DUN). In 1998 Intel, IBM, Toshiba, Ericsson and Nokia began developing a technology that would allow users to easily connect to mobile devices without cables. This technological vision became a reality through the synergy of market leaders in laptop computing, telecommunications, and core digital signal processing. May 20th, 1998 marked the formation of the Bluetooth Special Interest Group (SIG) with the goal to design a royalty free, open specification, de facto, short range, low power wireless communication standard, as well as a specification for small-form factor, low-cost, short range radio links between mobile PCs, mobile phones and other portable devices codenamed Bluetooth. The result was an open specification for a technology to enable short-range wireless voice and data communications anywhere in the world. A simple way to connect and communicate without wires or cables between electronic devices including computers, PDA's, cell-phones, network access and peripherals.

Bluetooth is named after Harald Blatand, "Bluetooth", a Viking 10^{th} century king. Harald had a penchant for surrounding himself with the right group of people, which enabled him to strategically secure new lands for Viking settlements. Harald conquered all of Denmark and Norway and made the Danes Christian. Thus Harald's conquest inspired the name of a global wireless specification achieved through the cooperation of many leading companies within the computer and telecommunications industries. The technology operates in a globally available frequency band ensuring communication compatibility worldwide.

One of the primary advantages of the Bluetooth system is ease of computer vendor product integration. Other key benefits of this technology are low power, long battery life, low cost, low complexity, and wireless connectivity for personal space, peer-peer, cable replacement, and seamless and ubiquitous connectivity. To achieve the Bluetooth goal, tiny, inexpensive, short-range transceivers are integrated into devices either directly or through an adapter device such as a PC Card. Add on devices such as a USB or Parallel port connections are also available for legacy systems. By establishing links in a more convenient manner this technology will add tremendous benefits to the ease of sharing data between devices.

One universal short-range radio link can replace many proprietary cables that connect one device to another. Laptop and cellular users will no longer require cumbersome cables to connect the two devices to send and receive email. Possible health risks from radiated RF energy of cellular handsets are mitigated with lower transmission power of the Bluetooth enabled ear set. (The ear set solution does not require the handset to be close to the head.) Moreover, unlike the traditional headset, the wireless ear set frees the user from any unnecessary wiring.

As Bluetooth offers the ability to provide seamless voice and data connections to virtually all sorts of personal devices the human imagination is the only limit to application options. Beyond un-tethering devices by replacing the cables, this technology provides a universal bridge to existing data networks, allows users to form a small private ad hoc wireless network outside of fixed network infrastructures, enables users to connect to a wide range of computing and telecommunications devices easily and simply, without the need to buy, carry, or connect cables. The Bluetooth technology allows users to think about what they are working on, rather than how to make their technology work. The Internal Documents and Presentations (IDC) forecast in 2004, 103.1 million devices in the United States and 451.9 million devices worldwide would become Bluetooth enabled [3].

2.3 Radio Specification

This section describes the radio frequency specification requirements for a Bluetooth transceiver operating in the Industrial Scientific Medicine (ISM) band. These requirements are take from the Bluetooth Core 1.0 specification and defined to provide compatibility between Bluetooth radios used in the system and to define the quality of the system.

2.3.1 Frequency Bands and Channel Arrangement

The Bluetooth transceiver operates in the globally available 2.4 GHz ISM band. In most countries around the world the range of this frequency band is 2400 – 2483.5 MHz. However, several countries have national limitations in this frequency range, and in order to comply, special frequency hopping algorithms have been specified for these countries. The US and Europe have a band available of 83.5 MHz ranging from 2400-2483.5 MHz. The 79 RF channels are spaced 1 MHz apart. Products implementing the reduced frequency band are not interoperable with products implementing the full band. The Bluetooth SIG has launched a campaign to overcome these difficulties and reach total harmonization of the frequency band. A guard band is used at the lower and upper band edge to comply with out-of-band regulations. [1]

2.3.2 Frequency Hopping Spread Spectrum

The ISM band is occupied by a plethora of other RF emitters, ranging from WLANs, baby monitors, and cordless phones. Bluetooth is based on a critical technology known as Frequency-Hopping Spread Spectrum (FHSS), applied to combat interference, fading, and to facilitate optional operation at power levels up to 100 mW. The Spread spectrum technique spreads the narrowband data signal over the radio frequency band of 2.400 – 2.4835 GHz, 79 hops displaced by 1 MHz. FHSS spreads the signal by transmitting a short burst on one frequency and then hops to another frequency for another short burst and so on. In the FHSS system the carrier frequency of the transmitter hops in accordance with a pseudo-random hopping sequence, unique to each piconet. The frequency-hopping rate is 1600 hops/s for a single slot packet and slightly diminishes for multi-slot packets. The hopping rate will increase to 3200 hops/s when a link is being established (e.g. paging mode and inquiry mode). The transmitter and receiver synchronize to the hop sequence to ensure communication. The average signal strength on any given frequency is relatively low. The data signal is spread out over several MHz in the frequency spectrum, thus the resulting power spectrum also spreads out.

Transmitted power spread over a wide frequency bandwidth makes detection very difficult without the code sequence. Hopping also provides enhanced data reception in the presence of interfering signals, like fixed frequency radio networks or microwave ovens. Interference is resisted because a short time is spent on each given frequency. If interference at a specific frequency is experienced, only a portion of the frequency hops will be blocked instead of the whole signal. The unblocked hops make it possible to recover the original data by and re-transmitting the-message. Constant interference on a given frequency affects the radio network for only a short time on that specific frequency. In the US, there are five types of hopping sequences for the 79-hop system: page hopping, page response, inquiry, inquiry response, and channel hopping. The hop selection scheme consists of selecting the sequence and mapping this sequence on the hop frequencies. The hopping sequence is controlled by a 28- bit clock and lower 28-bit of BD_ADDR (Bluetooth device address, total 48-bit) embedded in the Bluetooth Device, and is determined by mapping with multi-stage butterfly operation.

2.3.3 Radio Characteristics

The Bluetooth core specification classifies the transmitter equipment as having three classes of radio transmission power, namely 100mW(20dBm), 2.5mW(4dBm) and 1mW(0dBm). With 0dBm power, the communication range may be up to 10 meters (30 feet) while 20dBm transmit power increases the range to100 meters (328 feet). Above 4dBm, there is power control to transmit appropriate radio power corresponding to the communication distance. The specification targets power consumption of the device from a "hold" mode, consuming 30 micro amps to the active transmitting range of 8-30 milliamps. [1]

The receiver actual sensitivity level is defined as the input level for which a raw bit error rate (BER) of 0.1% is met for 723kbps. The Bluetooth receiver requires an actual sensitivity level of –70 dBm or better. The carrier to interference ratio (C/I) requirement is 11 dB for Co-Channel interference. Adjacent interference on 1 MHz channels is 0dB and -30dB on 2MHz channels. Adjacent channels greater than 3 MHz require a signal to interference ratio of -40dB. [1]

2.3.4 Modulation Characteristics

The Bluetooth modulation scheme is GFSK (Gaussian Frequency Shift Keying) with a symbol rate of 1Ms/s and modulation index between 0.28~0.35. The Gaussian-shaped, binary FSK modulation minimizes transceiver complexity. Using positive frequency deviation a binary one is represented while a binary zero is represented by a negative frequency deviation as seen in Fig. 2.1. During one time slot the data can change value every 1us, so the transmit frequency oscillates back and forth around the channel center frequency. The minimum deviation can never be smaller than 115kHz. Maximum frequency deviation is between 140 kHz and 175 kHz. If the frequency change is allowed to occur instantaneously this can lead to inter-symbol interference (ISI) at the receiver. ISI makes it difficult to interpret what state the bit is trying to represent which leads to bit errors in the transmitted data. To reduce the spectral spreading that causes ISI, Bluetooth uses a .5BT Gaussian Filter to slow the transitions between the two frequencies.

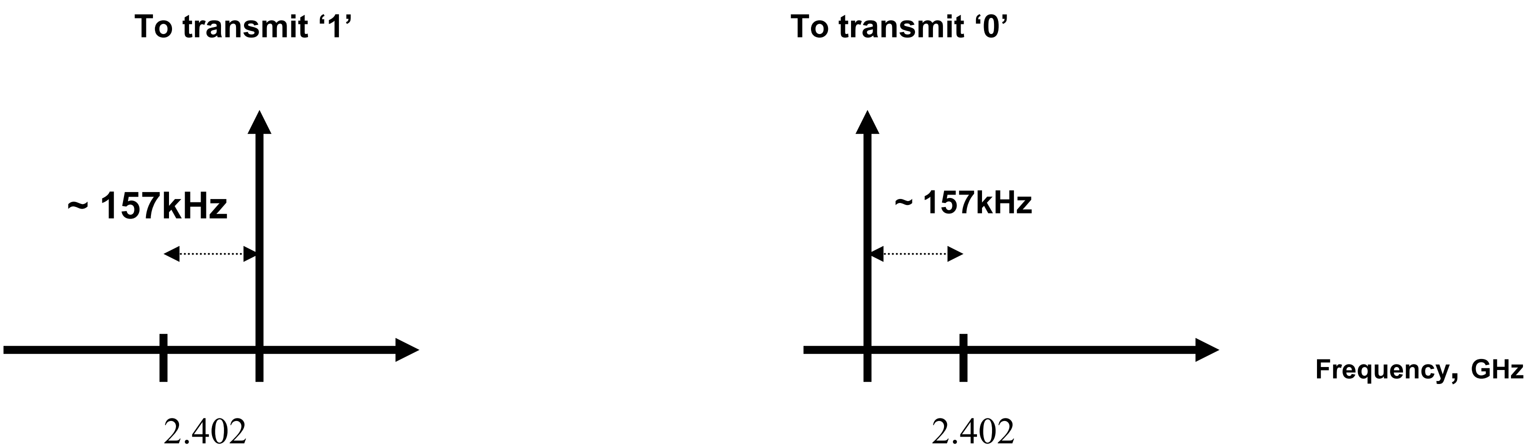

Figure 2.1 Modulation example for Channel 0 (Frequency 2.402 GHZ)

2.4 Baseband

The Bluetooth system consists of a radio unit, a link control unit, and a support unit for link management and host terminal interface functions. (Figure 2.2) The Link Controller (LC) is responsible for carrying out link level operations in response to higher level commands from the Link Manager (LM). The LC will manage the process of establishing a link once commanded by LM and will maintain the link once established.

The OSI Physical (PHY) layer is represented by the radio and the baseband. The baseband is responsible for channel coding and decoding and low level timing control and management of the link within the domain of a single packet transfer.

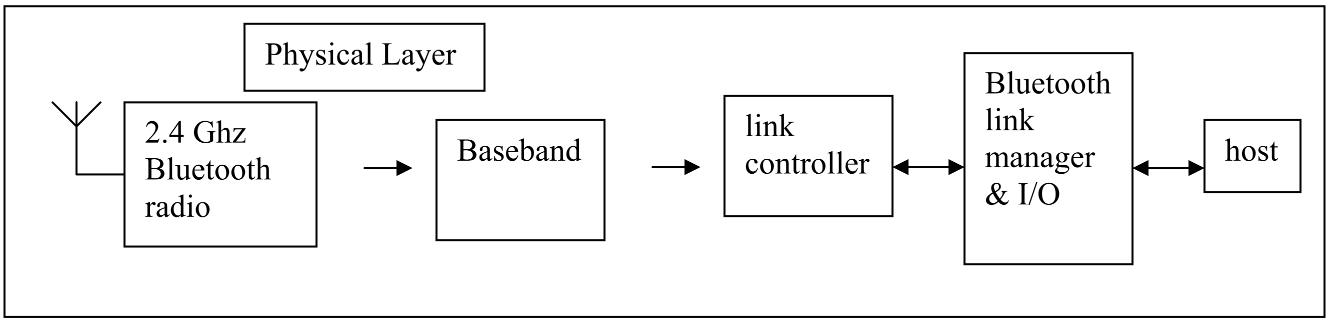

Figure 2.2: Functional blocks of the Bluetooth system

Bluetooth transmits data and voice in ***piconets***, point-to-point (only two units involved), or point-to-multipoint connections, see Figure 2.3. A piconet is formed when two or more devices share the same channel**,** connected via Bluetooth technology in an ad hoc fashion. All devices are peer units and have identical implementations, however when establishing a piconet, one unit will act as a master and the other(s) as slave(s) for the duration of the piconet connection. Two connected devices, such as a portable PC and cellular phone initiate a piconet, however, it may grow to eight connected devices, seven active slaves and one master. In addition, many more slaves can remain locked to the master in a so-called parked state. These parked slaves cannot be active on the channel, but remain synchronized to the master. There is no upper limit for the number of devices that can be within range of each other, however, only 255(passive) + 7(active) devices can be in the same network. In general, a Master can support up to 7 simultaneous links to 7 active Slaves whereas other devices (Parked Slaves) are still synchronized to the piconet but do not participate in the traffic. Any device in a piconet can act as Master or Slave, however, a device can only be active on one piconet at a time. If it is active on one piconet and wishes to switch to the other, the device must put itself in park, hold, or sniff mode or disconnect itself to be able to access the other piconet. The master controls the channel access for both active and parked slaves. The master unit is also the device in a piconet whose clock and hopping sequence are used to synchronize all other devices in the piconet. Slave units are all devices in a piconet that are not the master.

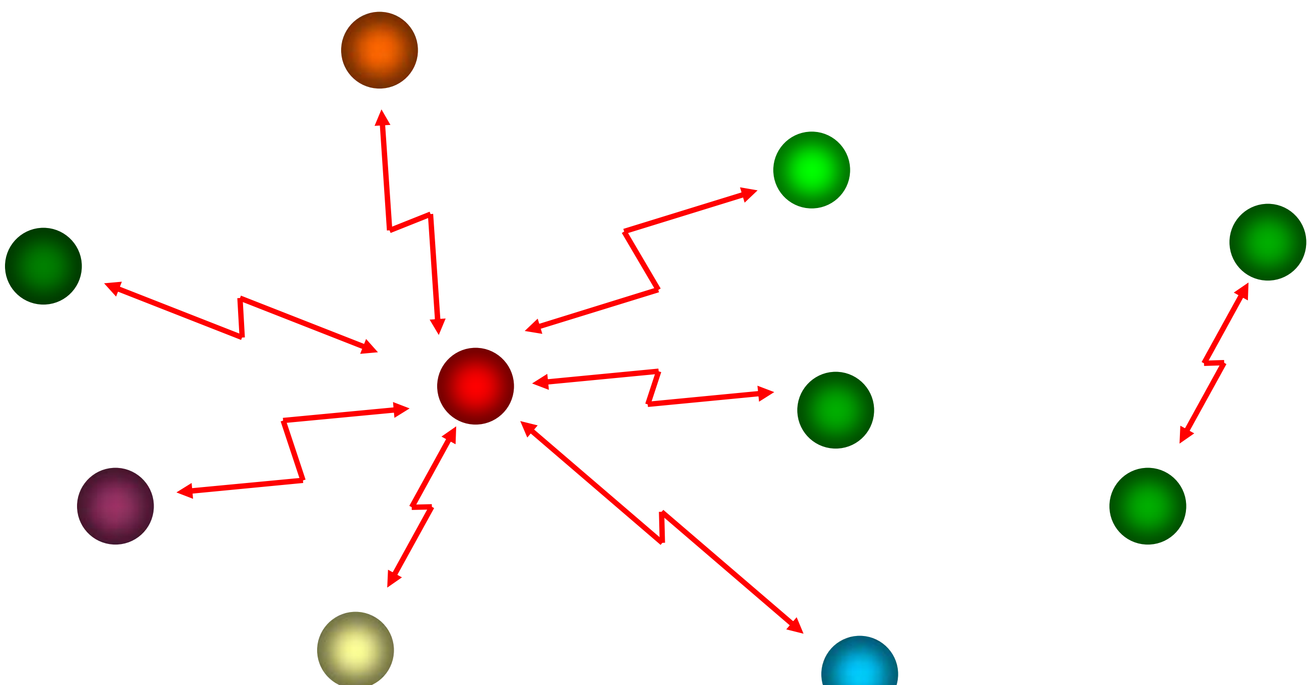

Figure 2.3: Piconet with a:) Point to Multipoint operation (Master at center of piconet) b:)Point-to-Point operation

2.4.1 Physical Channel

A pseudo-random hopping sequence through the 79 RF channels represent the channel. Each piconet has a unique hopping sequence that is determined by the Bluetooth device address of the master, while the phase in the hopping sequence is determined by the master clock. The channel is divided into time slots of 625 microseconds in length and is numbered according to the clock of the piconet master. Each slot corresponds to a unique RF hop frequency. All devices participating in a piconet are time- and hop-synchronized to the channel with a nominal hop rate of 1600 hops/s. Master and slave devices are allowed to transmit packets in the time slots [1].

2.4.2 Time Slots

A Time Division Duplex (TDD) scheme is used where master and slave alternatively transmit (figure 2.4) TDD is a method of utilizing radio spectrum by dividing time into slots, providing each user access to the entire frequency channel for a brief period, during which the user transmits data. The baseband burst rate is 1Mbps. A TDD user frequency channel is shared with other users who have time slots allocated at different times. For example, each channel may be shared by seven users by assigning time slots to each user and transmitting pieces of each voice or data transmission via synchronized timed bursts. Bluetooth allocates one slot at the transmit frequency and one slot on the receive frequency. The master only starts its transmission in even numbered time slots while the slave starts its transmission in odd-numbered time slots. Packet start is aligned with the slot start and may extend up to five time slots for both the master and slave. The RF hop frequency remains fixed for the duration of the packet. A single packet obtains the RF hop frequency to be used from the current Bluetooth clock value. Multi-slot packet obtains the RF hop frequency to be used for the entire packet from the clock value in the first slot of the packet. Figure 2.5 illustrates the hop definition on single and Mulit-slot packets. The hop frequency applied for muli-slot packets is the hop frequency applied in the time slot the packet transmission was started.

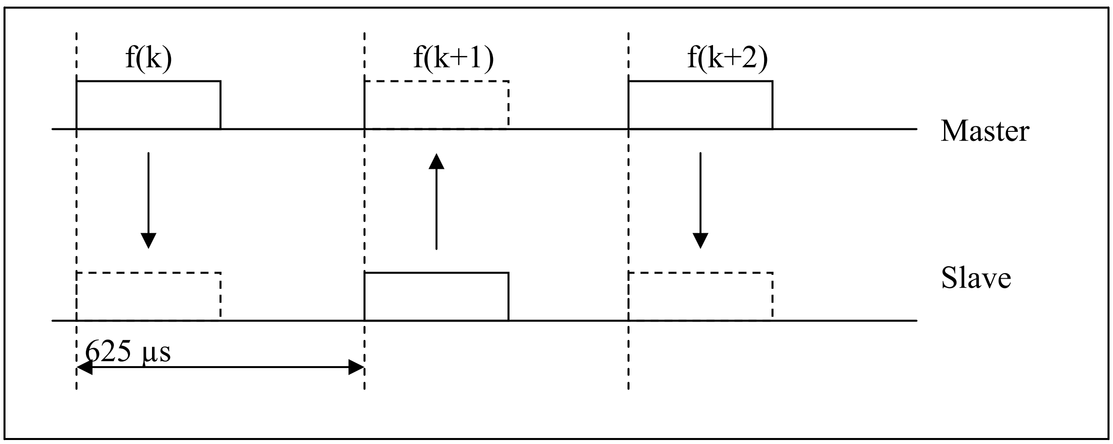

Figure 2.4 TDD and timing

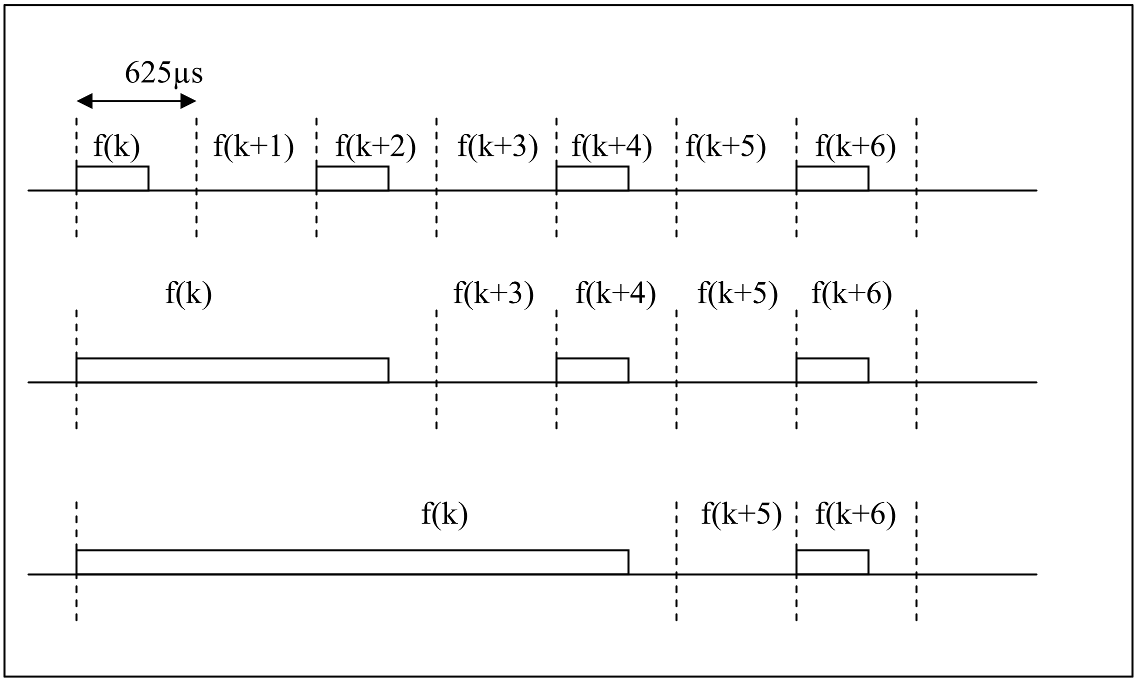

Figure 2.5: Multi-slot packets

2.4.3 Physical Links

A master can create tow types of logical channels with a slave, namely Synchronous Connection-Oriented (SCO) and Asynchronous Connection-Less (ACL) type. SCO is a point-to-point circuit switched link that provides real time unreliable connection with a guaranteed bandwidth primarily used for voice. Voice channels are supported with a 64 kbps synchronous link. Voice packets are always given higher priority to transmit over the reserved slots to ensure the integrity and quality of voice transmission. ACL is point-to-multi-point packet switched link that provides a reliable data connection with a best effort bandwidth dependent on radio performance and number of devices participating on the piconet. The ACL data channel can support an asymmetric link of 721 kbps or symmetric link of 432.6 kbps. All Bluetooth devices are peer units and have identical procedure to establish a connection. Before any connections in a piconet are created, all devices are in standby mode.

2.4.4 Packets

This section introduces the Bluetooth packet structure and the different types of data packets that are used for communication over ACL links. The packets are broken down into their constituent parts such as access code, packet header, payload header, and payload. There are currently 14 packet types defined, split into 4 segments; Common Packets (both ACL & SCO), Single slot, ACL 3 and ACL 4 slot packets. Each packet type has a different level of error correction and protection and different size payloads. The general packet format is shown in fig 2.6.

LSB 72 bits	54 bits	0-2745 bits MSB
Access code	Header	Payload

Figure 2.6: Standard packet format

The Access code is used to detect the presence of a packet and to address the packet to a specific device. The header packet contains control information associated with the packet such as the address of the Slave for which the packet is intended. Finally, the payload contains the message information.

The payload field of all ACL packets (Fig. 2.7) is split into the payload header, the payload data and the Cyclic Redundancy Check (CRC) field.

8 or 16 bits	0-2712 bits	16 bits
Payload Header	Payload Data	CRC

Figure 2.7: ACL Payload structure

Table 2-1 list all the ACL data packet types and their particular characteristics. We observe the DH5 packet type trades off FEC coding for higher throughput rates and less robustness. At the expense of data redundancy and data throughput, shorter packets such as DH1, provide greater protection against errors.

Table 2.1 ACL Data Packet Types

Type	Payload Header (bytes)	User Payload (bytes)	FEC	CRC	Symmetric Max Rate (kbps)	Asymmetric Max Rate (kbps) Forward	Reverse
DM1	1	0-17	2/3	YES	108.8	108.8	108.8
DH1	1	0-27	NO	YES	172.8	172.8	172.8
DM3	2	0-121	2/3	YES	258.1	387.2	54.4
DH3	2	0-183	NO	YES	390.4	585.6	86.4
DM5	2	0-224	2/3	YES	286.7	477.8	36.3
DH5	2	0-339	NO	YES	433.9	723.2	57.6
AUX1	1	0-29	NO	NO	185.6	185.6	185.6

2.4.5 Error Correction

Three data error-correction schemes defined for the baseband controllers are: 1/3, 2/3 rate forward error correction code (FEC), and automatic repeat request (ARQ) scheme. FEC is implemented on the data payload to reduce the number of retransmissions. In a reasonable error-free environment, FEC adds unnecessary overhead, which reduces the throughput. 1/3 FEC uses a simple repetition code that repeats the bit three times. The 2/3 FEC scheme encodes data using a (15,10) shortened hamming code. Each block of 10 information bits is encoded into a 15-bit code word that can correct all single errors and detect all double errors in each codeword.

In the ARQ scheme packets are transmitted and retransmitted until the transmitting device receives an acknowledgement of a successful reception.

2.4.6 Summary

Bluetooth devices operate at 2.4 GHz in the globally available, license-free ISM band. The use of this band by many other systems including the operation of microwave ovens makes this a hostile environment. Bluetooth employs a fast frequency-hopping scheme to mitigate interference. The baseband is responsible for channel coding and decoding the low level control of the timing and management of the link. Addressing and link control fields are added to the raw payload data and provide error detection and correction. Bluetooth devices exist in either Slave or Master modes of operation and communicate between each other in miniature networks known as piconets. SCO and ACL links exist between devices for time bounded data such as audio and for packet based data. The frequency-hopping algorithm is based on the device clock, which ensures devices maintain time synchronization by repeatedly synchronizing to the Master's transmission.