Examensarbete MMK 2000:81 MDA138

KTH

Bluebus

Protocol Conversion for Wireless Data Exchange

By

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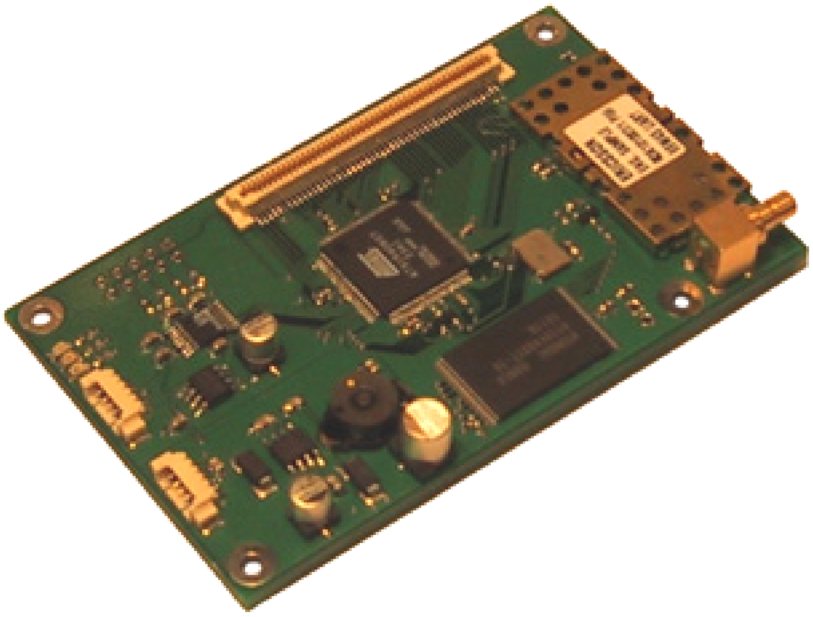
Kevin Rebenius



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Examensarbete MMK 2000:81 MDA138

MMK
Maskinkonstruktion KTH
Mekatronik

Bluebus
Protokoll-konvertering för trådlös dataöverföring

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Godkänt 2000-11-08	Examinator Mats Hansson	Handledare Martin Törngren
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Sammanfattning

I och med den växande trenden av trådlösa tekniska lösningar avsedda för korta avstånd, intresserade sig Tritech för en tillämpning med den trådlösa teknologin, Bluetooth. Visionen är att utveckla en produkt med en så generell lösning som möjligt, där nätverk, fältbussar och egentligen vilka enheter som helst kan kopplas samman via en trådlös länk. Utvecklingen av denna produkt startar med detta examensarbete. Projektet och även produkten går under namnet *Bluebus*. Examensarbetet behandlar hur överföring olika protokoll/standarder kan realiseras med Bluetooth. Fokus ligger i att utreda en teknisk lösning och implementera en Bluebus-enhet, som i par bildar en *brygga* för utbyte av data.

Kärnan i examensarbetet var Bluetooth teknologin som har studerats ingående. De protokollstandarder som utretts är *Controller Area Network (CAN), RS-232* och *Keyword Proctocol 2000 (KWP-2000). Slutsatsen av arbetet är* att *RS-232* och *KWP-2000* lämpar sig väl för trådlös tillämpning i Bluebus. En CAN tillämpning är möjlig, men full transpararens kommer inte kunna uppnås. Bluebus utbyter data över en asynkron länk med omsändning av korrupta meddelanden. Med en asymmetrisk konfiguration där data sänds med DH5 paket i en riktning skulle Bluebus kunna användas i en loggningsapplikation i CAN nätverk med överföringshastigheter upp till 500 kbps. Meddelanden kommer att skickas om en med en viss fördröjning. För att hantera dataöverföring, konvertering och kontroll i Bluebus anses ett RTOS vara nödvändigt. En fördjupningsstudie resulterade i att realtidsoperativsystemet, eCos valdes. Försök gjordes för att porta eCos till Atmel AT91EB01 som tyvärr inte lyckades fullt ut. Tills portningen blir tillgänglig hanteras istället alla processer i Bluebus av mjukvara i den samma.

I arbetet ingick även att ta fram en fungerande prototyp. Prototypen består av två huvudkomponenter; ett Atmel ARM processorkort och ett Ericsson Bluetooth utvecklingskort. Den första versionen stödjer RS232 i både hårdvara och mjukvara. Två Bluebus-enheter kan koppla upp sig mot varandra och bildar tillsammans en virtuell serielänk. I prototypen kommunicerar processor och Bluetooth-modul med överföringshastigheten 57,6 kbps och radiolänken med 108,8 kbps. Dessa hastigheter kan givetvis konfigureras. Den maximala praktiska överföringshastigheten (*bit rate*) in till Bluebus från periferienheter är 230,4 kbps. En egen kompaktare hårdvara har designats med Bluetooth-modul, processor, minnen, RS232-anslutning och en kontakt för expansionskort.

Master Project MMK 2000:81 MDA138

Protocol Conversion for Wireless Data Exchange

MMK
Machine Design KTH
Mechatronics

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Approved 2000-11-08	Examiner Mats Hansson	Supervisor Martin Törngren
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Abstract

The trend for short-range wireless technical solutions have made Tritech interested of an implementation with the wireless technology, Bluetooth. The vision is to develop a general product solution, were networks, standard protocols and virtually any devices are connected over a wireless link. The development of this product starts with this thesis work. The project and consequently the product name have been settled to *Bluebus.* The focus was to investigate a technical solution and implement a *Bluebus* prototype, which in pair form a *bridge* for wireless data exchange.

The core in the project is the Bluetooth technology, which has been studied firmly. The protocol standards that have been investigated are the Controller Area Network (CAN), RS-232 and the Keyword Protocol 2000 (KWP-2000). KWP-2000 and RS-232 are well suited for a wireless implementation in *Bluebus.* A CAN implementation is obtainable, but full transparency will not be achieved. Bluebus operates over an asynchronous link, where corrupt messages are re-transmitted. In an asymmetric configuration where data is transmitted with DH5 packets in one direction, Bluebus could be used in a log application retrieving messages from a CAN network operating with up to 500 kbps. Messages will with high certainty be transmitted though with a slight delay. In order to handle data transmission, conversion and control in Bluebus a RTOS is preferred. A study resulted in the choice of the RTOS, eCos. A profound attempt was made to port eCos to the chosen processor evaluation board, Atmel AT91EB01. Unfortunately the porting work was never successfully completed. Until the port is available Bluebus processes are handled by Bluebus software.

The project also included developing a working prototype. The prototype consists of two main components, an Atmel ARM processor circuit board and an Ericsson Bluetooth development board. The first version supports RS232 in both software and hardware. Two *Bluebus* devices can connect and form a virtual serial link. In the prototype the processor and Bluetooth module, and the radio link communicate with the data rate 57,6 kbps and 108,3 kbps, respectively. A more compact hardware has been designed, with Bluetooth module, processor, memory, RS-232 connector and an expansion connector.

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Per Olofsson, Tritech Mekatronik AB

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LIST OF FIGURES AND TABLES

1 Terminology

Authentication	A procedure where a unit requests another to prove itself to be the entity it claims to be.
Baseband	The digital part of the Bluetooth module.
Baseband Packet	The smallest unit of data that is transmitted from one Bluetooth device to another.
Baud	Number of times a physical transmission medium can change state per second.
BD_ADDR	The unique 48-bit Bluetooth device address. The address Is divided into three parts: • LAP: Lower Address Part (24 bits) • UAP: Upper Address Part (8 bits) • NAP: Non-significant Address Part (16 bits) The address is derived from the IEEE802 standard with 48-bits, but of these essentially 32 bits are used.
Bluebus	Project work name and consequently product name. The device supports conversion and wireless transmission of several network protocols, over Bluetooth. For example, one Bluebus on two separate networks would connect these making them appear as one network.
Bridge	Designed to connect two physically separate LANs, operating at the Media Access Sublayer. The bridge checks the packet destination address, sends it along to the other side if the address is found at that side, if not the packet is ignored (Jordan, Churchill, 1990). **Here**: A bridge denotes the functionality of two Bluebus devices, each connected to one of two separate networks, allowing exchange of data between the two networks, over the bridge.
Channel	The Bluetooth channel represents a pseudo-random hopping sequence through 79 or 23 RF channels (23 channels in Japan, Spain and France). The channel is divided into time slots where each slot corresponds to an RF hop frequency.
Data Link Layer	Describes the logical organization of data bits transmitted on a particular medium. Ex: this layer defines the framing, addressing and checksumming of Ethernet packets.
Fieldbus	Communication network with associated protocol(s).

Host	The Host denotes the user, e.g. a PC, mobile phone or a processor that uses a Bluetooth module to communicate with a remote system.
Host Controller	Denotes the controller inside the Bluetooth module that communicates with the Host via the Host Controller Interface (HCI).
J1587	Joint SAE/TMC electronic data interchange between microcomputer systems in heavy-duty vehicle applications. The physical hardware is specified in the standard J1708.
KWP-2000	(KeyWord Protocol) communications protocol and services for vehicle diagnostics. The physical medium used is referred to as K-line.
OSI	Open System Interconnection. A model for how open data communication is conducted. Used to define interfaces and protocols (Ewert 1999)
Physical Layer	Describes the physical properties of various communications media, as well as the electrical properties and interpretation of the exchanged signals
Piconet	A collection of devices connected via Bluetooth in an ad Hoc fashion. In a piconet one unit acts a master and the other(s) as slave(s). All devices share the same physical channel defined by the master device parameters (clock and BD_ADDR).
RTOS	Real Time Operating System
Scatternet	Multiple independent and non-synchronised piconets form a scatternet.
Tester	Diagnostic unit. **Here,** connected to the KWP-2000 diagnostics bus
Time Slot	In the Bluetooth protocol each slot is 625 µs long, numbered according to the Bluetooth clock of the piconet master. The slot numbering ranges from 0 to 2^{27}-1 and is cyclic with a cycle length of 2^{27}. In the time slots, master and slave can send data.

Transparent	A process that exists, but does not appear to (Jordan, Churchill, 1990). **Here**: The transparency is a logical process or activity that cannot be seen or touched. For some networks 100 % transparency is not possible. However, a bridge can appear transparent to some extent. If 100% is not obtained this should be pointed out.

2 Introduction

2.1 CAN Bridge

The Controller Area Network is widely used in the automotive industry today, and its popularity is growing. In a network with separate CAN-busses, a bridge between them would be desirable.

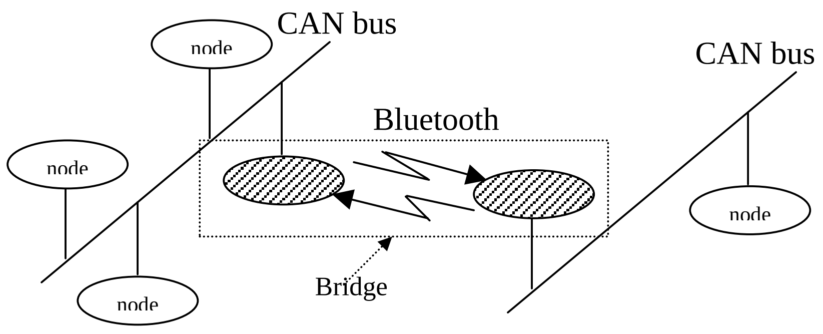


Figure 2.1. CAN bridge

Using Bluetooth for this application has its drawbacks. CAN is not suited for packet radio transmission, one of the reasons for this being that CAN relies on simultaneous transmission and reception of bits to achieve arbitration. This demands that the nodes are synchronised to each other within a fraction of a bit time. Also, a node on the bus must acknowledge that it has received a package correctly within a very short time, typically from 2µs and up depending on the bit rate used. This is simply impossible to achieve using Bluetooth as a transfer medium. In non-realtime applications such as automotive diagnostics this is not a problem, and guaranteeing that messages reach their destination, preferably within a certain time, is sufficient. Unfortunately some of the built-in error handling features of the CAN protocol will be lost or degraded.

The original project idea was to design and implement a universal converter that with the Bluetooth technology connected to an arbitrary communication network, could communicate wirelessly with a remote unit. In this thesis project the possibility to bridge data is investigated for networks, in a point-to-point connection with the same network protocol on each end of the connection.

As for any great product there is a need of a name. The project work name and consequently the product name, has after consideration been settled to: ***Bluebus.***

2.2 Problem and Objective

As the Thesis description evolved, the project was aimed for a specific industry, the automotive industry, and initially for the heavy vehicle industry. The advantage of aiming for a specific market is to get a fast response on interest and feedback on customer needs. After contact with Volvo and a Tritech consultant working for the Swedish company Autodiagnos, the decision was made to investigate the possibilities to bridge the Controller Area Network (CAN), KWP-2000 and RS232, which are all widely used in the vehicle industry today. The standard J1587 was also mentioned and should be considered for future expansions.

To limit the scope of the thesis work, a software implementation will only cover a wireless serial interface with RS232. However, considerations are made to allow future expansion of software to cover protocols mentioned above.

The objective of the project was to supply the customer with a prototype able to connect and sustain a wireless serial connection. The hardware could consist of development board circuitry, but schematics for the first compact version should be submitted. In addition, thought should be given on in what context this kind of product could appear.

2.3 Method of Attack

The Bluetooth technology was to be used as medium for the wireless link. This was stated by the employer and is a core requirement for this project. The Bluetooth technology and protocol was studied extensively and is described in chapter four. Different communication networks used in the vehicle industry have been overviewed. In this thesis the CAN, KWP-2000 and RS232 protocols are covered in chapters five, six and seven. In these chapters an understanding of how the protocols work is governed. The possibilities, requirements and limitations for bridging these protocols are extracted and discussed. Moreover, a study had to be conducted to select appropriate hardware. Among other things a Bluetooth module and microcontroller had to be chosen, where the microcontroller handles control and data conversion. The hardware study is presented in chapter nine. For the software implementation the possibility of using an RTOS is investigated in chapter eight. The architecture and operation of the software for packet conversion and Bluetooth control is presented in chapter ten.

3 Product Idea

The vision is to design a small device, cheap and small enough to be fitted in a vehicle or virtually any industrial product, allowing a wireless link for short-range data communication. The device would supply a logically transparent connection between two separate networks of the same type making them appear as one. In a future perspective the device may even be able to bridge information between two or more entirely different communication networks. In this scenario Bluebus would have the characteristics of a gateway. As described by Jordan and Churchill, (1990) the function of a gateway is to allow two or more dissimilar networks to communicate as a single logical entity. Dissimilar means that the transport protocols and the underlying physical networks are different. According to Ewert (1999) a gateway is essentially a bridge. The difference is that a bridge operates in the data link layer (layer 2) in the OSI model (Ewert 1999, page 110), were as a gateway operates in layers 4 to 7. Bluebus may operate, though most often in the data link layer, in any layer. No matter in which layer it does operate, Bluebus is considered by the authors to bridge information and the term bridge will be used in this thesis report.

3.1 Specification

3.1.1 Hardware

The hardware shall…

… have a Bluetooth interface.
… have an RS232 physical interface.
… be designed so that it is easily expandable. It shall be possible to add more physical interfaces to the hardware if necessary.
… be optimised for low price and small size.

The hardware should…

… have CAN, J1708, and K-Line physical interfaces.
… have low power consumption.

3.1.2 Software

The software shall…

… be able to set up and sustain a connection with one remote Bluebus unit.
… be able to wirelessly send and receive serial data to/from a remote device.
… be designed so that more protocols can be added.
… not affect other connected nodes in a negative way. It shall not disturb communications between other nodes or by itself initiate communication with a node.

The software should…

… transfer CAN messages between two fieldbusses via the Bluetooth interface. In the future, transferring messages between three or more busses is desirable.
… also be able to transfer the J1587 and KWP-2000 protocols.
… configure itself as much as possible. It should be able to determine which physical bus/busses are in use at the moment.
… be "self-learning". In the case of a CAN bridge, some information about the connected nodes will be necessary. The system should collect as much of this information as possible by itself. Self-learning in this context means that the unit would be able to filter messages that is not intended to be transmitted over the air.

3.2 Scenarios

In order to avoid or at least minimize built-in limitations when designing the product it is important to think through the possible scenarios the product may be involved in. A bunch of implementations could be thought of for this kind of product. Here, four of the most interesting and likely scenarios for Bluebus are presented.

3.2.1 Raw Data Exchange

Imagine two mobile units within relatively short range (10-100 m) from each other. In each of these units there is a network, for instance a Controller Area Network. There are possibly a number of nodes in each, exchanging data over the internal network. Now, if information were to be exchanged between the units, how would this be realized? The simplest solution would be to hardwire them to each other with a cable. Thus, the two essentially becomes one network, but the mobility is lost. The two units would have to follow each other around, so that the cable between them is not broken. In this scenario two Bluebus units could be connected, one on each mobile unit. The information would be bridged between them and mobility and flexibility would be saved.

Along the same lines, Volvo has expressed interest in using Bluebus for an even simpler matter (initially). Volvo would like to use Bluebus as a wireless serial link. Instead of having a physical RS-232 line for raw data exchange, Bluebus could accomplish the same thing but over the air.

3.2.2 Automotive Diagnostics

In most of today's vehicles, different kinds of communication networks are incorporated. Such a network could be an onboard diagnostics bus, which is used to obtain vehicle status information. The information is transmitted by a physical connection, with a cable, between the vehicle and the receiving diagnostic unit. It would be desirable to break this connection, and instead use wireless communication. This way the diagnosis could be made both easier and more flexible. An interesting application could be, for example, if a car or truck broke down, the driver could connect his cellular phone to the diagnostic system and send information to a service station. Right away, the driver could get information about if there is anything he can do himself to fix the problem, or he could find out where the closest repair shop is located. If a service truck has to be sent out, they would know what tools and spare parts to bring. In this scenario, our product would be fitted into the vehicle, and in modified form in a mobile phone or in a diagnostic unit.

Work developing a diagnostics application has already been initiated at Tritech Mekatronik AB, as a thesis project. In this scenario a Bluebus unit would be connected as a node on a diagnostic bus and another, possibly, in a PC (diagnostic unit).

3.2.3 Bluebus in Line Production

Cars and trucks contain software to a large extent, which is downloaded at the end of the production line. A cable is connected for download. A Bluetooth application would be ideal. This idea is shared with (Lars-Berno Fredriksson) who describes how this could be implemented in a car production line.
“When car on line gets connected to the Bluetooth base station, it uploads it serial number. The production computer then downloads the software for this very car via the fieldbus to the basestation, who in turn transmit to the car…”
(Fredriksson, 2000).

3.2.4 Ethernet Implementation

Imagine connecting an Ethernet circuit to the product, opening the opportunity to access a network via Internet. In this scenario an OS would have to be considered, preferably supplying a software stack for TCP/IP.

3.3 Proposed Solution

3.3.1 Method

The general idea is to design a simple universal protocol common for communication between all networks supported by the system. All information exchanged between Bluebus modules should be packaged in a standard Bluebus packet frame. In this way, Bluebus becomes independent of which protocol is being used by the network it is connected to, i.e. Bluebus would not care which protocol a specific network is using. All communication could be conducted by means of the Bluebus packet (specified in section 3.3.4). In context form the situation is sketched in figure 3.1 for CAN. The situation would be the same for any network protocol.

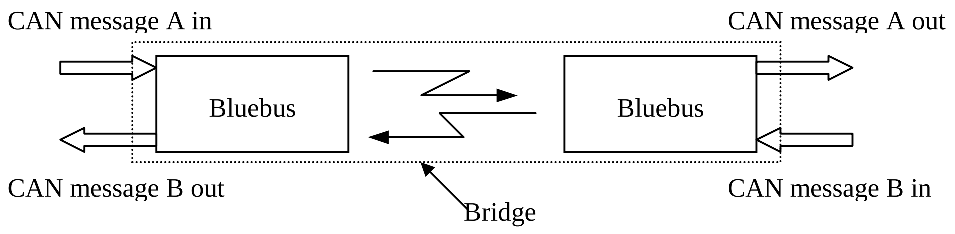


Figure 3.1. Bluebus context diagram

Alternatively, messages from different protocols could be individually programmed for in Bluebus. The protocol message would be sent to the Bluetooth module (when using the Bluetooth unit for means of transportation) and then packaged into a Bluetooth packet. This means that the Bluetooth unit needs knowledge about the protocol structures for each protocol supported by the system.

The advantage of using a standard frame is the flexibility. Additional networks, or rather protocol standards, could easily be added to the Bluebus system. A newly added protocol only needs software for conversion to the Bluebus format, and of course appropriate hardware. This modularized thinking is also applied to means of transportation. As mentioned earlier, network information should not solely be communicated over Bluetooth, adding other means of transport should also be possible. By adding destination information, i.e. for example in figure 3.2 the destination information would determine whether the packet is transported via Bluetooth or the Serial box in the figure. The destination information would also determine which Bluebus unit may receive the transmitted packet. Moreover, these two boxes would only have to be able to transmit Bluebus packets. On the other hand, if each protocol message were to be transmitted in their original format, the software would become very large and inflexible, supporting all these separate protocols. Essentially, the entire program in Bluebus would have to be re-programmed in order to support a new protocol. To gain flexibility and to assure ease of expansion, the first alternative using a standard Bluebus packet frame seems to be the most appropriate solution.

A third appealing solution would be to transmit data bit-by-bit over a radio interface. For a CAN implementation this solution would have the advantage of making it possible for message acknowledgement as described in the CAN specification. The Bluetooth radio could theoretically be used with gross rate of 1 Mbit/s. However, bit-by-bit transmission is not supported by the Bluetooth standard. Therefore, this method cannot be used.

3.3.2 Universal Packet Example

Suppose a CAN message was to be communicated from one network to another. In this scenario, Bluebus would be connected as a node on each Controller Area Network. When Bluebus retrieves the message, relevant information is extracted and packaged into the Bluebus packet frame. The protocol includes information regarding its destination, or means of transportation. In this case, the message is to be transmitted over Bluetooth (It should be possible to transmit the message by other means, such as over a serial interface). In the Bluetooth Module, the Bluebus message is in itself also packaged in a standard Bluetooth packet and transmitted over the air. On the other end, the Bluetooth module of the receiving Bluebus unit receives the message. The message is unpacked and consequently in Bluebus format again. The message is passed along to the application, were it is interpreted. It becomes apparent that the received message was a CAN message. The content is extracted and a CAN message is formed and transmitted on the local Controller Area Network.

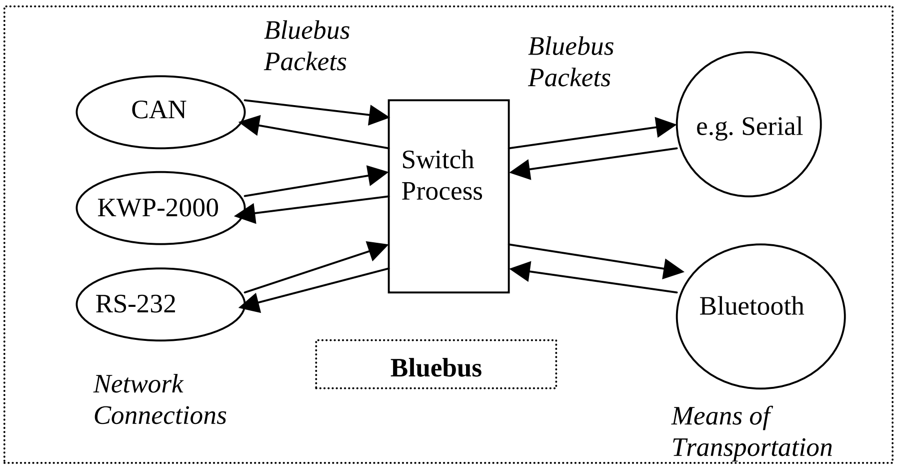


Figure 3.2. Bluebus concept idea

The switch process is basically an array with destination information, steering Bluebus packets along the right track, i.e. it makes sure the packets are transmitted with the desirable means of transportation (in this case over Bluetooth or the serial interface). At this point, in the implementation part of the thesis work, Bluetooth alone is used for means of transportation.

3.3.3 Additional Aspects

Additional aspects are configuration capabilities, reliability and filtering. Depending on connection the demand for flawless versus fast transmission may vary. For flawless connections, Bluebus should be able to re-transmit corrupt messages. Bluebus should also be configurable for faster transmission with high data rate, if a connection is relatively error free and high data rate is required. The question whether to use an RTOS should also be raised and will be discussed in chapter 8. Do tasks need to be scheduled? Can we get extra functionality for free, using an RTOS?

Bluebus could be programmed for raw data exchange and take no consideration to if a message is intended for the remote network, or if it is local message only. A filtering mechanism should be considered so that only relevant information is passed along to a remote destination. Filtering would increase performance and efficiency since time is not wasted on unnecessary transmissions.

3.3.4 Proposed Packet Frame

The Bluebus packet frame could consist of Source, Target, Data length, Data and Checksum. The Source field would provide a receiver with information what Bluebus device sent a specific message. If there are several Bluebus units active, the source information would allow the receiver to respond to a specific Bluebus device.

The second field, Target, would provide destination information, i.e. targeted Bluebus unit. This segment could possibly include what type of message is being transmitted: CAN, KWP-2000, and J1587 etc. A question is if protocol type should be included in the Bluebus frame or if that information should be a configuration aspect?

The remaining fields are essentially mandatory. A data length field is needed to be able to interoperate the data field, which is of variable length. The data field includes the actual message being transmitted, i.e. appropriate parts of for example a CAN, KWP-2000 or J1587 message. To conclude the frame a checksum may be added to provide means for error checking. The maximum overall size of the packet is 64K, which is the maximum allowed L2CAP payload. The layout is sketched in figure 3.2.

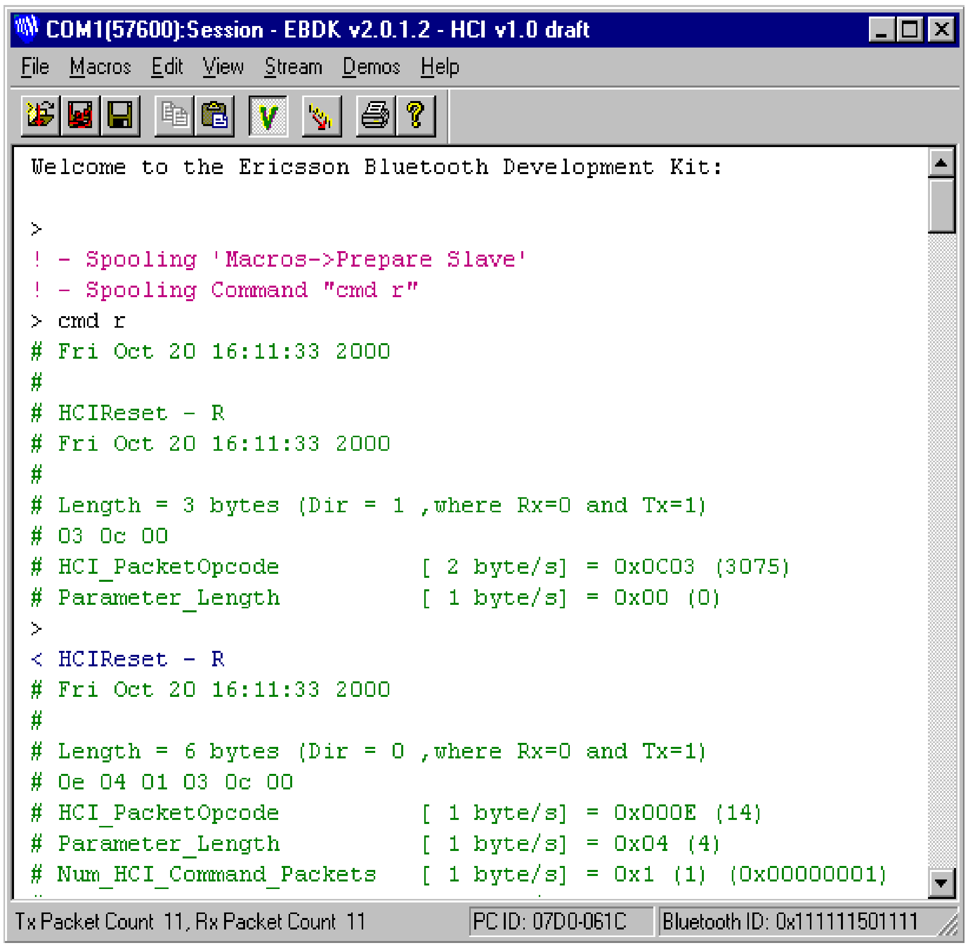
Source	Target	Length	Data	Checksum

Figure 3.3. Bluebus packet frame

Segments could be included or excluded and this proposal should be seen as foundation on which further work is based.

3.4 Test Specification

For initial testing and verification of product functionality, the converter will go through the test procedures described in the subsections below. As a first step for the thesis implementation wireless transmission of serial data will be tested. Moreover, a proposal for CAN implementation tests is presented.


COM1(57600):Session - EBDK v2.0.1.2 - HCI v1.0 draft
File Macros Edit View Stream Demos Help

```
Welcome to the Ericsson Bluetooth Development Kit:

>
! - Spooling 'Macros->Prepare Slave'
! - Spooling Command "cmd r"
> cmd r
# Fri Oct 20 16:11:33 2000
#
# HCIReset - R
# Fri Oct 20 16:11:33 2000
#
# Length = 3 bytes (Dir = 1 ,where Rx=0 and Tx=1)
# 03 0c 00
# HCI_PacketOpcode          [ 2 byte/s] = 0x0C03 (3075)
# Parameter_Length          [ 1 byte/s] = 0x00 (0)
>
< HCIReset - R
# Fri Oct 20 16:11:33 2000
#
# Length = 6 bytes (Dir = 0 ,where Rx=0 and Tx=1)
# 0e 04 01 03 0c 00
# HCI_PacketOpcode          [ 1 byte/s] = 0x000E (14)
# Parameter_Length          [ 1 byte/s] = 0x04 (4)
# Num_HCI_Command_Packets   [ 1 byte/s] = 0x1 (1) (0x00000001)
```

```
Tx Packet Count 11, Rx Packet Count 11    PC ID: 07D0-061C    Bluetooth ID: 0x111111501111
```

Figure 3.4. Ericsson's Graphical User Interface

3.4.1 Bluebus to PC

Included in the Bluetooth development kit is a graphical user interface (GUI) allowing the user to send HCI commands directly via the PC's serial port to the Bluetooth device. The program also displays received data and informs the user when connection or disconnection occurs. Chapter 8 will cover the choice of Bluetooth development tool. The GUI is a very useful tool to confirm a connection, i.e. that Bluebus software is able to perform a connection. Once the connection is up data may be sent from Bluebus. If data is sent successfully the GUI will display the received data on the PC screen. This setup can also be used to perform endurance tests, i.e. test if a connection can be sustained when data is sent over a longer period of time.

3.4.2 HyperTerminal Test

The HyperTerminal program is a PC program that is included on most PCs. The terminal can be used to send serial data on a PC’s COM port. Typically, a serial cable is connected to another computer in the room. Data, for instance keyboard input, can be sent to the other computer showing up on the HyperTerminal window. Two Bluebus units replace this physical cable. The data exchange could then be tested wirelessly. The HyperTerminal can also send complete files and this would be the ultimate test for Bluebus.

3.4.3 PC/CANAlyzer Test

The GUI allows the user to send HCI commands directly, via the PC’s serial port, to the Bluetooth device. One can simulate a CAN message by sending the contents of it in a Bluetooth packet from the GUI command line. The message is sent over the air and received by the device on the other end of the connection. Inside Bluebus the received data packet is unpacked. The CAN content is extracted and re-assembled in CAN message format and then transmitted on the local CAN bus. Hence, a CAN message from one network has been transmitted to another.

In order to analyze the message and verify its content, a CAN analyser, called CANAlyzer may be used. The CAN analyser is connected directly on the outgoing CAN port of Bluebus listening to all outgoing traffic. The CANAlyzer consist of a CAN-PC-card and an application program. The application passively retains messages and displays their contents on the screen. The situation is depicted in figure 3.5.

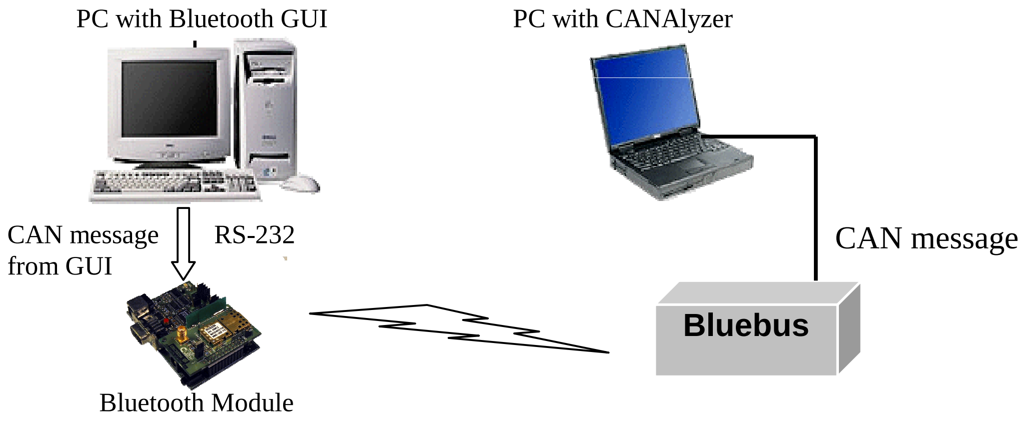


Figure 3.5. PC/ CANAlyzer test setup

3.4.4 LP transducer/ PC Test

A device, developed by Tritech, called LP transducer with CAN bus interface (LP), may be used to send CAN messages (represents a CAN network). The LP is a depth-sensing device developed for Atlas Copco’s drill rigs. The depth is determined by measuring an electrical field, which is dependent on the position of a magnetic ring on a steel rod. The value is transmitted on the bus and a host node with a graphical interface displays the current depth, among several other things. Additionally, our device could be connected as a node, transmitting the “depth” wirelessly to a remote unit. The receiving unit may, as a first step, be the GUI included in the Bluetooth starter kit, displaying the contents of received messages. As a second step, there would be one Bluebus on each end. The receiving Bluebus once again packs the user data into a CAN message frame and transmits it on the local CAN network. Again, the CANAlyzer may be used to verify functionality.

4 Bluetooth

Bluetooth is the name of a new standard for short- range radio communication. Mobile phone and computer manufacturers developed the technology. Companies interested in developing their own Bluetooth application are members of the Bluetooth Special Interest Group (SIG). The group include founding members Ericsson, Nokia, IBM, Intel and Toshiba. Since its formation in May 1998, close to 1800 companies (May 2000) have joined the Bluetooth SIG. Members get free access to the technology, which in some aspects is protected by patent. As a member, the company commits to not block or limit the Bluetooth technology. The company is still permitted to develop and patent applications, of which Bluetooth is a part. Originally, the objective was to form a standard for short-range radio communication, to provide an easier connection between mobile phones and mobile computers. Nevertheless, a wide range of companies and industries has embraced the technology. Bluetooth will cut the wire or cable connection between different devices such as mobile phones, headsets, fax machines, printers, mobile computers, or to almost any digital peripheral device. Only the imagination sets the limit.

The Bluetooth unit is a small, ready to mount, circuit for a wide range of products. The connection is achieved by radio with a carrier frequency of 2.4-2.5 GHz. This frequency band is globally designated for similar purposes. A binary FM modulation is used, which minimizes transceiver complexity. The gross data rate is 1 Mb/s. The standard uses frequency hopping, which means that the sending unit sends one data packet, changes frequency, sends a new packet, and changes frequency again. The procedure is then repeated over and over. The advantage of this technique will be discussed in a subsequent section.

The following sections in this chapter will cover how data information is communicated between Bluetooth units. Voice transmission is beyond the scope of this paper and will not be described in any detail. In addition, essential Packet structures and protocol architecture will be discussed.

4.1 Network Topology

A Bluetooth unit can establish a point-to –point connection, or a point-to-multipoint connection. In the later case, several Bluetooth units share the same channel (see section 4.2). Two or more units sharing the same channel form a piconet. In a piconet, one unit acts as master and the others as slaves. Up to seven slaves can be active in one piconet. However, more slaves can be locked and synchronized to the master, but they have to be inactive, in park mode. The master for both active and parked slaves solely controls the access to the channel.

When different piconets are connected, a scatternet is formed. The options are shown in figure 4.1 below. Slaves can participate in different piconets and a master in one piconet can be a slave in another net. The piconets are not time-or frequency synchronized, and each piconet has its own hopping channel.

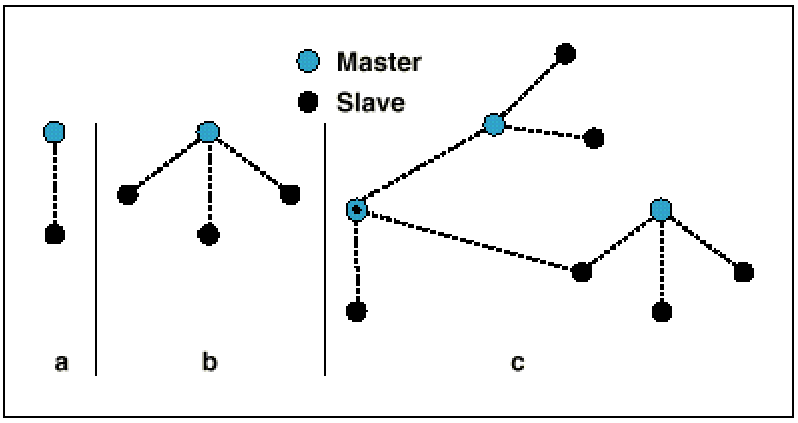


Figure 4.1. Bluetooth connections.
(a) Point-to-point piconet, (b) multislave operation, (c) Scatternet

A device participating in several piconets apply time multiplexing, where it reserves time for each net. As a result of this, its performance will be slightly decreased. For further information, please refer to (SIG 1999, section 10.9, pp. 122-125).

4.2 The Baseband

The Baseband circuit is the digital part of the Bluetooth module, controlling radio, Bluetooth clock, radio frequency, frequency hopping, and the hop sequence. Information is exchanged using packets. Each packet is transmitted at a different hop frequency in a Bluetooth channel. The channel is defined by a unique sequence of frequency changes, hopping at a maximum rate of 1600 hops/sec.

The technique used is called Frequency Hop Spread Spectrum (FHSS). The spectrum allows up to 79 channels with a channel bandwidth of 1 MHz. The sequence is determined by the Bluetooth device address of the master. All Bluetooth units participating in a piconet are synchronized to this channel. The channel is divided into time slots, where each slot corresponds to an RF hop frequency. The frequency stays the same for one slot time, which is 625 µs long, provided that the packet does not occupy more than one slot. Packets covering one, three, or five time slots are defined. In each case the frequency remains fixed for the duration of the packet.

The advantages of using frequency hopping are that several transmitters can send at the same time and a connection is tolerable to interference. The data throughput might be degraded, but the connection will, with high certainty, not collapse. The challenge with Spread spectrum is to find the hop sequence, which most certainly is a reason for why the military has used this technique for safe communication.

The Bluetooth standard supports one asynchronous channel, up to three simultaneous synchronous channels, or a channel that supports an asynchronous and a synchronous channel at the same time. Each synchronous channel can transmit 64 kb/s full duplex, which mainly is used for voice transmission. Each asynchronous channel can transmit up to 723.2 kb/s in one direction and up to 57.6 kb/s in the return direction. In the case of symmetric transmission the data rate is up to 433.9 kb/s. In order to limit the impact of noise on the Bluetooth radio, forward error correction (FEC) can be used. This reduces the number of retransmissions, but also decreases the data rate. For detailed information about the Baseband and the Bluetooth channel, see (SIG 1999, part B).

4.3 Network Configurations

There are two types of links defined in the Bluetooth specification.

- ACL-Asynchronous Connectionless Link
- SCO-Synchronous Connection Oriented Link

4.3.1 ACL Link

In an ACL link most ACL packet types are retransmitted, if not transmitted or received correctly. Therefore, this is considered to be a reliable link. The ACL link provides a packet switched connection with one or all slaves in the piconet. The master transmits packets, on a per slot basis, at “even” time slots. Independent of the packet length, one, three, or five slots, a slave is only allowed to respond in the next “odd” time slot, provided that it was addressed in the preceding master-to-slave time slot. An ACL packet with the Active member Address (AD_ADDR) 0 is interpreted as a broadcast message and is received by all connected slaves. In case of a broadcast message, no slave is allowed to return a packet (an exception is found in the access window for access requests in Park mode, see SIG 1999, section 10.8.4, pp. 115). As implied in part of the name, connectionless, no transmission shall take place if there is no data to send.

The associated packets are listed in table 4.1

Packet Type	Number of Slots	User Payload (bytes)	FEC[1]	Symmetric Max. Rate (kb/s)	Asymmetric Max. Data Rate (kb/s)		Overhead[2] In (%)
					Forward	Reverse	
DM1	1	17	2/3	108.8	108.8	108.8	62.8
DH1	1	27	No	172.8	172.8	1727.8	41.0
DM3	3	121	2/3	258.1	387.2	54.4	40.1
DH3	3	183	No	390.4	585.6	86.4	9.4
DM5	5	224	2/3	286.7	477.8	36.3	37.5
DH5	5	339	No	433.9	723.2	57.6	5.4
AUX1	1	29	No	185.6	185.6	185.6	36.6

Table 4.1. ACL data packets

[1] FEC: Forward Error Correction
[2] Number of overhead bits by the total number of bits in respective packet type

The ACL data packets use CRC (Cyclic Redundancy Check), with exception for the AUX 1 packet, to check for error. Hence, in case of an error a packet is retransmitted. Except for the AUX 1 packet, there are two types of packets: The DM (Data Medium Rate) and DH packet (Data High Rate). The difference is that DM packets use FEC (Forward Error Correction), for which the data rate is slightly reduced. One the other hand the FEC allows the payload to be reconstructed if corrupted, for instance, by random noise. As indicated by the packet name, a packet occupies one, three or five time slots. The slot length is 625 µs, and up to 366 µs is used for transmission. The remaining time is needed to switch to the next frequency in the hop sequence. If both master and slave sends packets covering a single time slot the time division scheme in figure 4.2 is obtained.

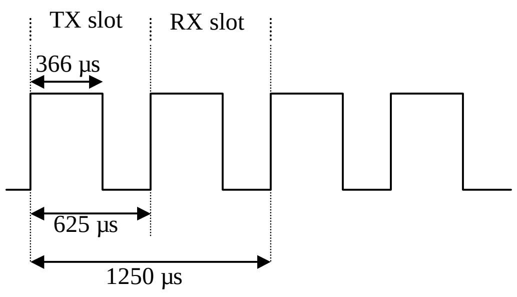


Figure 4.2. Slot timing, using one slotted packets.

The example is seen in the eyes of the master and DM1 or DH1 packets are used (AUX1 packets could also be used). In figure 4.3 an asymmetric situation is shown.

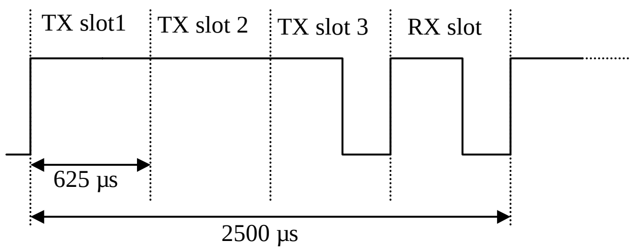


Figure 4.3. Slot timing (master: 3 slots, slave: 1 slot)

In this case the master starts transmission on an even time slot using a DH3 packet, or a DM3 packet. The slave responds with a 1 slotted packet. The selection of high-rate data or medium-rate data shall depend on the quality of the link. When the quality is good, the FEC in the data payload can be omitted, resulting in a DH packet. Otherwise, DM packets must be used.

From the examples the effective data rates in table 4.1 can be derived. Consider the case when the master sends DH3 packets with up to 183 bytes every 2500 µs and the slave responds with DH1 packets, with up to 27 bytes. The maximum forward asymmetric data rate for DH3 packet is 183·8 bits/2500 µs= 585.6 kb/s and in reverse with DH1 packets 27·8 bits/2500 µs = 86.4 kb/s. The remaining fields are determined in the same manner. Detailed information about all data and control packets can be found in (SIG 1999, section 4.4, pp.54-61).

4.3.2 SCO Link

The SCO link operates on reserved time slots. This provides a fast transmission of packets with a guaranteed time interval, but is not considered a reliable link since the SCO packets are never retransmitted. The SCO link is a symmetric, point-to-point connection between the master and a specific slave. This type of connection is considered to be circuit-switched since it operates on reserved slots. The SCO link typically supports time bound information like voice. As for the ACL link an addressed slave may respond to the master in the next slave-to-master time slot. Even if the SCO slave fails to decode the slave address in the packet header, it is still allowed to return an SCO packet in the reserved SCO slot. The SCO link is not used in this project and will not be further discussed. For additional information on the SCO link, refer to (SIG 1999, section 3.2, pp.45, 46).

4.4 The Baseband Packet

This section describes in more detail the format of the baseband packet and is not crucial to understand how Bluetooth operates. Therefore, the reader may skip to the next section if not particularly interested in the baseband packet format.

All information is physically transported via the baseband, and the baseband packet. The standard frame is shown in figure 4.4. The packet can consist of, the access code only and is used in paging and inquiry procedures, access code and header, or of access code, header and payload. The access code is used for synchronization; DC offset compensation, and identification.

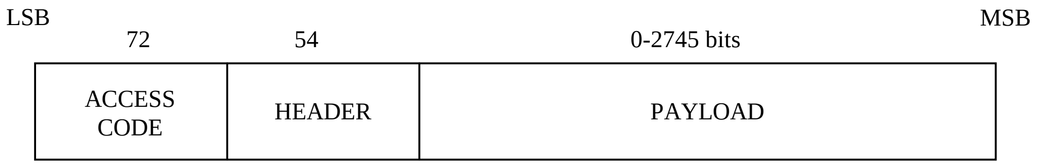


Figure 4.4. Standard packet frame

Three different access codes are defined.

- Channel Access Code (CAC)
- Device Access Code (DAC)
- Inquiry Access Code (IAC)

The different codes are used depending on operation mode. The channel access code defines the channel of a piconet, and is include in all packets sent by the master. The code is derived from the lower address part of the master Bluetooth address (BD_ADDR). The device access code is used during page, page scan and page response substates. This code is derived from the unit’s BD_ADDR. Finally, the IAC is used for inquiry operations. The code can be of two kinds: First, the General Inquiry Access Code (GIAC), which is used to discover all Bluetooth units within range. The second is the Dedicated Inquiry Access Code (DIAC), which is used to discover a group of units sharing a common characteristic.

As indicated by the figure the length of the access code is 72 bits. However, if a DAC or IAC is sent no header is present and the access code field can be reduced. A part called the trailer (4 bits) of the field is excluded. In this scenario the length of the access code is reduced to 68 bits. For further detail, refer to the Bluetooth baseband specification (SIG 1999, part B).

The next part of the frame is the header field; see figure 4.5 showing its content

LSB 3	4	1	1	1	8 MSB
AM_ADDR	TYPE	FLOW	ARQN	SEQN	HEC

Figure 4.5. Header content (lengths in bits)

AM_ADDR	Active member address, which is used to distinguish between the members of a piconet. This address is included both in master-to-slave and slave-to-master communication. For broadcast messages this field is set to all zeros.
TYPE	There are sixteen packets defined. Firstly, the type determines if a packet is sent on a SCO link or an ACL link. Secondly, it determines how many slots the packet occupies. The sixteen packets are divided into four segments. The first segment contains four packets that are common for both ACL and SCO packets. Segment two includes six packets, all occupying only one time slot. Segment three and four are for packets occupying three and five time slots, respectively.
FLOW	When the receiver buffer is full and not emptied a stop indication is returned (FLOW=0) to stop the transmission temporarily. Packets including only link information (ID, POLL and NULL packets) or SCO packets may still be received
ARQN	ARQN is an acknowledge indication used to inform the source of a successful transfer of payload data. The success is checked with a CRC code and the acknowledge is piggybacked in the header of a return packet.
SEQN	This is used to distinguish between retransmitted packets and new packets. Each time a packet containing data with CRC, the SEQN bit is inverted. If a retransmission is made due to a failing ACK the destination receives the same packet twice. By comparing the SEQN of consecutive packets, correctly received retransmissions can be discarded.
HEC	8-bit header error check (see section 4.5 error correction).

The last field is the payload field, which can include ACL or SCO payload information. Here, only the data field structure will be handled. The field consists of three segments: a payload header, a payload body and a CRC code. See figure 4.6.

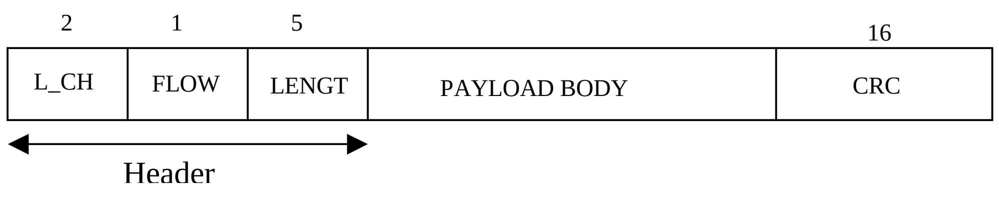


Figure 4.6. Payload segment

L_CH	Logical Channel Field, see table 4.2

L_CH Code	Logical Channel	Information
00	NA	Undefined
01	UA/UI	Continuation fragment of an L2CAP message
10	UA/UI	Start of an L2CAP message or no fragmentation
11	LM	LMP message

Table 4.2. Logical channel field

FLOW	Controls flow on the L2CAP level. The Link manager is responsible for setting this bit. (FLOW=0; flow off)
LENGTH	Number of bytes in the payload body.

The information in this section is extracted from (SIG 1999, chapter 4, pp.47-66).

4.5 Error Correction

4.5.1 FEC Coding

The Data Medium rate ACL packets are protected by a 2/3 Forward Error Correction code (FEC). The scheme is a (15,10) shortened Hamming code. The generator polynomial used is g (D) = (D+1)(D^4+D+1). Essentially a 15-bit code word is used to represent 10 bits. The code is able to correct all single errors and detect all double errors in each codeword. For a connection not producing many errors the FEC only impose unnecessary overhead, reducing the data rate to 2/3.

The packet header is also protected. The header is always protected by 1/3 FEC because it contains important link information and needs to be sustained. The code is implemented by simply repeating each bit in the header three times.

4.5.2 ARQ (Automatic Repeat reQuest) Scheme

All the ACL data packets, except the AUX1 packet, include a 16-bit Cyclic Redundancy Check (CRC) for the packet payload. The polynomial used to generated the CRC is g (D) = $D^{16}+D^{12}+D^{5}+1$. Furthermore, the packet header is checked with an 8-bit checksum called Header Error Check (HEC). The HEC is generated by the polynomial g (D) = $D^{8}+D^{7}+D^{5}+D^{2}+D+1$. For detailed information on checksum generation, see (SIG 1999, Chapter 5, pp.66-76).

Upon reception of a packet these checksums are calculated and confirmed. If the checksum for the payload fails the receiver requests a retransmission of the packet. Bluetooth uses an unnumbered acknowledge scheme, where an ACK or a NAK is returned in the packet header of the responding packet of the slave. The response is transmitted on the next slave-to-master slot following the reception of the packet from the master. The master will respond the next time it addresses the slave, which may be after addressing several other slaves.

The ARQ scheme is only applicable to links using packets including CRC. The data payload is retransmitted until a positive acknowledge is received or a time out is exceeded. For some communication links only a limited delay is allowed and new payload must be allowed. In case of timeout, the old packet is flushed and the controller is forced to consider the next data instead. Details on the ARQ Scheme may be found in (SIG 1999, Section 5.3, pp.68-77).

4.6 Error Checking

Packets are checked for errors or wrong delivery using the channel access code, the HEC in the header, and the CRC in the payload. At packet reception the access code is checked first. Since the 64-bit sync word in the access code is derived from the 24-bit master LAP (Lower Address Part of Bluetooth Device Address), this checks if the LAP is correct, and prevents the receiver to accepting packet of another piconet. The HEC and CRC are used to check both for errors and wrong address. For detailed information of how the HEC and CRC is generated please refer to (SIG 1999, section 5.4, pp.73).

4.7 The Bluetooth Connection

The steps for connection between units can be summarized like:

- Initialisation of Bluetooth units
- Inquiry Phase- discovering units within radio range
- Connection set-up
  - Includes Page phase
- Data and/or voice transfer
- Disconnection

4.7.1 The Inquiry Procedure

The first step after initialisation, to create a connection, is the inquiry phase.
A unit waiting to be discovered periodically enters the Inquiry scan state, listening for an inquiry messages from the master. The unit scans over a sequence of 32 hop frequencies and when it detects an IAC it can respond to the inquiring (master) unit. As response the device sends a FHS packet containing its address and clock value. The scanning unit can either be listening for general access codes (any unit) or for dedicated inquiry access codes (a specific type of unit).

The master sends ID packets continuously over a range of hop frequencies and scans for response after each transmission. The inquiring unit does not acknowledge any inquiry responses it receives. The Inquiry continues until it is terminated by the Link Manager (enough responses received) or a timeout occurs.

4.7.2 The Page Procedure

As explained in the Bluetooth specification, paging is used to set up a connection with a known unit. To connect to an unknown unit, the slave must respond to the inquiry message as explained above. Once the unit is known a connection can be established by paging the unit. The page procedure is very similar to the inquiry procedure.

During this phase the master estimate the slave clock offset, and uses this to start the page on frequencies close to this estimate by sending ID packets containing the slave’s address. To ensure connection the master uses a “Train” that is 10ms long consisting of 16 time slots at different frequencies. The train include the estimate; eight preceding frequencies and seven frequencies post the estimate. If this would not be enough a second train of additional 16 frequencies will be used. Eight frequencies placed on each side of the first train, broadening the frequency range even more.

The slave is in Page Scan state and listens for its device access code i.e. a page message from the master. The slave stays fixed at one hop frequency, at least 18 consecutive slots, while looking for its Device Access Code (DAC). The scan frequency is derived from the unit's address (BD_ADDR) and its native clock. Every 1.28 s the scanning frequency is changed. Once the slave recognizes its ID packet it responds. Upon response, the master sends a Frequency Hop Sequence (FHS) packet supplying the slave with the master's clock offset and Bluetooth address. Furthermore, the master assigns an active member address to the slave that is used for the remainder of the connection. The slave can now start hopping with the master. For more information about access procedures refer to (SIG 1999, section 10.6, pp.99-107). Figure 4.7 below displays the connecting states discussed above and other possible states of a Bluetooth unit.

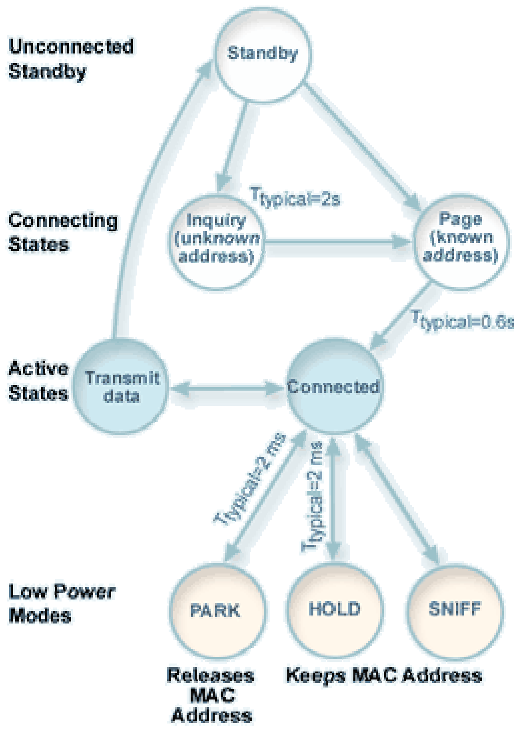


Figure 4.7. Bluetooth device states

4.7.3 Active States

In the Active state mode, a Bluetooth device actively participates on the channel. The master schedules all transmissions to the slaves. Active slaves listen in the master-to-slave slots for packets. If not addressed at the time, the slave may sleep until the master transmits again. However, periodic transmission is needed to keep the slave synchronized to the channel. This is easily obtained since only the channel access code is needed for synchronization, which is included in all messages sent by the master.

4.7.4 Park Mode

If a slave does not need to participate in a channel, at the time, it can be placed in park mode. The slave gives up its Active Member Address, but still stays synchronized to the master. The slave can wake up again at a master beacon instant. The beacon is repeated periodically and the master can activate the slave, transmit broadcast information, or change park mode parameters at the beacon instant.

4.7.5 Hold Mode

An ACL link between two Bluetooth devices can be placed in hold mode for a specific hold time. The master will send no ACL packets during this time. This mode can be entered if no data needs to be transmitted for a long time. The transceiver can then be turned off to save power.

4.7.6 Sniff Mode

When a link is in sniff mode the master can only start a transmission in a sniff slot. The interval of these slots is a result of a negotiation between the master and the slave. Both units, must agree to enter sniff mode, and can request to enter sniff mode.

4.8 Bluetooth Software Stack

The essential Bluetooth software stack is shown in Figure 4.8. The Bluetooth host denotes the user, e.g. a PC or a processor that uses the Bluetooth module to communicate with a remote system. The bottom layer of the Bluetooth module provides means for the physical transmission of packets as described in section 4.3.

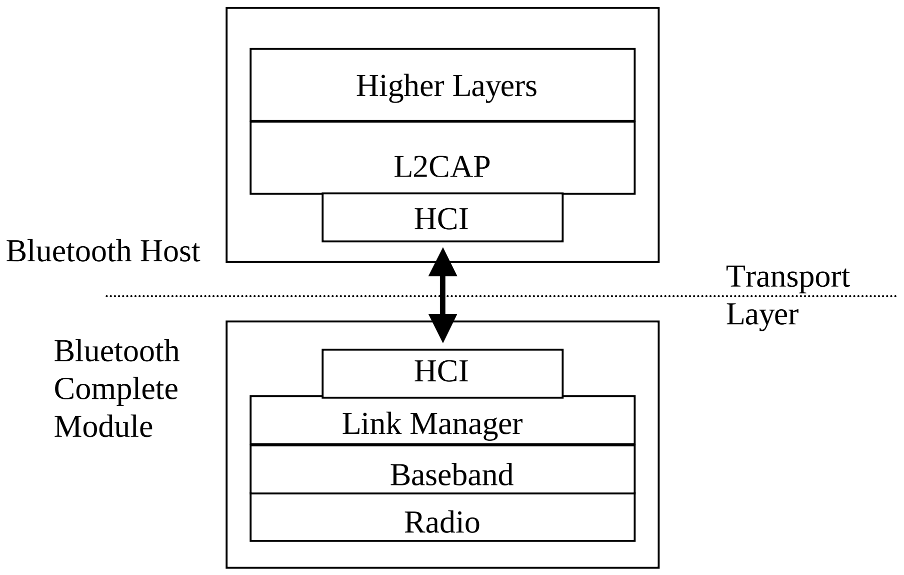


Figure 4.8. Bluetooth software stack

The Link Manager (LM) is responsible for link set-up, security and control. LM messages have higher priority than user data, and are transferred in the payload instead of data. The message is distinguished by a reserved value in the payload header. Messages are filtered out and interpreted by the Link Manager on the receiving end and is not propagated to higher layers. How the Link Manager actually works inside is not essential and is left for the reader to learn about. Information can be found in (SIG 1999, part C, pp.191-239).

The Host Controller Interface (HCI) is the programming interface to access the Bluetooth device and will be handled in section 4.8.1. The Host controller represents the controller inside the Bluetooth module that communicates with the host. Via the HCI the host can set up and maintain a link with a remote system over Bluetooth.

The Logical Link Control and Adaptation Layer Protocol (L2CAP) is layered in the data link layer and is only used for ACL links, i.e. there is no support for SCO links. The purpose of L2CAP is protocol multiplexing, enabling usage of higher layer protocols such as RFCOMM, HID and TCP/IP. Essentially, L2CAP hide the data link packet lengths for higher layer protocols. Moreover, it segments higher layer packets (up to 64k bytes) into appropriate data link packets and reassembles them again on the receiving end. Channels as described, recognize connections between devices. The end points of an L2CAP channel have its own channel identifier (CID), which provide the end points with a local name. Each channel can only use one higher-level protocol and is recognized by L2CAP. In other words multiple channels can use the same protocol, but a channel cannot be used by multiple protocols.

Only a portion of L2CAP will be used in this project. The reason is that the Ericsson Bluetooth module requires the use of the L2CAP packet format when sending data. Except from this all control of the Bluetooth module is handled with HCI commands. This deviation from the Bluetooth specification is further discussed in section 9.2. For details on L2CAP refer to (SIG 1999, part D, pp. 245-313).

4.8.1 Host Controller Interface (HCI)

The Host Controller Interface, part of the Bluetooth firmware, provide a format to reach the Bluetooth hardware capabilities. It is a command interface to the baseband, the Link Manager, and to various host controller registers. In this project all control of the Bluetooth device is done using HCI commands. The functionality could be fully implemented in the host software, but then losing the advantages of a flexible and structured layered software.

The HCI is divided into Command and Event. Typically, the host sends a command to the host controller and when the controller has carried out its task, it responds with a command complete event. The HCI driver converts commands into HCI packets and the packets are transported by underlying software to the Bluetooth module. The use of HCI packets makes the layer independent of means of physical transportation. In the Bluetooth specification USB, UART and RS-232 are mentioned for physical transportation. Once in the Bluetooth module the physical bus driver converts the data back into HCI packets. The packets are transported to the HCI firmware, where the commands are interpreted and actions are taken accordingly.

HCI commands may take different amounts of time to carry out. For this reason, the host controller responds with the result of the command in form of an event. To detect errors on the physical link a time out shall be defined. The Host Controller Interface Functional Specification recommends a default time out of one second; from the time a command is received to the moment a response is sent.

4.8.2 HCI Packets

The Host can send HCI commands, ACL data and SCO data to the Host Controller. In the opposite direction the Host controller can send HCI events, ACL data and SCO data to the Host. All parameter values, unless noted, are sent in "Little Endian" format, i.e. the least significant byte is transmitted first. The parameters in non-arrayed and all elements in an arrayed parameter have fixed size. Parameters are noted: parameter A[i]. If multiple arrays are used the order of the parameters are as follows: Parameter A[0], Parameter B[0], Parameter A[1], Parameter B[1], … Parameters A[n], Parameters B[n].

4.8.3 HCI Command Packet

The format of the HCI Command packet is sketched in figure 4.9. Each command contains an Opcode (2 bytes), uniquely identifying different commands. The OpCode consist of two components. First, the OpCode Group Field (OGF) identifying a specific cluster of commands, such as Link Control Commands, Link Policy Commands, Host Controller & Baseband Commands, etc. Secondly, the OpCode Command Field (OCF) defines the commands in a specific cluster. The OGF occupies the upper six bits and the OCF the remaining lower ten bits of the OpCode.

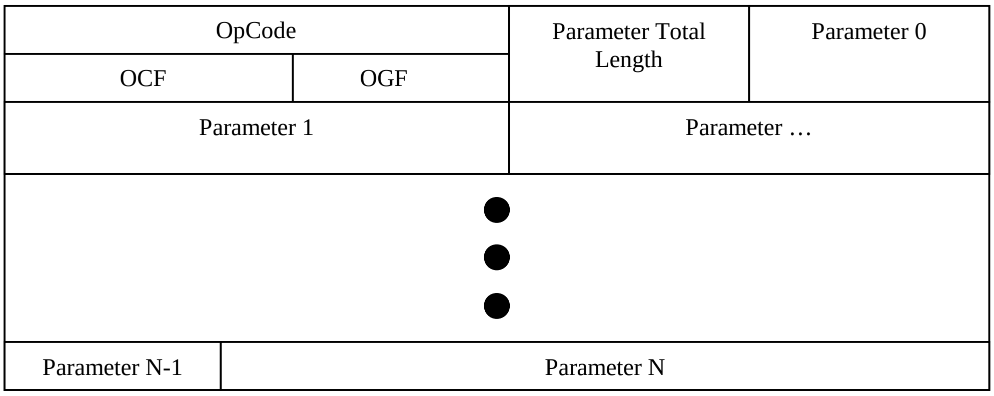


Figure 4.9. HCI command packet.

The Parameter Total Length (1 byte) field defines the number of bytes in the following parameters, and not the number of parameters. The Host Controller must be able to receive up 255 bytes of parameters plus the three-byte header.

In most cases, when a command has been executed, the Host Controller returns a Command Complete Event to the Host. However, some commands are not verified with a Complete Event. Instead a Command Status event is sent back when the command execution has started. In case of an error the cause of the error will be included in the Command Status event. Later on when the command is carried out, a command complete event may be sent. Each command is specified in (SIG 1999, parts 4.5-4.10, pp. 540-702) with command parameters, return parameters and associated events generated for that command.

4.8.3.1 An Example

As an example one command, the HCI_Inquiry command, can be defined in short (extracted from the Host Controller Interface Functional Specification):

Description:
The HCI_Inquiry command causes a device to enter inquiry mode to discover units within range. The command belongs to a group named Link control Commands with the OGF 0x01. The OpCode Command Field for this command is 0x0001.

Command parameters:

- LAP (3 bytes): The value from which the inquiry access code will be generated.
- Inquiry_Length (1 byte): Maximum amount of time before the inquiry procedure is stopped. Range: N = 0x01-0x30. Time = N*1.28 seconds.
- Num_Responses (1 byte): Maximum number of responses accepted before the inquiry process is halted. Range: 0x01-0xFF.

Return parameters:

- None

Events generated:

- Command Status Event, when inquiry is started.
- Inquiry Result Event, when a device responds.
- Inquiry Complete Event, when the inquiry procedure is finished in compliance with the command parameters.

4.8.4 HCI Event Packet

The format of the HCI Event packet is shown in figure 4.10. Each Event is distinguished with an Event Code (1 byte) in the first segment of the packet. The number and kind of parameters are specific for the respective event. The possible events are defined in (SIG 1999, chapter 5, pp. 703-744).

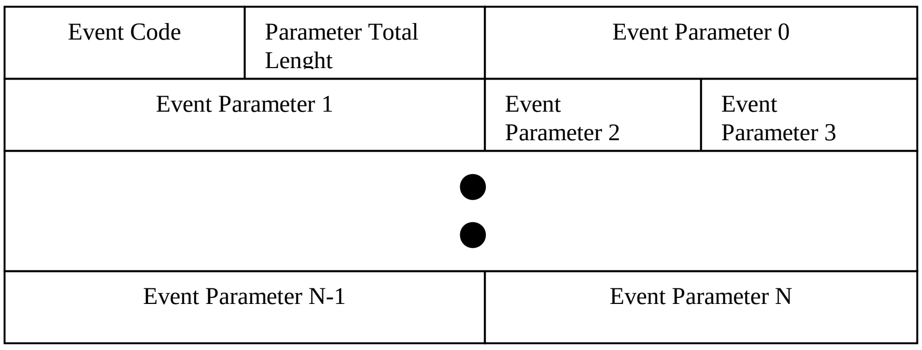


Figure 4.10. HCI event packet

The Host must be able to accept HCI Event packets with up to 255 bytes of data excluding the packet header.

4.8.5 The HCI ACL Data Packet

The HCI Data Packet is used to exchange data between the host and the host controller and is sketched in figure 4.11 below. Here, only the ACL data packet will be described. The SCO data packet is defined in (SIG 1999, section 4.4.3, pp.538, 539).

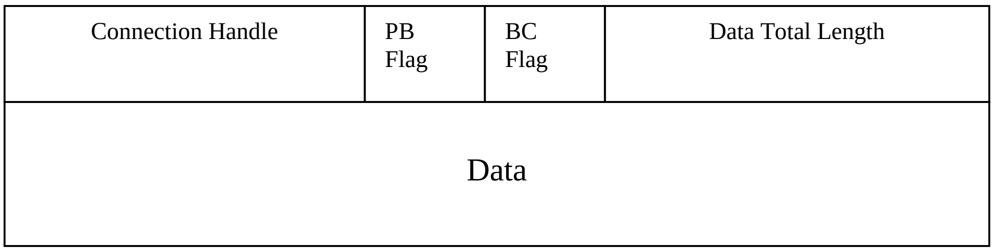


Figure 4.11. HCI ACL data packet

The Connection Handle, a 12-bit identifier for transmitting and receiving voice or data, is used to identify a connection between two Bluetooth devices. An assigned connection handle is used by the host Controller for the remainder of the present connection. The Packet Boundary Flag (PB Flag, 2 bits) indicate weather or not the packet contains a continuing fragment of a higher layer message or if it is the first part of a higher layer packet (so far only a L2CAP message). The Broadcast Flag (BC Flag, 2 bits) set to 00 indicate a point-to-point transmission, 01 means the packet will be sent to all active slaves (Active Broadcast), 10 indicates that the packet will be sent to all the slaves, including slaves in ‘Park’ mode (Piconet Broadcast). The Data Total Length (2 bytes) gives the number of bytes in the Data segment.

4.9 Data Transfer using L2CAP

A master can transfer information to a slave whenever it wishes to. However, if a slave wishes to transfer data the master must have addressed it. If the master has no data to send to the slave, it invokes a polling mechanism by sending Poll Packets to the slave. This way the slave is given the opportunity to transfer data.

To explain the transfer procedure and how two devices interact, consider the following example:

Host 1 (local) wants to transfer 26 bytes of information to host 2 (remote). A connection is established and the packet type used for the session is the DM1 packet. The 26 bytes of data represent the L2CAP messages and do not fit into one DM1 packet. Therefore the data is segmented and sent in two DM1 packets.
The situation is sketched in figure 4.12.

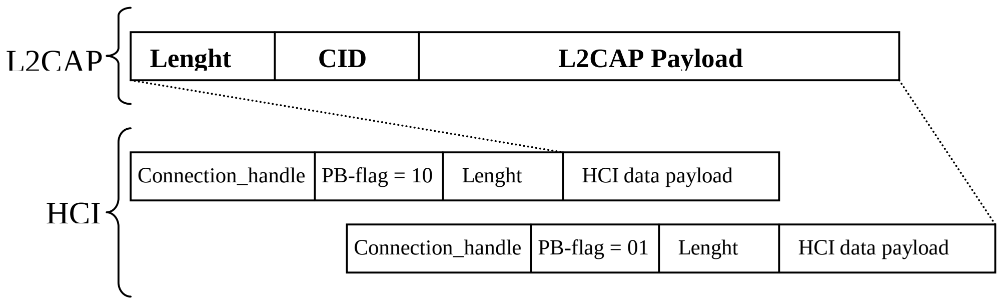


Figure 4.12. segmentation of L2CAP packet.

The first HCI packet includes the L2CAP header, namely Length and CID (4 bytes) and 13 bytes of data in the HCI data payload. The Packet boundary flag (PB-flag) is set to “first packet of higher layer message”. The second HCI packet includes the remaining 13 bytes of data in the HCI data payload. This time the PB-flag is set to “continuation of higher layer message”. On the receiving end the host software will re-assemble the two packets in order to create the 26 bytes of information packet originally sent.

4.10 Bluetooth Security

The Bluetooth standard provide two types of security measures, authentication and encryption. Authentication is used to verify, before information is exchanged, that a counter part really is the individual it claims to be, and not an intruder. Encryption is the process where sent information is encoded in such way that only the addressed device is able to decode it. Other units shall not be able to listen to this private information. The system is not airtight and with high effort an intruder could decode an encoded messages, and/or illegally pass the authentication. For most applications the security is considered to be satisfactory. The security is adjustable by a variable key used for encryption. The size of key may vary between 1 and 16 octets. If further security is needed this shall be implemented at the application layer. For the first connection between two devices, the security procedure is depicted in figure 4.13.

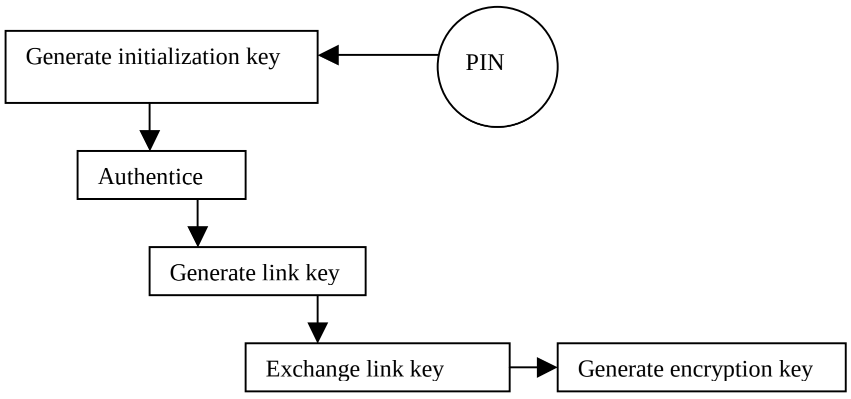


Figure 4.13. Security, first connection

The PIN code can be a fixed number provided with the Bluetooth the user could arbitrarily change unit, or it if a Man Machine Interface (MMI) is present. In the later case the number is entered in both units and later matched. The security procedure for following connections between the same units is depicted in figure 4.14.

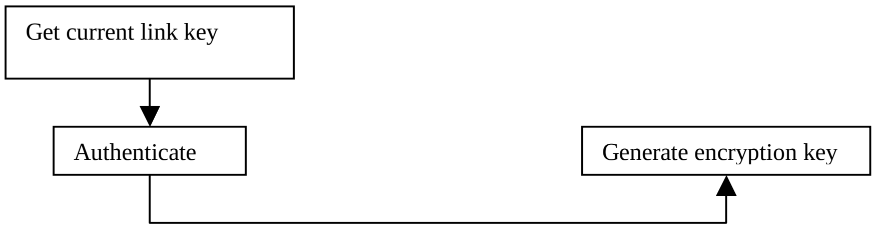


Figure 4.14. Security procedure (following connections)

The link key is a 128-bit random number, which is shared between two or more parties and is the base for all security transactions between these parties. The link key is used in the Authentication routine. Furthermore, it is used as one of the parameters when the encryption key is derived.

4.10.1 Authentication

The authentication is based on a challenge-response scheme. The unit requesting another unit to prove himself is called the verifier and the requested unit, claimant. For the authentication to succeed, the procedure requires that both units share the same secret key. The verifier, e.g. unit A, sends a random number AU_RAND_A to the claimant, unit B. The situation is displayed in figure 4.15. Both units calculate an authentication code, SRES, using the algorithm E_1 with the inputs AU-$RAND_A$, BD_ADDR_B and Link key (128-bits). The verifier compares its result with the claimant’s, and if they coincide, the authentication is a success.

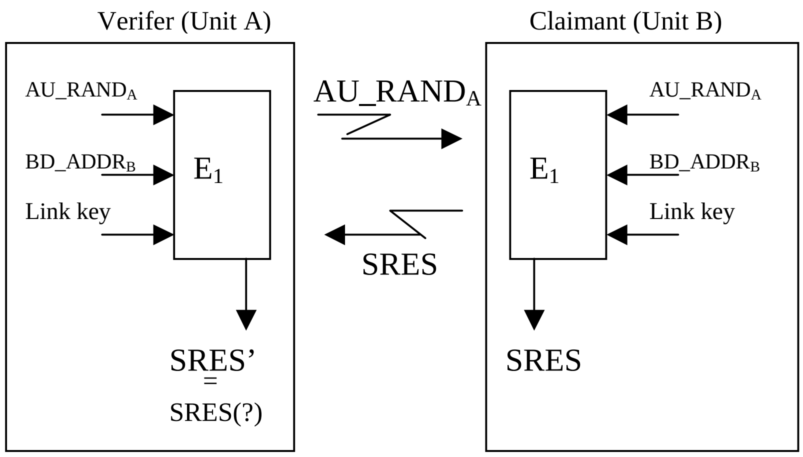


Figure 4.15. Challenge-response

In some peer-to-peer communications, mutual authentication might be appropriate. In this case, unit a first request unit B to authenticate as described above, and then the procedure is reversed. Only, this time unit B sends the random number, AU_RAND$_B$, and BD_ADDR$_A$ is used to determine SRES. The order in which to authenticate is decided by the link managers.

If an authentication fails, the time between attempts will be increased. For each subsequent authentication failure with the same Bluetooth address, the waiting interval is increased exponentially and decreased if new attempts do not fail. This procedure prevents an intruder to repeat the authentication procedure with a large number of different keys. For greater detail about Authentication, see (SIG 1999, section 14.4, pp. 169-171).

4.10.2 Encryption

Protecting user data is done through encryption, where ciphering bits are bit-wise modula-2 added to the data stream. The cipher is symmetric, meaning that the deciphering is done exactly the same as encryption with the identical key. The payload is ciphered, including the CRC bits, but not the forward error correction code. Each packet payload is ciphered separately with the cipher key, K $_{\text{Cipher.}}$ The cipher key is determined by the algorithm E$_0$, using the master Bluetooth address, 26 bits of the master real-time clock and the encryption key, K$_c$, as inputs. The effective cipher key length can be set to any multiple of eight between one and sixteen (8-128 bits). The situation is sketched in figure 4.16.

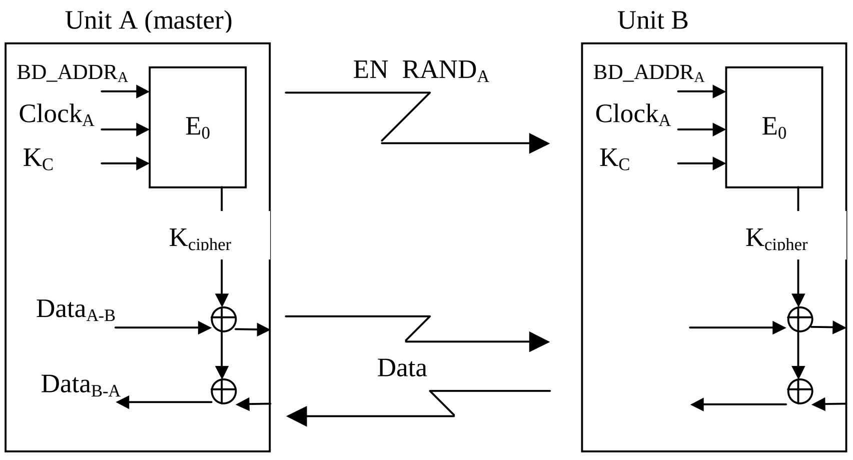


Figure 4.16. Encryption procedure

Before the master enters encryption mode, the master sends a 128 bit random number, EN_RAND$_A$, allowing the slave to determine K$_c$ together with the current link key and a 96-bit Cipher Offset number (COF). Since at least the clock value changes for each transmission, the cipher key is continuously changed, making it hard for an intruder to encode a message. The cipher algorithm is defined in (SIG 1999, section 14.3, pp.159-169).

4.11 Observations

The data throughput and error tolerance can be set using different packet types. If a connection is relatively error free the DH packet should be used, providing the highest data rate. Depending on the amount of data DH1, DH3, or DH5 may be chosen. For instance a CAN message would fit into a DH1 packet, providing the fastest possible transmission of that particular message. On the other hand accumulated packets, if heavy traffic on the CAN network, could be bridged using a DH3 or DH5 packet, providing a much higher data rate (see table 4.1, pp.14).

When a connection has to work in a noisy environment, the forward error correction code (FEC) can be added, increasing error tolerance. Using FEC will reduce the data rate, but effectively the throughput may be increased since the FEC decreases the number of re-transmissions due to packet errors.

The Bit Error Rate (BER) is important to keep in mind while designing a Bluetooth implementation. According to the specification the BER is set to 0.1% at range limit. Consider the case when the longer packets are used. For instance the DH3 and DH5 packets contain about 1500 and 2700 bits, respectively. With BER at 0.1%, i.e. one out of a thousand bits are corrupt; the consequence will be that these packets will essentially be retransmitted infinitely. The cure for this problem is simply to send data in shorter packets.

5 The Controller Area Network

BOSCH developed the Controller Area Network (CAN) in the early eighties for the car industry. CAN offer a high-level safety, reliable and robust data link, over a two wire serial bus. The acceptance today is worldwide and CAN is used in a wide range of products. Industrial examples are marine control and navigation systems, agricultural machinery, medical systems and textile production machinery. Two of the most important features of CAN are the automatic error handling, done by hardware and the guaranteed latency for bus access, which especially makes it very suitable for real-time applications.

CAN covers layers 1 and 2 in the ISO/OSI model and are described in the international standard ISO 11519-2 for low speed applications and ISO 11898 for high speed applications. Enhancements of the original specification are available for the application layer such as CAN Kingdom, SDS, CANopen and DeviceNet.

The data link layer services are implemented in the Logical Link Control (LLC) and Medium Access Control (MAC) sub-layers of the CAN controller. The LLC handles acceptance filtering and services for data transfer and data requests. Furthermore, it provides overload notification and recovery management. The MAC is responsible for frame creation, error detection, error signalling, and acknowledgement and controls the access to the bus. The physical layer provides means for transmission of dominant and recessive bits, where the dominant bit overwrites the recessive bit if transmitted at the same time.

5.1 Physical Layer

The CAN bus basically consist of two lines CAN_H and CAN_L with terminating resistors in both ends as shown in figure 5.1.

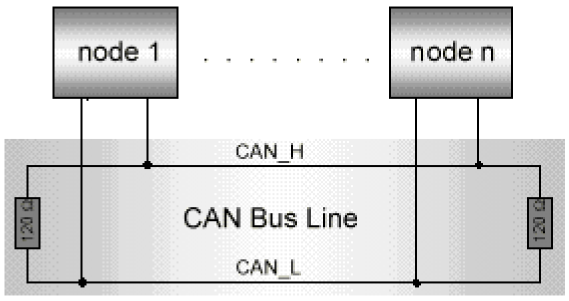


Figure 5.1. Network setup

However, CAN do not require a specific medium. Optic fibre or even radio could be used, but the most common is the use of twisted pair cables, as described in the specification ISO/WD11898-2 (1999).

Whichever medium, the bit level is always interpreted by the differential between CAN_H and CAN_L. The bus state can either be dominant (normally referred to as a logical 0) or recessive (normally logical 1). See figure 5.2.

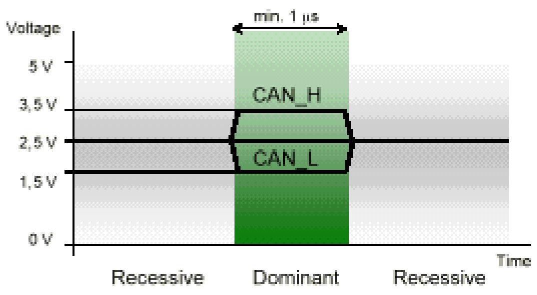


Figure 5.2. Nominal bus levels.

A recessive bit is detected when CAN_ H is less than 0.5 V higher than CAN_L. If the CAN_H is more than 0.9 V higher than CAN_L a dominant bit is detected.

The differential nature for bit representation provides a great advantage against electromagnetic interference. Bus lines exposed are both affected, but the differential is still unaffected.

A disadvantage however is the limited bus length. At maximum bit rate of 1Mbit/s the overall bus length may not exceed 40 meters and connecting stubs should not exceed 0.3 meters, for proper functionality. The reason for this is that all nodes in the network checks the bit value simultaneously and therefore a transmitted bit must be allowed to propagate throughout the system before a second bit can be sent. At lower bit rates the bus length and number nodes can be increased. Refer to ISO/WD11898-2 (1999) for further information.

5.2 Message Frames

Every CAN message consists of a number of bits divided into fields. The message can be one of two kinds. The difference is basically the length of the message identifier. The standard message frame consists of an 11-bit identifier (CAN 2.0A) allowing 2032 different logical addresses, i.e. 2032 communication objects or messages can be present in Standard CAN. In the other case the message has an extended identification field of 29 bits, allowing 2^{29} (536,870,912) unique CAN messages (CAN 2.0B).

Four kinds of frames are defined for CAN:

- Data Frames
- Remote Frames
- Error Frames
- Overload Frames

5.2.1 Data Frame

A data frame is created by a node when it wishes to transmit data or if it has been requested to do so by another node. The frame format, as described in (ISO/WD11898-1, 1999, pp.24-30), can be seen in figure 5.3 below.

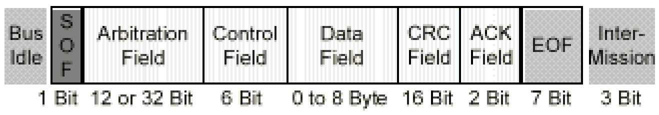


Figure 5.3. CAN data frame

<u>SOF</u>
The data frame starts with a dominant Start of Frame (SOF) bit for hard synchronization of all nodes. Hard synchronization is performed whenever there is a recessive-to-dominant edge during bus idle, suspend transmission or during the last bit of intermission.

<u>Arbitration Field</u>
The arbitration field looks different depending on if it is a standard or extended data frame. The difference can be seen in figure 5.4.

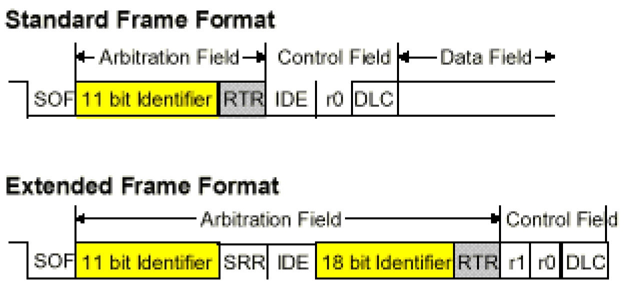


Figure 5.4. Arbitration field

The arbitration field determines the priority of a message if more than one node wants to send a message. The lower the numerical value the higher the priority. The standard frame arbitration field contain an 11 bit identifier, which mask incoming messages in order to determine if a message is relevant, or not, to this node. The following field is the RTR (Remote Transmission Request) bit. The RTR bit is used to distinguish between data frames, in which case the bit is dominant, and remote frames, where a remote node requests data.

In the extended format the 11-bit base ID is followed by the Substitute Remote Request (SRR) bit, Identifier Extension (IDE), extended ID bits and the RTR. The SRR is always recessive in the extended format and only replaces the RTR bit in the standard frame. This way a standard frame always gets priority over an extended frame if a collision occurs. The IDE bit indicate weather a frame is of standard or extended format.

<u>Control Field</u>
In the standard frame format the IDE bit is included in this field followed by r0 and the Data Length Code (DLC). Bit r0 is reserved for future use and the DLC indicate the number of bytes in the data field. The frame size is in this way not made any larger than it needs to be. The Control Field for the Extended Frame Format has two reserved bits r1 and r2 before the DLC bits.

Data Field
The data field contain the application data of the message. The field can be zero to eight bytes long. A frame containing no data (zero bytes) could be used to indicate some event defined by the data frame identifier.

Cyclic Redundancy Check Field
The Cyclic Redundancy Check (CRC) field is a 15-bit checksum calculated for the preceding bits of the message. The checksum is used for detection only, i.e. no correction will be made. The sixteenth bit of this field is the CRC Delimiter, which is fixed formatted recessive. This bit is checked by the receiver and indicates whether the frame is legal or not.

ACK Field
The Acknowledgement Field is two bits long and an ACK slot and an ACK Delimiter (figure 5.4).

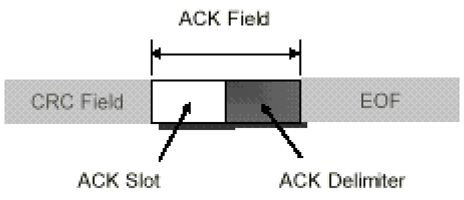


Figure 5.4. Acknowledge field

The transmitting node sends a recessive bit in the ACK slot of the message. Every node receiving the message correctly overwrites the ACK slot with a dominant bit. The transmitter reads the ACK slot back and if a dominant bit is sensed the node can be sure the message was transmitted correctly and at least one node got the message correctly.

End Of Frame Field
EOF closes the frame with seven recessive bits. Normally, after the fifth bit of equal polarity an additional bit with reversed polarity is stuffed into the bitstream, referred to as bitstuffing. During EOF this service is turned off, which would otherwise generate a bit stuffing error.

Intermission Field
The intermission field is used to separate two message frames. However, Error or Overload frames are allowed to be transmitted in this region.

5.2.2 Remote Frame

The remote frame is almost identical to the data frame. The difference is that the remote frame contains no data and the RTR-bit is set recessive to indicate a data request. A node can request data from a source by sending a Remote Frame with an identifier that matches the identifier of the required data frame. The corresponding node responds by send the required Data Frame.

5.2.3 Error Frame

A detected error is notified using an Error Frame (figure 5.5). The first field contain six consecutive dominant bits, which violates the rule of bit stuffing. This will cause all other nodes to realise the error and will start sending active Error frames them selves.

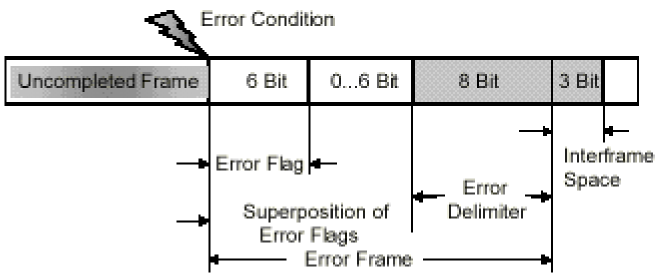


Figure 5.5. Error frame

All the nodes will ignore the originally corrupted message in the system and the transmitter will attempt to re-send the message as soon as the bus becomes available again. The Error Delimiter consists of eight recessive bits and allows restart of communication after an error.

5.2.3 Frame Coding

CAN use the method of Non-Return to Zero (NZR) for bit representation. During one bit time the signal stays constant and there are no edges between consecutive bits of the same level. To ensure synchronization of all nodes, CAN use bit stuffing. After five consecutive bits of the same polarity, a complementary bit is added into the bitstream. At the receiving end the bitstream is de-stuffed, i.e. added bits are removed.

The frame segments CRC delimiter, ACK field and EOF are fields of fixed format and are not coded with bit stuffing.

5.3 Arbitration

In a CAN network all nodes have their own unique identifier. The node identifier is assigned during the design phase and also indicates its priority in respect to the other nodes in the network. The lower the numerical value of the identifier the higher the priority. If more than one node wants to access the bus at one time the node with the highest priority will automatically gain bus access with no delay. This is one of the real advantages of CAN and is achieved by a non-destructive, bitwise arbitration process.

The arbitration process is well described as an example, as in Bagschik (2000). Consider the case in figure 5.6 where two nodes start transmitting at the same time. As long as the bits from the two are identical, nothing happens. The first time there is a difference the recessive (logical 1) bit of Node B will be overwritten by the dominant (logical 0) bit of Node A. Both nodes are at the same time listening to the traffic on the bus. As soon as Node B does not receive the same bit it transmitted it realises that a message of higher priority requests access to the bus and directly stops transmitting. Node B has lost the arbitration and is in receive mode for the remainder of the message. When the bus becomes free again Node B will make another attempt to transmit and the same procedure will be repeated in case of simultaneous transmission.

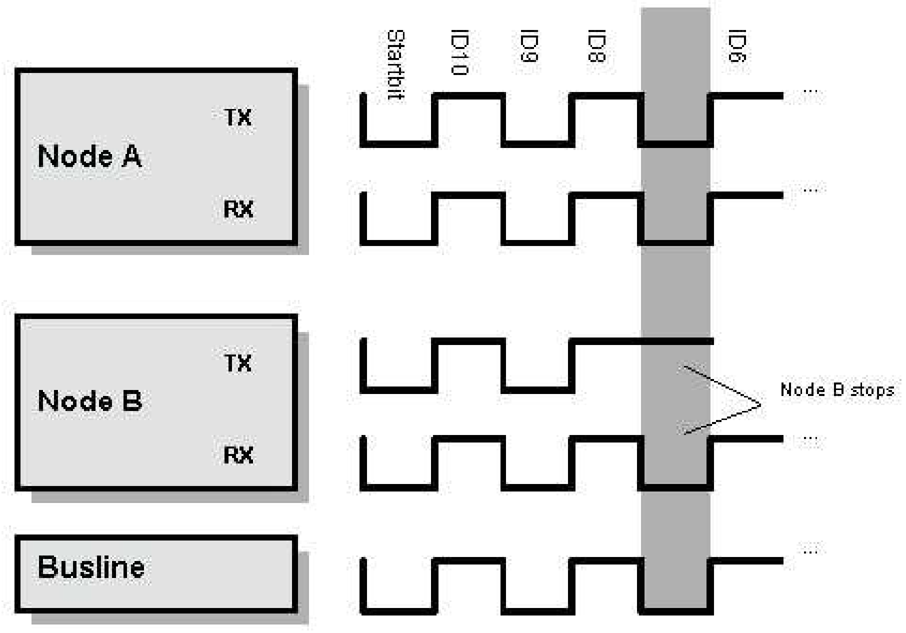


Figure 5.6. CAN arbitration

This technique enables all nodes to listen to every message on the bus. The identifier of a message could be said to work as a key. The message will only be let in if the key fits, i.e. the node determines if the message is relevant, if not the message is simply ignored. The acceptance evaluation can either be handled by the application, i.e. software, which is a Basic CAN feature or automatically by hardware (CAN controller), which is a Full CAN feature.

5.4 The Error Process

Errors are detected and handled by the error management unit of the CAN controller. The advantage of hardware management is that application software is relieved of this task, otherwise putting extra burden on the application processor.

In the event that a node sends erroneous messages repeatedly, error counters in the system guarantee that the bus traffic will not be permanently disturbed. For detailed information about error handling, please see (ISO/WD11898-2, 1999, pp.32,33) and Bagschik (2000).
The error handling procedure happens as follows:

- Error detection
- An error frame is transmitted
- The message is discarded by every network node

- The error counters of every bus node are incremented
- The message is retransmitted automatically

5.4.1 Error Detection

The CAN controller can detect five different errors.

Bit Error
A transmitter monitors the bits present on the bus and compares them with the bits transmitted. A bit error is raised if there is a mismatch and an error frame is generated. However, no error can occur during the Arbitration Field and the Acknowledge slot. In order to achieve arbitration and acknowledgement these fields need to be able to be overwritten by a dominant bit.

Bit Stuffing Error
In the areas where bit stuffing is applied, a Bit Stuffing Error is signalled if a node detects six consecutive bits of the same polarity.

Acknowledgement Error
Upon transmission the ACK Slot is recessive and will be overwritten with a dominant bit by the first node to receive the message correctly. If the transmitter does not read back a dominant bit an error frame will be generated.

CRC Error
The receiver also calculates the CRC code transmitted in a message. If they differ a CRC Error will be signalled.

Form Error
Parts of the CAN frame has predefined values such as the CRC delimiter, ACK delimiter and EOF field. If the bit values differ a Form Error is signalled.

5.4.2 Error Limitation

In order to prevent permanent disturbance by error frames, a node can enter states that limits the influence on the bus. The three possible states are Error Active, Error passive and Bus Off, as shown in figure 5.7. Two counters, a Receive Error Counter (REC) and a Transmit Error Counter (TEC) keep track of in which state the node is in. Depending on the error the counters are incremented by a specified value as described in CAN specification. Furthermore, if a message is transmitted and received correctly the counters will be decremented by predefined values.

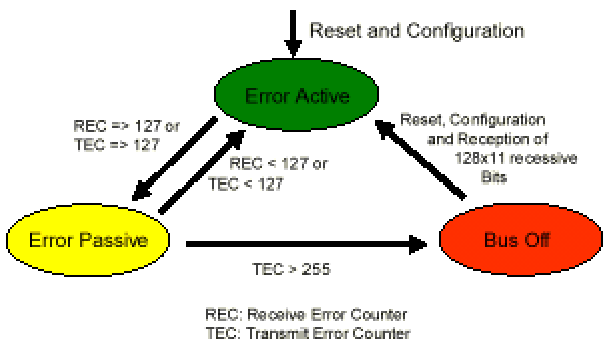


Figure 5.7. CAN error states

Error Active
This is the normal state of operation. The node will send Active Error frames upon a detected error. The node will stay Error Active as long as both TEC and REC are below 127.

Error Passive
This state is entered if the REC or TEC counter exceeds 128. In this state the node can still take part of the bus communication and sends Error Passive frames, which contain eight recessive flag bits, when an error occurs. Also, the node has to wait eight bits in between two transmissions. In order to get back to Error Active state, both counter need to be below 128.

Bus Off
A node, where the transmit error counter exceeds 255, is switched into bus off state. In the Bus Off state, a node can neither receive nor transmit any frames. Once in Bus Off the node has to be reinitialised to be able to become Error Active again.

5.5 Bit Timing and Synchronization

Four time segments construct one bit time: The Synchronization segment, propagation segment, Phase Segment 1 and Phase Segment 2. Each segment comprise of an integer multiple of the so-called Time Quantum. The Time Quantum is the smallest discrete programmable time resolution possible. The number of Time Quantum in each segment can be programmed, but the overall range for a bit time is 8 to 25 Time Quanta. The bit time is displayed in figure 5.8.

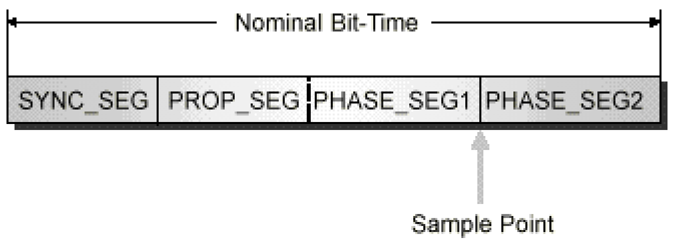


Figure 5.8. Bit segments

- The SYNC_SEG is one Time Quantum and is used to synchronize the nodes on the bus. An edge is expected to occur during this segment.
- The purpose of the PROP_SEG segment is to compensate for signal delays in the system. CAN controllers, transceivers and cables all add delay to the network and has to be compensated for. The programmable range is one to eight Time Quanta.
- PHASE_SEG1 and PHASE_SEG2 are used to compensate for phase shifts between the transmitting and the receiving node(s). In the former case the field length may be shortened and in the later lengthened.

Each node in a CAN network has its own individual oscillator. And when receiving a CAN frame there may be a phase shift. This offset is compensated for through resynchronization by the receiving controller (soft synchronization). Consider a slow transmitter, where the signal is not detected until in the PROP_SEG instead of in SYNC_SEG. For compensation PHASE_SEG1 is lengthened so that the sampling occurs at the right moment in time, see figure 5.9.

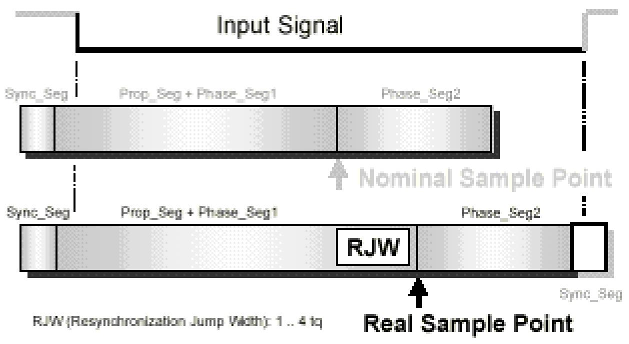


Figure 5.9. Resynchronization

In the event that a frame edge is early, i.e. occurs during a previous Phase Segment 2, PHASE_SEG2 is shortened so that the input signal seems o appear at SYNC_SEG. Only one resynchronization is allowed during a bit time.

The sample point always occurs at the end of PHASE_SEG1. At this point the actual bit value is interpreted, i.e. dominant or recessive. Because of this synchronization is important to sample at the right position in the bit segment. The recommended sample point is at 60 percent of the total bit time.

In addition to resynchronisation there is hard synchronization. As stated in the CAN specification, hard synchronization is performed during interframe space whenever there is a recessive to dominant edge. When it occurs the bit time is restarted and the edge will fall into the Synchronization segment. The physical signalling is explained in detail in (ISO/WD11898-2, 1999, pp. 35-40).

5.6 Converter Considerations

Due to the fact that Bluetooth does not support bitwise transmission, the bridge can never be made completely transparent over Bluetooth, i.e. two CAN networks connected via a Bluetooth link would never appear as exactly one network. The physical layer of CAN demands an acknowledgement of a sent message from the other node(s) within fractions of a CAN bit time. Hence, the receiver would have to be able to receive and acknowledge a message in a time window of 1 µs, at a bit rate of 500 kb/s (bit rate for CAN). Even if the bitrate was set as low as 10 kb/s, the Bluetooth link would still not be able to acknowledge in time.

In order to make the link as transparent as possible, one solution would be to let the converter in a first step receive and acknowledge the message. Then interesting information would be extracted from the message, namely the Arbitration, Control, and Data field. The maximum possible number of bytes in these fields together is 13 bytes. These bytes plus three bytes overhead from the converter packet fit nicely into a Bluetooth DM1 packet, allowing a payload of up to 17 bytes. If traffic is not too intense on the CAN network the Bluetooth link would after all exchange data reasonably fast. If one slotted Bluetooth packet was used for transmission in each direction, a CAN message could be transmitted every 1.25 ms assuming that the master transmits every second time slot (one time slot is 625 µs).

Several CAN messages could also be transmitted at one time using DH3 or DH5 Bluetooth packets, if traffic is intense. The converter would buffer a few messages and send them in a bundle, increasing the data rate but also the latency of the link.

6 The Keyword Protocol 2000

The Keyword Protocol (KWP2000) is specified in the international standard ISO/DIS 14230-1. Saab Automobile AB, Scania AB, Volvo Car Corp., Volvo Bus Corporation and Mecel AB have further developed the standard for Swedish implementations. All information in this chapter, regarding KWP-2000, is extracted from the Swedish implementation specifications SSF14230-1 (1997) and SSF14230-2 (1997).

6.1 Physical Layer

The Keyword protocol includes two lines, the K-line and the L-line. In the Swedish implementation only the K-line is used. The K-line is bi-directional and used for diagnosis, test or maintenance only.

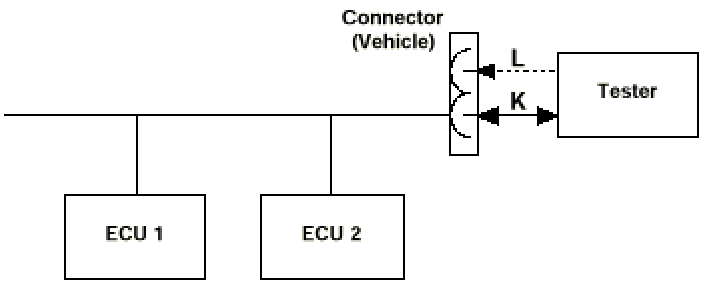


Figure 6.1. K-line configuration

The battery voltage, V_B can be either 12 or 24 V depending on the vehicle.
The signal levels on the bus are then expressed as percentages of V_B expressed as:

Shape	Transmit	Receive
Logical 1	80%	70%
Logical 0	20%	30%

Table 6.1. Logical levels (KWP-2000)

Voltage levels between 30% and 70% of V_B may according to the KWP2000 specification be detected as either a logical 1 or logical 0.

The bus operates with a standard bit rate of 10400 bit/s.

6.2 Message Structure

The message structure includes header, data bytes and a checksum, as shown in figure 6.2.

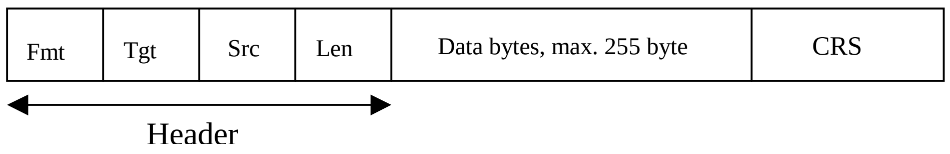


Figure 6.2. KWP2000 message structure

The Format field (Fmt) is 1 byte and contain 6-bit length information and 2-bit mode information. The mode can be one of two kinds, either indicating a header with physical address information or one with functional address information. The six remaining bits can be used to indicate message data length of 1 to 63 bytes, not including the checksum. In this case the Header could be decremented to 3 bytes taking away the Length field (Len). However, in the Swedish implementation these 6 bits shall all be set to zero (except in the StartCommuncationRequest message). The length is solely expressed in the Length field, allowing message lengths up to 255 bytes. Thus, the overall largest possible message is 260 bytes long.

The Target field (Tgt) contain the address of the receiver of a message. This address may be either physical or functional. Each ECU and Tester has a unique address and may be programmed by software. Physical addressing can be used for both request and response messages. Upon a request the target has the physical address of a specific node in the network and the source has the physical address of the tester.

The Functional addressing can only be used for request messages. In this case the request is aimed for a group of nodes. The address of the tester is still physical. Actually this is the only instant where the addressing is not physical. When a group request is inquired the nodes need to respond in an orderly manner. To obtain this the system must support arbitration.

The last part of the message is the Checksum field (CS) that is defined as an 8-bit sum series of all bytes in the message, excluding the checksum.

6.2.1 Key Bytes

The Format of the Header is specified by the Keybyte, which is sent to the tester by an ECU upon start of communication. The structure of the Keybyte is as follows:

KB1 (Low byte)		=0	=1
Bit 0	AL0	Length inf. In format byte not supported	Length inf. In format byte supported
Bit 1	AL2	Add. Length byte not supported	Add. Length byte supported
Bit 2	HB0	1 byte header not supported	1 byte header supported
Bit 3	HB1	Tgt/Src addr. In header not supported	Tgt/Src address in header supported
Bit 4	TP0	Normal timing parameter set	Extended timing parameter set
Bit 5	TP1	Extended timing parameters set	Normal timing parameter set
Bit 6	1	-	-
Bit 7	Parity (odd)	-	-

Table 6.2. The low key byte

In the Swedish implementation the keybytes have fixed values as:
KB1 (Low Byte)= 0xEA
KB2 (High Byte)= 0x8F

Thus, the header supports additional length bytes, header with target and source address information, and normal timing. The timing parameters may be changed, but it is then the responsibility of the designer to ensure proper functionality. Refer to the Data Link Layer specification for details.

6.3 Timing

There are four time slots identified in the KWP-2000 specification:

P1 Inter byte time in ECU response

P2 Time between the end of the tester request an the start of the ECU response **or** Time between the end of ECU response and start of the next ECU response

P3 Time between the end of the ECU response and the start of the tester request Or Time between the end of the tester request and the start of the next tester request if the ECU fails to respond

P4 Inter byte time for tester request.

Figure 6.3 shows the timing scheme of an example message stream.

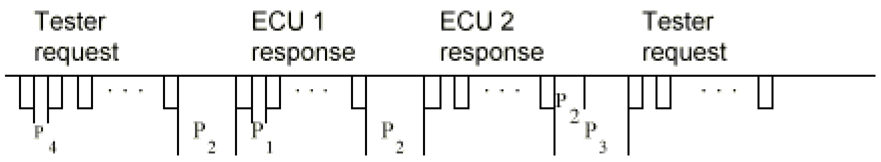


Figure 6.3. Message timing

Table 6.3 below shows the standard timing values (in ms).

Timing Parameter	Min. values default	Max. values default
P1	0	20
P2 **P2***	25 25	50 5000
P3	55	5000
P4	5	20

Table 6.3. Standard timing parameters

Note: *the timing parameter P2* becomes active if server (ECU) respondes with negative response or receives a specific response code (refer to ISO 14230-2).*

6.4 Initialisation

6.4.1 Communication Startup

The tester starts the communication with a node by sending a wake up pattern. Before the pattern is transmitted the K-line must have been in idle. The K-line is set low for 25 ms±1 ms and then high for (50-low time) ms. once the node is awake the tester transmits a Start Communication Request. The ECU responds with a Start Communication positive Response. All information for communication is included in this response.

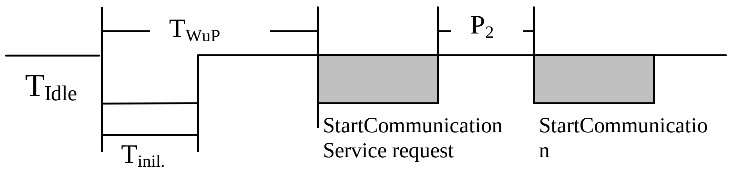


Figure 6.4. Fast initialisation

The initialisation can be functional. In that event arbitration, similar to the CAN arbitration, is applied to avoid collisions. For more detail refer to the SSF 14230-2 specification.

The connection to one node is active until the ECU detects a timeout or the node sends a Stop Communication Positive Response. If the tester does not send a request within $P3_{max}$ the connection is terminated instantly. $P3_{max}$ is typically 5 seconds. In order to re-connect the fast initialisation procedure has to be repeated.

6.5 Converter Considerations

The Keyword 2000 protocol is a serial like protocol operating at a slow pace. The Bluetooth radio will have no problem matching the bit rate 10400 bps on the K-line. Since the Keyword 2000 message can be fairly large (260 bytes) it could be sent over Bluetooth using a DH5 packet, which allow up to 339 bytes of user payload. Alternatively the message can be sent in a L2CAP message, were the L2CAP layer segments the message into appropriate DM1, DH1, DM3 or DH3 packets. On the receiving end the original packet is re-assembled. The data rate will be slightly reduced. On the other hand the probability for successful transmission is increased.

The challenging issue with KWP-2000 is rather the wake up procedure (WUP). When a Tester requests startup the WUP pattern will appear. However, a message has to be sent to the other end of the wireless connection, instructing the Bluebus module to perform the wake up procedure on that local bus. During “wake up” the state changes from idle to logical 0 for 25 ms and then to logical 1 for 25 ms. The bus will not start up until this sequence is present on the bus. To obtain this the UART would have to be set at a baud rate of 40. The UART on the present Bluebus hardware is not adjustable to this slow rate. A solution could be to let a timer control an I/O pin on the processor reconstructing the WUP pattern.

A transparent bridge between KWP-2000 networks is considered possible. The Bluetooth module is fast enough and several packet configurations can be used. A KWP-2000 implementation however does not have high priority. Potential customers Volvo and Berifors have shown greater interest in particularly a RS232 implementation and after that a CAN diagnostics application. For this reason not too much effort has been made to investigate the KWP-2000 in depth.

7 RS-232

7.1 Introduction

RS232 is a serial interface that was developed by today’s Electronic Industries Association (EIA) in the early 60’s. The standard interface use Sub-D 25 or 9 pin connectors or RJ45 connectors. A similar standard is available in Europe developed by the CCITT (Comité Consultatif International de Telegraphique et Telephonique). RS232 is an EIA/TIA norm, which specifies both the mechanical and electrical interface, and is equivalent to the standards V.24/V.28 from CCITT. V.24 is known as the functional description and V.28 is the electrical specifications (Koren 2000). The serial interface was developed for a single purpose, well stated by the title of the RS-232-C Standard:

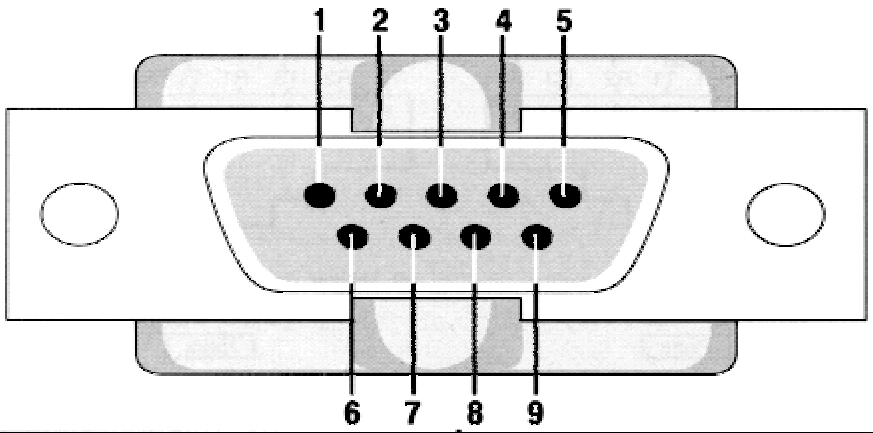
“*Interface Between Data Terminal Equipment and Data Communications Equipment Employing Serial Binary Data Interchange*.”

The device that connects to the interface is called the Data Communications Equipment (DCE) and the device to which it connects (computer for example) is called a Data Terminal Equipment (DTE). It is a single ended interface with one lead for every signal and a ground reference. Personal computers are most often equipped with a Sub-D9 male for serial connections. In that case the interface is referred to as RS232-D as apposed to RS232-C with 25 pin connectors. The entire TIA/EIA-232 standard may be ordered from *Global Engineering Documents.*

Although EIA-232 is still the most common standard for serial communication, the EIA has recently defined successors to EIA-232 called RS-422 and RS-423. The new standards are backward compatible so that RS-232 devices can connect to an RS-422 port.

7.2 Serial Asynchronous operation

Independent channels offer two-way full-duplex communication. The signals are represented with respect to a common ground. Positive 3 to 15 volts represents a logical zero and negative 3 to 15 volts indicate a logical 1, which is the “idle” state. The Sub-D9 pin-out is sketched in figure 7.1 below. Data is transmitted and received on pin two and three, respectively. The “dead area” between +3 and –3 volts is designed to protect against line noise. This interval may vary for different RS-232-like definitions, but the purpose remains.



Pin	Signal	Pin	Signal
1	Data Carrier Detect	6	Data Set Ready
2	Received Data	7	Request to Send
3	Transmitted Data	8	Clear to Send
4	Data Terminal Ready	9	Ring Indicator
5	Signal Ground		

Figure 7.1. Sub-D9 Pin-out

RS232 has numerous handshaking lines, which are primarily used with modems. The Data Set Ready (DSR) indicates to the computer that the modem is turned on. Similarly, Data Terminal Ready (DTR) is an indicator to the modem that the computer is turned on. Data Carrier Detect (DCD) indicates that a good carrier is being received from the remote modem. For control, signals Request to Send (RTS) and Clear to Send (CTS) are used. When a computer wants to transmit data RTS is raised. However, data is not transmitted until the modem confirms by raising CTS. Once transmission in done, RTS is dropped. In most asynchronous situations, RTS and CTS are constantly on throughout the communication session. The serial data is sent one byte at a time. For example consider the case when an ASCII character A is transmitted, see figure 7.2.

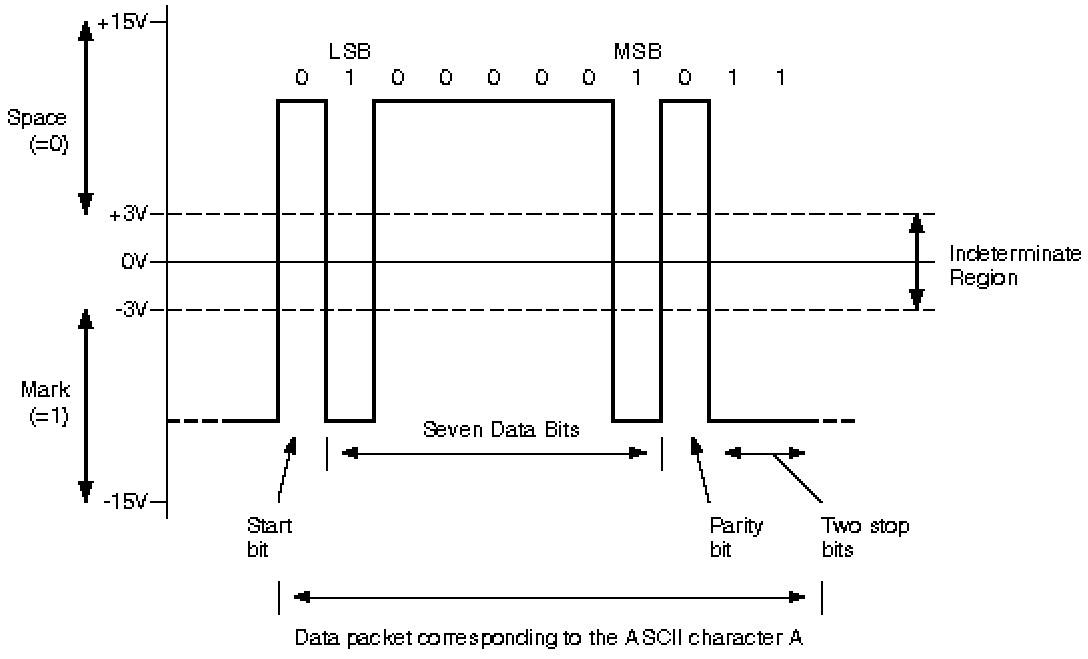


Figure 7.2. One byte of Asynchronous data

The transmitting line (line 3) is at first idling at negative 12 volts. The output signal usually swings between positive and negative 12 volts. The transmission starts with a start bit where a logical zero is put out. Following are seven bits of data representing in this example an A. An extra parity bit is frequently added for purposes of error detection. This extra bit is added to each group of seven bits such that the total number of ones in each block of eight bits is odd. When the total number of one bits in the block is odd, the parity is said to be “odd”. Alternatively, the parity bit could be chosen such that the total number of ones in the block is even, in which case the parity is “even”. Thus, if any single error bit error occurs during transmission this would be detected on the receiving end. Finally the byte is ended with two intermission bits, in the figure referred to as stop bits.

In this thesis project a simple three-line setup will be used for serial communication with a nine pin Sub-D connector. The lines used are numbers two and three for data exchange, and line five is used as common ground, which is mandatory.

7.3 Converter Considerations

The communication between the processor and the Bluetooth module is currently operating at the bit rate 57.6 kbps. The radio interface is configured for a data rate of 108.8 kbps (DM1 packet). This setup works fine in the Bluebus prototype. In general, the bit rate between processor and module must be higher than for the external serial communication and should be higher than for the ACL link since HCI packets and commands add overhead. Otherwise, a continous stream of data might cause serial buffer overflow. Additionaly, higher bit rates will also yield lower overall latency. The Bluetooth module informs the processor of buffer status and if there are no empty buffers, the processor must stop transmission until a buffer becomes available (the Ericsson Bluetooth module has eight transmit buffers).

The DH5 packet yields the maximum possible data rate of 433.9 kbps over the radio interface. However, the maximum usable bit rate for the external RS232 interface is considered to be 230.4 kbps. This should not be a significant shortcoming, PCs seldom operate faster than this and if higher data rates are required, RS232 is probably not the way to go. In the above configuration serial data are sent in large bundles. The stream of data would be somewhat irregular, but this should not cause any implications for the RS232 implementation. For other applications the issue should be kept in mind if there are latency requirements at hand.

8 The Real-Time Operating System

In order to make the development process easier and in order to make the system as flexible as possible, an operating system (OS) of some sort was needed.

The performance of our system is sensitive to timing issues and needs good and easily programmable interrupt handling, as it can be very I/O intensive and will potentially need quite a few different device drivers.

As a comparison, general purpose OS are often large and do not fit our cost and size constraints. They tend to have very flexible but cumbersome models for programming device drivers, and low latency between an interrupt and the start of a task, no matter how high priority it has, can not be guaranteed. (It can be statistically very low, though.)

On the other hand, many real-time operating systems (RTOS) are available with very modest memory and processor requirements. Device drivers for them are simple constructs with little or no abstraction of the actual hardware. This is of course less flexible and makes the application harder to port, but it is also a lot easier to program for. RTOS are almost always optimised for low latency interrupt handling.

Here, an RTOS was clearly the best choice.

8.1 What is an RTOS?

A classical quote referred to in many recent texts on real time computing is:

A real-time system is one in which the correctness of the computations not only depends upon the logical correctness of the computation but also upon the time at which the result is produced. If the timing constraints of the system are not met, system failure is said to have occurred. [Donald Gillies]

This serves well as a definition of the term real-time system but says little of what is needed for an OS to be considered an RTOS. The FAQ (Frequently Asked Questions) for the newsgroup *comp.realtime* (http://www.faqs.org/faqs/realtime-computing/faq/) has this to say on the subject:

1. *A RTOS (Real-Time Operating System) has to be multi-threaded and preemptible.*
2. *The notion of thread priority has to exist as there is for the moment no deadline driven OS.*
3. *The OS has to support predictable thread synchronisation mechanisms*
4. *A system of priority inheritance has to exist*
5. *OS Behaviour should be known*

So the following figures should be clearly given by the RTOS manufacturer:

1. *the interrupt latency (i.e. time from interrupt to task run) : this has to be compatible with application requirements and has to be predictable. This value depends on the number of simultaneous pending interrupts.*
2. *for every system call, the maximum time it takes. It should be predictable and independent from the number of objects in the system;*
3. *the maximum time the OS and drivers mask the interrupts.*

The following points should also be known by the developer:

1. *System Interrupt Levels.*
2. *Device driver IRQ Levels, maximum time they take, etc.*

8.1.1 Our criteria for choosing an RTOS

In deciding what RTOS to use, there are many things to consider. This list is by no means complete, but contains the things that were important in this particular case. Some inspiration for this was derived from Embedded Systems Programming, March 1999 issue and a special issue of Dedicated Systems Magazine titled "RTOS Evaluation", March 2000.

Processor support
The RTOS had to support our processor of choice, preferably several others in order to ease porting the application if needed.

Memory requirements
In order to keep size and cost down, neither the ROM nor RAM memory can be very large.

Hardware support (drivers)
Drivers for different field busses or rather standard integrated circuits for field bus interfaces would be a definite advantage. (For example, in the CAN case, a driver for the Philips SJA1000 would be desirable.)

Standards compliance
An application written for a standard API (such as POSIX) can more easily be moved to a different OS. This reduces the dependency on a particular OS and makes code reuse much more feasible.

Scheduling methods
The choice of scheduling method used in the RTOS. For many RTOS, there is a choice of several different scheduling methods.

Number of priority levels
A high number of priority levels is desirable since it is probable that the system will have many tasks running simultaneously, and with very different demands on latency.

Priority inversion handling
Priority inversion is an event where a task is preventing a higher priority task from running, thus inverting the threads' priorities. It can be bounded or unbounded.
An example of bounded priority inversion is where a low priority task is holding a shared resource that a high priority task wants. This is bounded in time as the high priority task can continue to run as soon as the low priority task releases the resource (the time required for this to happen is short, or there is something seriously wrong with the design of the program).
Unbounded priority inversion can occur in a similar manner; a low priority task is holding a shared resource that a high priority task wants. In the meantime, a middle priority task is preventing the low level task from running.
Here, the middle level task gets the highest effective priority and could continue to run indefinitely.

The first case is rather impossible to avoid in a preemptive multitasking system where there are shared resources, while the second must be avoided (Mason, 1998). If/how this is handled in the RTOS is of great interest.

Interprocess communication / Synchronization
The methods available for interprocess communication and for synchronizing the activity of different tasks should preferably be many. In a large selection it is more probable to find one that fits a particular case.

Interrupt handling
How interrupts are handled are of great interest. Are nested interrupts allowed? Can interrupt handlers have priorities too, or are all other interrupts masked when in an interrupt handler?

Reaction time
How long is the worst-case time between an external event and the start of a task?

Memory protection
Is there memory protection preventing a thread from destroying another threads code/data?

Development tools
What kinds of development environments are available for the RTOS? Ideally, it should be possible to use toolsets from different vendors for development.

Access to source code
Many RTOS are delivered as a precompiled library that is linked with the application, preventing access to the source code. In some cases it is possible to get access to the source for a large sum of money. The ideal here would be free access to the source.

Availability of add-ons
Are there add-ons available for the RTOS? TCP/IP stack and a HTTP-server would be especially interesting to us as these are very time consuming to implement.

Cost
The ideal cost would be zero, of course. The cost for a developer's license could be fairly high, but royalty payments are totally out of the question.

Reputation
A rather big part of choosing any OS or development tool is the reputation it has amongst its users.

8.2 eCos

eCos started out as "Embedded Cygnus Operating System", developed by Cygnus Solutions. When Cygnus was later acquired by Red Hat, Inc. the name was slightly adjusted to "Embedded Configurable Operating System".

As the name suggests, it is geared towards embedded systems. It was also designed to be highly configurable i.e. it is possible to choose how much or which kind of functionality is included in the kernel.

From the beginning it has been an open source operating system and as such, rather unusual in the RTOS world. Open source is a broad term and can mean many different things depending on whom you ask. In this case it is taken to mean that you…

… have free access to the source.
… can change the source as you please.
… can distribute the source further.

For further information, see http://www.opensource.org/

Something to look out for when using open source software is the licensing scheme used. In some cases (as in the GNU Public License or GPL, a very popular licensing scheme), an application including open source code must in itself be open source (or released under the GPL in that particular case).

This could prove to be problematic for companies that prefer to keep the details of their applications secret. Therefore, eCos is released under a special license called 'Red Hat eCos Public License' (RHEPL).

The highlights of this license are:

- The sources are totally free (as in free access and free of charge).
- It is not required to release the source code of any applications using eCos.
- Changes to sources covered by the RHEPL must be made public.
- Such changes will also fall under the RHEPL.
- It is not necessary to obtain a license from Red Hat, nor even to inform them that eCos is being used. It is, however, necessary that a small notice is included in the documentation of the product stating that it uses eCos.

8.2.1 eCos features

It is not easy to describe which features are implemented in eCos, as it is highly configurable. It is said to have more than 200 configuration points and this can be a bit overwhelming at first. The configuration options are organised in a tree-like structure however, which enables control on a high level as well as detailed control when needed. It is further helped by a configuration tools that keeps track of dependencies and incompatibilities between options. The feature list also differs some depending on the capabilities of the underlying hardware platform.

8.2.2 Is eCos an RTOS?

Many operating systems are marketed as real-time operating systems where the term real-time means: “We’ll do this as soon as the OS is done processing things. It’ll be real soon, but we can’t say when exactly.” Examples of this might be Windows NT Embedded or an ordinary Linux distribution with real-time extensions.

This is not the case with eCos, though. It should be quite possible to write applications with it that are deterministic in their behaviour and have defined maximum response times. Priority inversion is handled and the multitasking is preemptive in nature. There are not as many priority levels as one might wish for, but overall eCos should be considered a ‘real’ RTOS.

8.2.3 How well did it fit this application?

As our application is very cost-sensitive, the fact that eCos is license and royalty free is a definite advantage.

However, in some areas it is very clear that eCos is still under development. New features are introduced at a very rapid pace and bugs are fixed at an even more rapid pace. This is of mostly a good thing, but it may take a while for things to settle down and reach a steady state. In addition, at the time when we first tried to port eCos to our platform, the documentation for doing this was in a rather sad state. It has improved a great deal since and porting should prove much easier now, were we to try again.

8.3 eCos in comparison to other RTOS

In order to get a relevant comparison for our application, some RTOS that run on an ARM7 platform are compared in categories that were seen as important during the selection process. The different RTOS are:

eCos
See 8.2.

OSE
Is used in the Ericsson Bluetooth module and seems to be popular for use with ARM7 type microcontrollers. Marketed as a highly fault tolerant OS and is well suited for distributed systems. It is targeted at the telecom industry. There are several variants of OSE, OSE for high availability systems, OSE for DSP and OSE for small to midsize applications. The small to midsize variant, which is the only one that runs on an ARM7 processor, will be referred to as just OSE below.

VxWorks
Has the biggest market share of all RTOS worldwide. It is available for many different platforms, and is also claimed to be highly portable. The whole development system is now referred to as Tornado, VxWorks is the runtime component.

Name	Ecos	OSE	VxWorks
Processor support	ARM7, ARM9, PowerPC, StrongARM, Fujitsu SPARClite, Hitachi SH, 80386, Matsushita MN10300, NEC V800, MIPS, Toshiba TX39	ARM7(TDMI), Infineon C16x, NEC V850, Atmel AVR, Mitsubishi MELPS 7700, 8051, 68HC11	PowerPC, Motorola 68K/CPU32/ColdFire/ MCORE, 80x86 and Pentium, i960, ARM, StrongARM, MIPS, Hitachi SH, SPARC, NEC V8xx, M32 R/D, RAD6000, ST 20, TriCore
Minimum memory requirements	3kB ROM, 1kB RAM	5-6 kB ROM, unknown amount of RAM	15 kB ROM, 5 kB RAM
Scheduling methods	Bitmap, multi-level queue, random	Cyclic, priority based, round robin	Rate monotonic, round robin
Priority levels	Configurable, 64 max	32	256
Priority inversion handling	Priority inheritance		
TCP/IP available	Yes, but it is large	Yes, but as an addon	Yes, but as an addon
Addons available	None really. If a feature is available, it is already included.	Bluetooth host stack, web server, WAP server.	Almost anything imaginable
Standard APIs supported	µITRON, EL/IX (POSIX subset)	POSIX file system	POSIX 1003.1b

Name	Ecos	OSE	VxWorks
Initial cost	$0	n/a	$16500
Royalties	No	Yes	Yes
Vendor	Red Hat	Enea OSE Systems	Wind River Systems

Table 8.1. RTOS comparison

Comments to table 8.1:

- In the case of eCos (and probably OSE also), the minimum memory requirements can't be taken at face value. It is highly unlikely that an application doing any work will get by with a kernel of that size.
- The TCP/IP implementation for eCos is based on the OpenBSD networking stack (http://www.openbsd.org/), which is very complete and well tested. Unfortunately, it is also quite a bit too large for this application as OpenBSD is geared towards server/desktop use where size is a minor issue. It probably can't be used with the Bluebus hardware without adding external RAM.
- The table is a bit sparse. This derives from the fact that some RTOS companies are not too forthcoming when it comes to price and performance information. It is not clear why this should be so, as it can't possibly benefit them in the long run.

8.4 Experiences from the porting effort

Since eCos wasn't available for our particular variant of ARM7, we had to try to port it somehow. It was seen as a difficult but definitely possible task since eCos is already available for several other ARM7-based microcontrollers and the 'only' thing we had to do was fix the startup code and replace some peripheral drivers. The startup part is typically the toughest part in getting any embedded system to run and when that is done, adding the drivers is nowhere near as hard. The better part of a month was spent trying to get eCos to even start and it proved to be impossible to manage within the timeframe of the thesis.

In retrospect it is clear that trying to port eCos before using it in our application was a bit too ambitious and it would have been far better to use a microcontroller for which there was a finished port or possibly to have used a different RTOS altogether. Some advice to give to anyone trying to port an RTOS is:

- Know the processor architecture. It is highly unlikely that the startup code can be written in C alone, and quite a bit of knowledge of assembly language is needed. It is possible to learn as you go along, but it is very hard to debug an application before the hardware platform it runs on is set up properly. Do <u>not</u> try to port an RTOS as your first project on a new architecture.

- Make sure to collect as much documentation as possible about the processor and the RTOS and read it.

- Check errata sheets for the processor and possibly other hardware as well. The main problem when trying to get eCos to run was that the evaluation board reset itself rather randomly (or so it seemed). At the time, we had no idea how to fix this and it was only later that it became clear that this was caused by a hardware bug.

- Use a hardware debugger or even a processor emulator. Debugging by serial port, or even by flashing LEDs, is <u>not</u> recommended.

9 Hardware

A part of the thesis was to develop a hardware platform for our application. The specification of this hardware platform was very vague at the beginning so there was a great degree of freedom in choosing a solution.

9.1 Microcontroller choice

The application would hardly have been possible without a microcontroller. A hardware solution in programmable logic would be theoretically possible but not very practical. In deciding what microcontroller to use, the most important factors were:

Expandability
The microcontroller had to be fairly fast, i.e. it shouldn't just barely manage our application but rather have a respectable amount of spare 'power', so that features can be added without running into performance problems. The same goes for the memory requirements, of course.

I/O capabilities
The microcontroller had to have at least two serial ports built in, preferably more. Built in interfaces/controllers for different fieldbusses (e.g. CAN) would be a major bonus.

Price
Our intended customer, the automotive industry, is very price sensitive and price was therefore an important factor.

Size
The physical size of the microcontroller itself is not a very important factor as most different types are of comparable size, but the amount of support circuitry is (external RAM, flash memory, I/O circuits). It is also often preferable from a cost perspective to minimize the number of external circuits.

Availability
Many electronic components are very hard to come by in smaller quantities these days. The situation is not likely to improve in the near future and controllers had to be checked for availability.

Power consumption
As the device is likely to be battery powered, its current draw should be as low as possible. Many recent microcontrollers can enter an idle state or temporarily shut down unused parts to conserve energy. This is of course a preferable feature.

Development support
It was felt that a reasonably priced evaluation kit had to be available for the microcontroller as it speeds up the software development process. A cheap or even free software development environment would also be ideal.

OS support
The microcontroller should be supported by several operating systems.

Many of these factors contradict each other, so the microcontroller chosen needn't necessarily be the best in all categories.

During the first stages of the hardware development, mainly two different microcontrollers (or rather two different types of microcontroller) were considered:

- An Infineon C167-type microcontroller, probably the C167CR. The advantages of this choice would have been that a development system was already available at Tritech and also C167 variants with a built in CAN interface are available.

- An ARM7-based microcontroller. The ARM7 is a 32-bit RISC core developed by ARM Limited (http://www.arm.com). It is licensed to other companies who then add peripherals and memory interfaces to it. Therefore, there are many variants available for applications where I/O demands differ and they are also available in many different speed grades from about 20 up to 150Mips.
  There is a large selection of development tools for ARM7-based microcontrollers and there are evaluation boards available from many different vendors.

The Bluetooth module from Ericsson (and indeed most other Bluetooth solutions from other vendors) is built around an ARM7 core and in order to make it possible to migrate the application to a one-chip solution in the future, it was best to choose a code compatible processor. We were also concerned that the C167 parts would be a little too slow to cope with future applications.

As mentioned above, there are quite a lot of different microcontrollers that have an ARM7 core. All have relatively low power consumption, comparable size and most of them fulfil the I/O requirements. Therefore, the main factors in deciding which one to use were price, availability and development/OS support.

The choice fell on an Atmel AT91R40807.

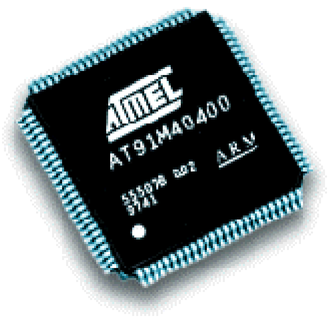


Figure 9.1. The AT91M40400
(The 40400 is very similar to the 40807 and was used in the evaluation kit for this entire family of controllers.)

The Atmel AT91R40807 has 8kB + 128kB internal RAM, a hardware multiplier, two serial ports, three 16-bit timers, one watchdog timer, 32 general purpose I/O-lines, 8-level interrupt controller and a very configurable external memory interface. It is available in a TQFP-100 package, which occupies a board area of approximately 16x16mm. The power consumption depends highly on how busy the processor is and what peripherals are used at the moment, but a fair estimate would be 4,7mW/MHz maximum (Atmel, AT91R40807 Electrical Characteristics).
At 33MHz, this would come to around 150mW or 45mA current draw from a 3,3V rail. The clock to the processor core and the peripherals can be shut down when they aren’t needed, which can drastically decrease the power consumption.

The AT91R40807 is based on a variant of the ARM7 core, ARM7TDMI. This features a strategy called THUMB, which makes it possible for the processor to switch between a normal 32-bit and a compact 16-bit instruction set. This technique reduces the code size to about 65% of normal, but also decreases performance when running from the internal 32-bit memory. When running from slower external 16-bit memory, performance is actually increased when using the THUMB instruction set, as the average time to fetch a new instruction is reduced by almost half. Both instruction sets can be used in different parts of the same program but there is a minor time penalty for switching between them.

This controller fits the functional demands nicely, but is perhaps a bit expensive. In addition, internal flash memory would have been better. Another part in the AT91 series, the AT91FR4081, has internal RAM and internal flash but was not available at the time.

9.2 The prototype

An absolute must in the thesis work was to develop a prototype and the best way to achieve this was by purchasing already working hardware so that the development effort could be focused on getting the software right first.

9.2.1 Atmel AT91EB01

The AT91EB01 is a kit for evaluation of Atmel's AT91M40400 family of microcontrollers. It is available from many different vendors, e.g. Acte and Hatteland in Sweden as well many foreign companies.

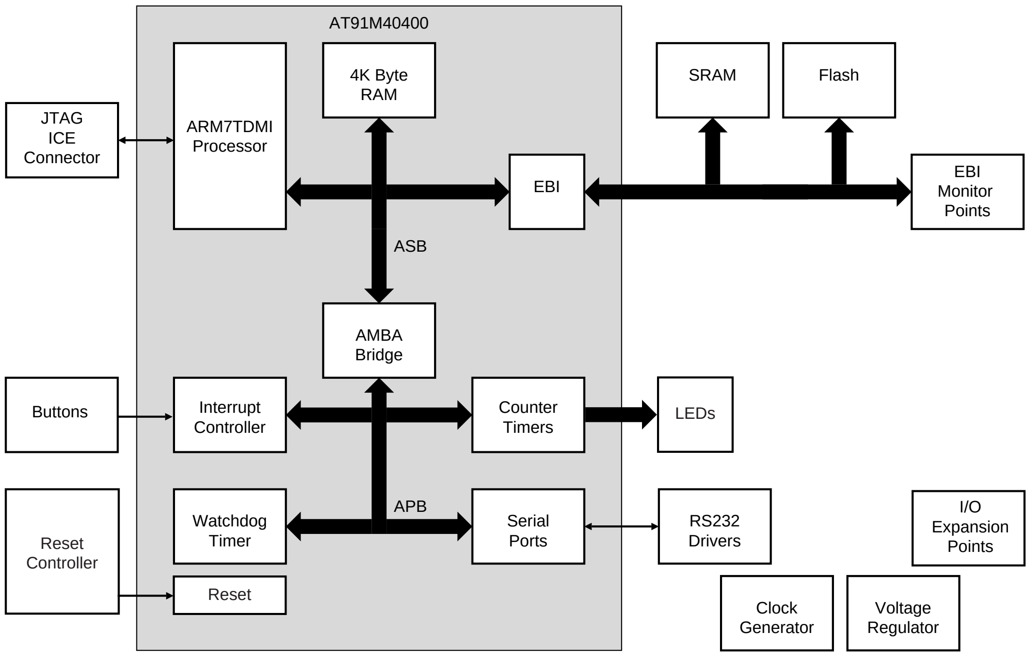


Figure 9.2. AT91EB01 block diagram

It has two serial ports, 512kB 16-bit SRAM (upgradeable to 2048kB), 128kB 16-bit Flash (of which 64kB is available for user software), 20-pin connector for connecting a JTAG debugger. It also has an expansion bus connector that makes it possible to develop add-on cards for more I/O, memory etc.

Furthermore, it has built in monitor software that makes it possible to download and debug programs via one of the onboard serial ports. This is of course a very cheap and sometimes quite adequate solution and all that is needed on the host platform is a free serial port. It was not very good in this case as both the on board serial ports were needed for the application, making debugging impossible. It was therefore only good for downloading new code. In the beginning when source debugging was an absolute must, one serial port had to be simulated.
Since then, we have purchased a debugger that connects via JTAG to a built in debug cell in the processor. This has sped up the development process a great deal, board startup routines can now be debugged and downloading of new code is now accomplished in under one second.

Unfortunately, the AT91M40400 that is on our two evaluation boards is of an early silicon revision and hence has a few bugs. This was not obvious from reading the user manual and one bug cost us at least one week, probably much more, in debugging time. First for finding out that there was indeed a bug in the hardware and second to find a way to get around it.
Since this bug was unknown at the time, the porting effort also suffered and time was lost assuming all the problems resulted from programming errors.

9.2.2 Ericsson EBSK

The Ericsson Bluetooth Starter Kit is basically an ROK 101 007/1 Bluetooth module equipped with all possible physical connectors and interfaces. It is intended as a relatively low-cost tool for developing Bluetooth host applications and can be purchased from Ericsson Microelectronics.

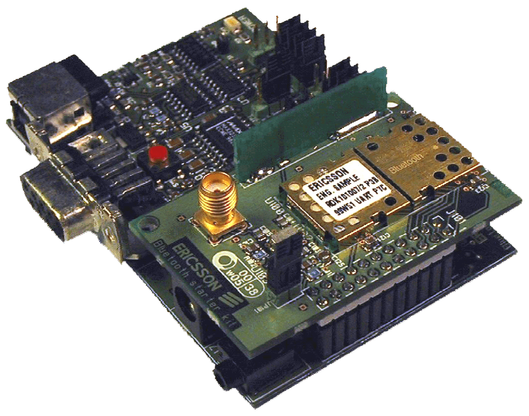


Figure 9.3. Ericsson Bluetooth evaluation kit

The interfaces used to control the EBSK are either RS-232 or USB and the connectors for these are located on the bottom board together with an audio coder/decoder (codec) for voice communication, jumpers for configuration, the power supply and also some glue logic. The top board is connected to this via a pin header and houses the Bluetooth module and antenna. An external antenna connector is also available.

9.3 Bluebus hardware

The actual hardware to be used in production of the Bluebus device. Descriptions of the hardware will be in the form of an overview, since this is somewhat classified.

9.3.1 Block schematic

The schematic very much resembles the prototype (Figure 10.2). This is no coincidence, as there aren't many other ways to connect the different parts together. The main differences are the fact that the microcontroller has RAM built in and no RS-232 level translators are needed for the serial link between to Bluetooth module and the controller.

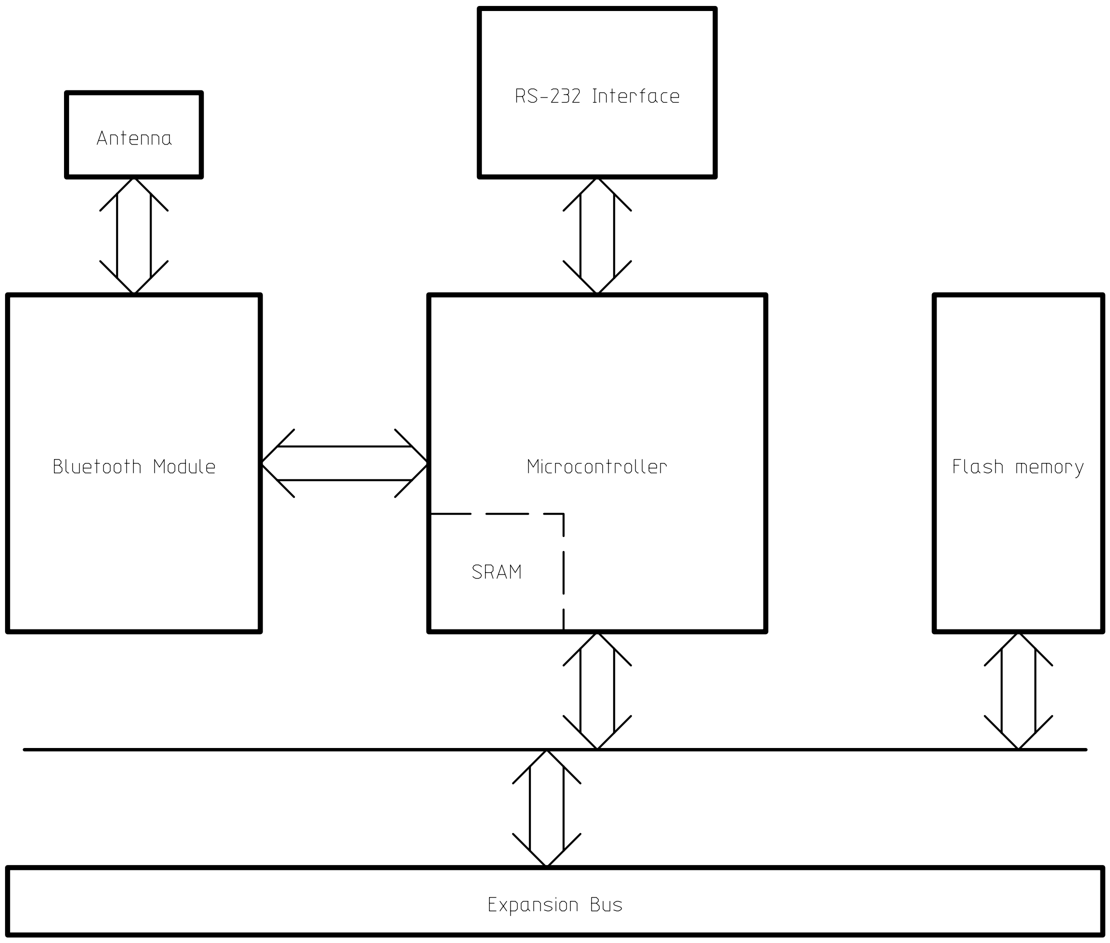


Figure 9.4. Bluebus hardware block schematic

9.3.2 Physical Layout

The size of the card was chosen, rather arbitrarily, as the same size as a normal calling card, or 90*55mm. It may seem like a strange way to design, but it has been very efficient for describing the hardware as it is a size that everyone can relate to.

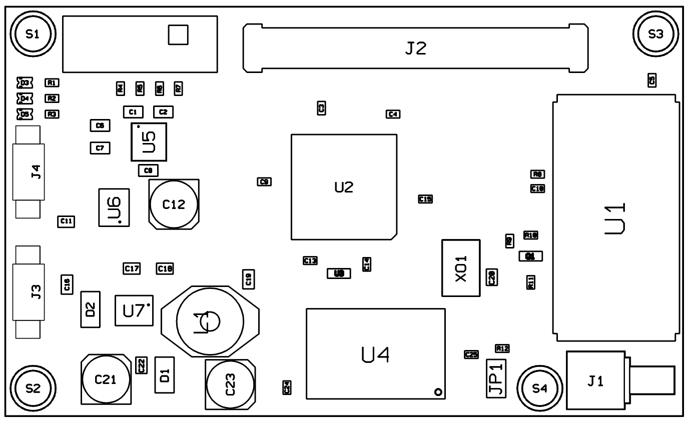


Figure 9.5. Bluebus board/component outline (actual size)

9.4 Discussion and experiences

So, how well does the hardware implementation fit the specification?
Rather well, which is hardly surprising as we wrote it.

One experience from this is that things take more time. The hardware design itself did not necessarily take longer time than planned but since the software development took up all available time for several months, the hardware design had to be postponed.

Another is to always check availability of components. The current situation with regards to this is simply horrible with lead times of up to 30 weeks for one of the components used. The solution will most likely be to redesign that part of the circuit.

10 Prototype Software

In this paragraph, the software structure when using Bluetooth as means of transportation will be described. The prototype software consists of several layers, which comply with the suggested Bluetooth architecture described in the Bluetooth specification. The layer structure is shown in figure 10.1.

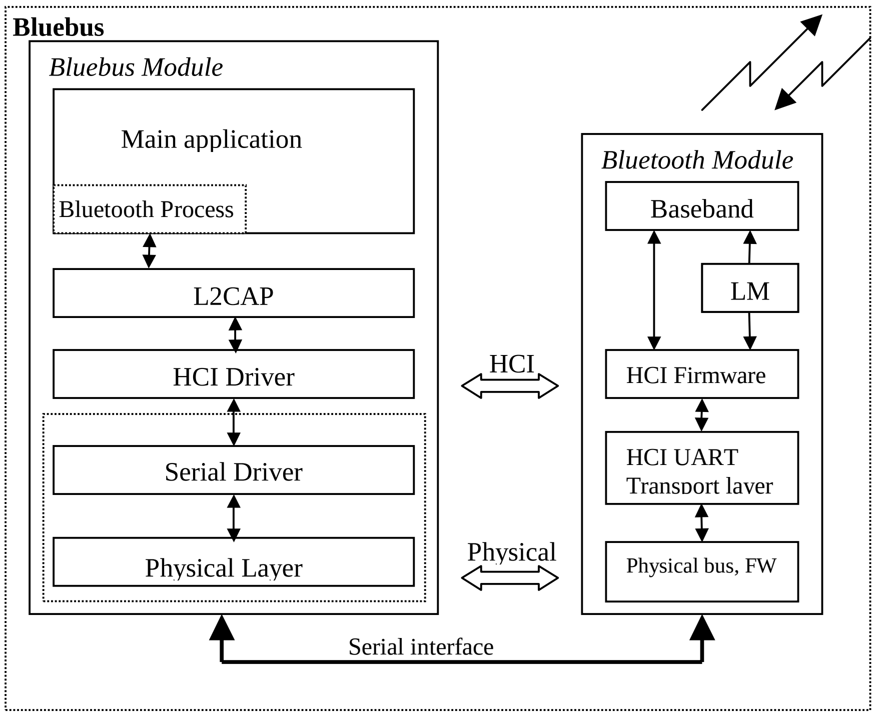


Figure 10.1. Software architecture with Bluetooth

The left box in the figure represents the Bluebus module and the right box represents the Bluetooth module. The two are interconnected via a serial interface between two UARTs. The development prototype consists of two connected evaluation boards and in block diagram form Bluebus could be sketched as follows:

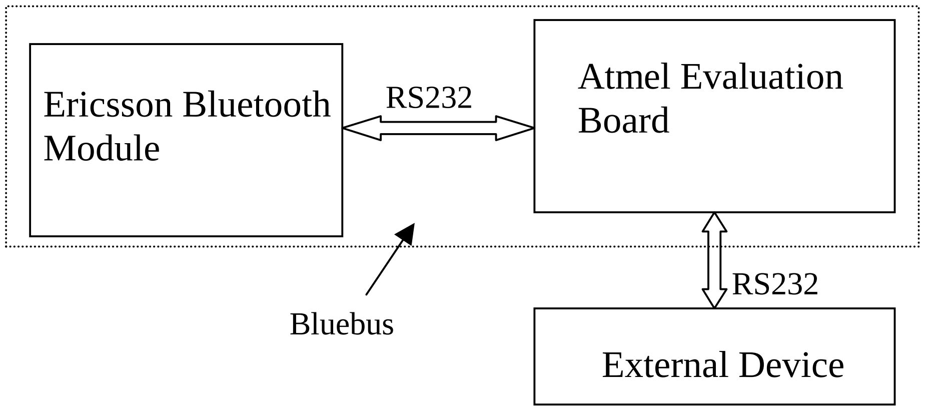


Figure 10.2. Block diagram of development prototype

Some source code for the different Bluetooth stack layers is included in the Bluetooth Starter kit from Ericsson. However, the code is written in C++, is not complete and would have to be adapted, to quite a large extent, to fit into this project. In order to govern proper understanding and to have the same software language throughout the system, the software for the project was mostly written in C. Some parts where precise control of the hardware is needed, such as the startup code and a few peripheral drivers, are written in ARM7 assembly language.

10.1 Bluebus in the OSI Model

The International Standards Organization (ISO) has developed the Open Systems Interconnection (OSI) networking suite. The model is mostly used as a reference model, which, as shown in figure 10.3, is divided into seven layers.

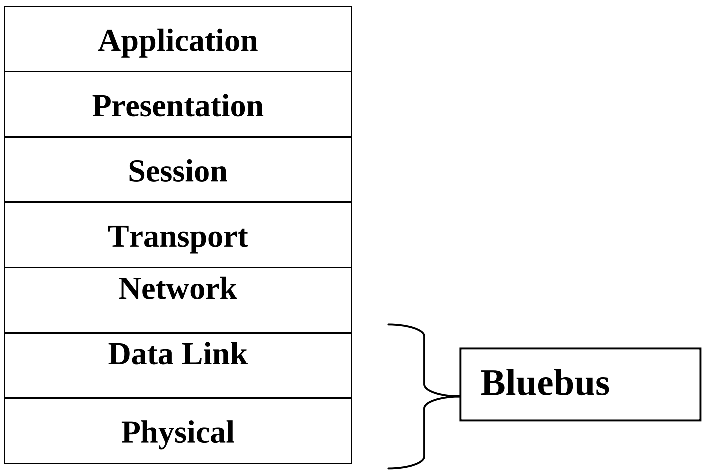


Figure 10.3. The ISO/OSI model

The model is sometimes hard to use when defining how a product fits into the model. It may not have been considered at all during the design phase and software layers may later be interpreted to fit into more than one of the OSI layers. However, the model offers a convenient standard for describing a software design.

Bluebus would, in the OSI model, fit into the two lower layers, namely the data link and physical layer. The data link layer describes the logical organization of data bits transmitted on a particular medium. The physical layer describes the physical properties of the various communications media, as well as the electrical properties and interpretation of the exchanged signals.

10.2 Remarks and Deviations

The actual code for this project will not be included in this report since the employer has stated this as classified material.

The Bluetooth specification specifies a bundle of HCI commands, which are to be implemented in firmware from Bluetooth module suppliers. However, in the early version of the Ericsson ROK 101 007/1 Bluetooth module the firmware only include partitions of the specified commands. The commands used in this thesis are listed in appendix B and firmware implemented commands are specified in (Ericsson, 2000, pp. 5-12).

The highest layer for the project was supposed to be the HCI layer. Portions of the L2CAP layer had to added though. In (Ericsson, 2000, pp.4) it is stated that all ACL data that is sent in HCI data packets must have L2CAP format. For this reason functions sending and receiving L2CAP packets had to be implemented.

As an additional remark it should be noted that the parameter, Allow_Role_Switch, in the HCI command, Create_Connection is not included in the Ericsson firmware as specified in the Bluetooth specification 1.0B. Thus, this parameter has to be left out for proper functionality. Further shortcomings do exist; please refer to (Ericsson, 2000).

10.3 Development Tools

Two PCs and the following tools were used during the development work:

Compiler:	GNU gcc 2.9.2
Assembler:	GNU as (development snapshot from 20000412)
Linker:	GNU ld 2.10.90
Make program:	GNU make 3.77
Debugger:	GNU gdb (development snapshot from 20000428)
Editor:	Emacs for Windows NT version 20.6
Version handler:	Microsoft Visual Source Safe

10.4 HCI Driver

The Bluetooth module is solely controlled using HCI commands. To send and receive data, HCI functions are used indirectly through the higher L2CAP layer. All names in the HCI driver have the same names as in the specification (SIG, 1999) and the same order of parameters is used. The most essential functions have been implemented and all functions belonging to the HCI layer start with HCI.

10.4.1 HCI Commands

When a HCI function is called it checks for parameter errors before the command or data is passed on to the transport layer. The functions return a boolean value, if the packet was passed along successfully the functions return true, otherwise false.

As an example, consider the command, HCI_Create_Connection. The command is used to create a connection to a device with a known Bluetooth address. The exact meaning of function parameters can be found in SIG 1999, page 542 - 741. As a response, the host controller will return specific events depending on issued command. Each command has a set of expected returning events.

10.4.2 HCI Events

Events are received from the HCI UART transport layer and function parameters are copied into the event parameters. The transport layer is responsible for loading the right information into the proper event. In the example, the host is expecting a command status event, which is returned as soon as the controller receives the create connection command. This event informs the host of command status, which is expected to be 0x00 (command pending). Other status values indicate an error and (SIG 1999,pp. 745, table 6.1) lists associated error codes. The other event parameters inform the host of number of packets it is allowed to send to the host controller at the time and what command caused this event. Finally, a connection complete event including event parameters is sent from the host controller to the host indicating whether the command was successful or not.

10.5 HCI UART Transport Layer

As mentioned in section 4.8.2, there are four kinds of HCI packets: The HCI command packet, HCI event packet, HCI ACL data packet and HCI SCO data packet. However, HCI does not provide the ability to differentiate between the four packets. For this reason, an 8-bit indicator is appended to the beginning of the HCI packet when it is sent over the transport layer. The indicators are listed in table 10.1.

HCI packet type	HCI packet indicator
HCI Command Packet	0x01
HCI ACL Data Packet	0x02
HCI SCO Data Packet	0x03
HCI Event Packet	0x04

Table 10.1. HCI packet indicator

The transport layer adds packet indicators to the HCI commands or data packets coming from the HCI driver, and passes the information on to the physical layer. In the opposite direction, the indicators are removed before being passed on to the

HCI driver (this procedure is valid for the HCI UART Transport Layer, see SIG 1999, part H: 4).

In the Bluetooth specification a difference is made between the HCI UART transport layer and the HCI RS232 transport layer. They are very similar, but the RS232 transport layer provides means for synchronization and error correction. The HCI UART transport layer assumes that the communication is error free. In the Bluebus case, this serial interface connects two UARTs on the same PCB with short trace lengths and the probability for errors is very low. Hence, the Bluetooth HCI UART transport layer will be used according to the specification (SIG 1999, part H: 4) and layered in the serial driver field, as shown in figure 10.1.

10.6 Main Program Structure

The Bluebus system consists of a number of processes. Originally, these processes were supposed to be handled by the real-time operating system, eCos.
Since eCos was not ported for the Atmel evaluation board, and this work proved to be much too extensive for the scope of this thesis, a kind of scheduling had to be implemented by hand. Some operations involve the system waiting for a command response. If the processor were tied up with this operation alone, it might miss some other important event. For this reason it is important for a process to be able to return control to the main application, allowing the processor to handle multiple operations at a time. In order to achieve this, the processes are constructed as state machines. Each time a process returns the control to the main application the state is remembered and operations will be continued at the same place the next time processor resources are available. All processes are stepped through in this manner in an infinite while loop:

```
while(running == TRUE) {

     if(inquiry_requested == TRUE)
         Inquiry();

     if(connection_requested == TRUE)
         Create_Connection();

     Send_Data();
     Receive_Data();

} /* while */
```

10.6.1 The Inquiry Process

The inquiry process is entered when Bluebus wishes to find new unidentified devices within range. The state machine is shown in figure 10.4 below.

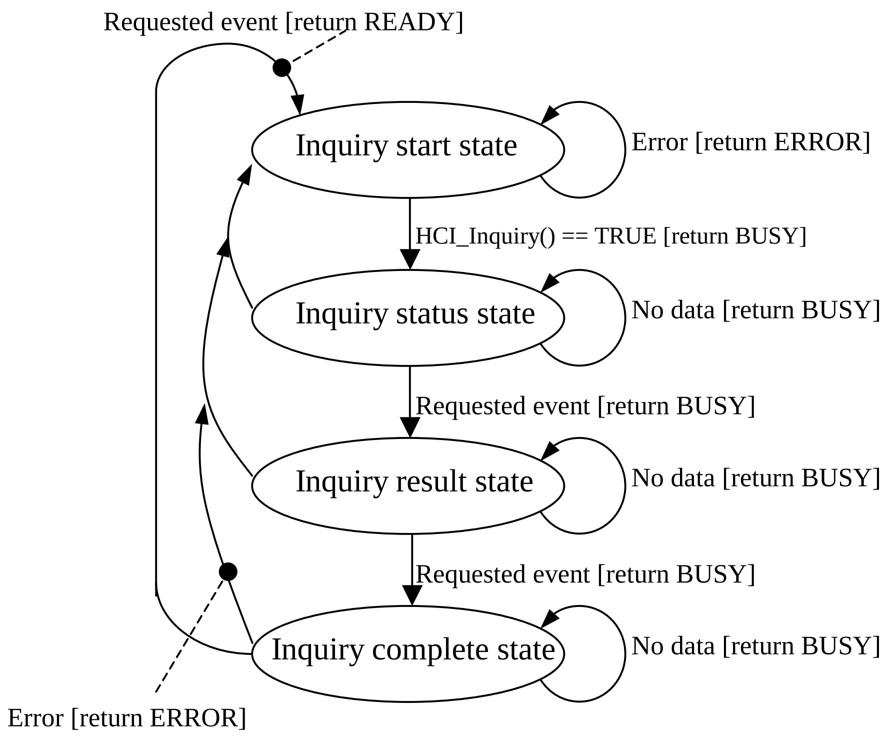


Figure 10.4. Inquiry state machine

When entering the start of the process the HCI command, HCI_Inquiry() is issued. The inquiry is finished when three associated events are returned from the host controller to the host. The higher layer is informed of the state machine status each time it releases control. The possible return values are: ERROR, BUSY, or READY. Another Inquiry attempt cannot be made until the present process is ready or an error occurs and the state is reset to Inquiry start state. If the process is processing, BUSY is returned implying that once processor resources are available the process should be allowed to continue where it previously left off.

10.6.2 The Create Connection Process

If a connection is required the create connection state machine is entered. The functionality is similar to that of the inquiry state machine. Figure 10.5 below displays the situation.

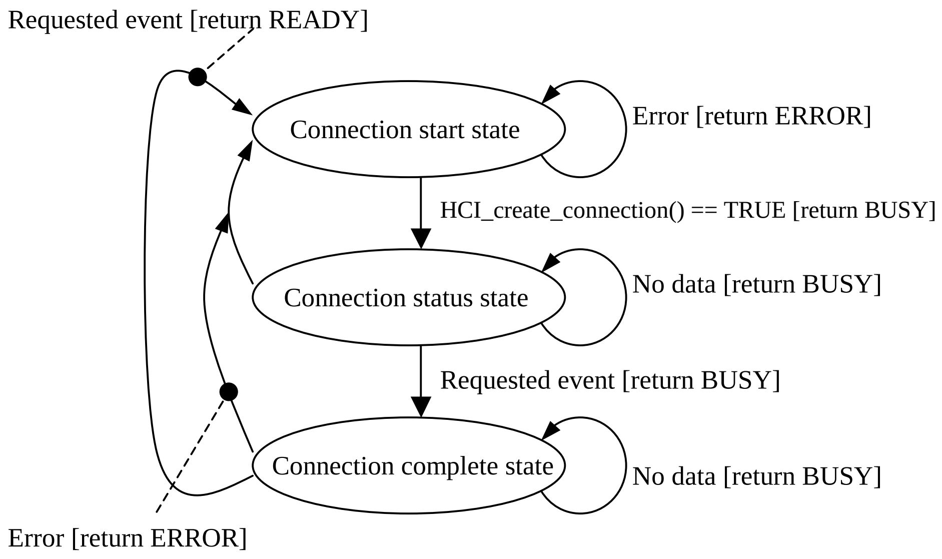

Requested event [return READY]
Connection start state
Error [return ERROR]
HCI_create_connection() == TRUE [return BUSY]
Connection status state
No data [return BUSY]
Requested event [return BUSY]
Connection complete state
No data [return BUSY]
Error [return ERROR]

Figure 10.5. Create connection state machine

As the state machine is entered, the HCI command HCI_create_connection is issued. The command has two associated events to it: connection status and connection complete event, sent from the host controller to the host.

10.6.3 Data Handling

On the Atmel development board there are two RS232 serial ports, both operating with interrupt driven software. Each time a byte from an external device has been received by the serial port (refer to figure 10.2), an interrupt is generated. The interrupt routine stores the received byte in a ring buffer, which the main application then checks periodically for available data. When there are one or more bytes available, the L2CAP output function is called to send the information through all the underlying layers and over the air to a receiving Bluetooth module. If necessary, the L2CAP output function breaks the information into adequate sizes depending on which ACL data packet is used for transmission. The packet type (DM1, DH1, DM5) is determined during the connection phase, but can also be adjusted during the life of the connection. In the opposite direction incoming ACL data packets over the air are transmitted via the serial interface to the Atmel board, were it is temporarily stored in the incoming ring buffer. The received ACL packets are then sent up to the L2CAP layer, were a function assembles the smaller ACL data packets into the original message sent by a remote device. The assembled data is then sent, passing the outgoing ring buffer, to the external serial port. The Send_Data() function handles the case when external serial data is transmitted over the air and Receive_Data() manages data coming in from a remote Bluetooth device and outputs it via the external serial port. Both processes work as state machines, in the same manner as Inquiry() and Create_Connection().

11 Test Procedure and Response Time

The first important implementation step was to create a Bluetooth ACL connection with project designed software. One Bluetooth development board was connected to a PC (RS232). This module was controlled by the Ericsson GUI application and was configured as a slave. The counterpart, the Bluebus prototype, was set up to execute inquiry and create connection, i.e. to become the master. Since the GUI responds with a message for a successful connection, connect procedure in the Bluebus software was confirmed. With a working connection, the next obvious step was to transmit data. The same setup was used and successfully transmitted data over the ACL link is displayed on the GUI. Endurance tests were made transmitting data to the GUI overnight, verifying a sustainable connection.

From this point on the goal was to exchange remote serial data over the wireless link between two Bluebus units. Remote serial data was transmitted via the COM port of a PC using a terminal program. The data was sent over the air and the received data was forwarded to the outgoing serial port also connected to a PC running the same terminal program. As of now, serial data can be wirelessly exchanged both ways between two PCs. Attempts to send files have been made, but so far without success. The probable reason for this is that data is sent without any consideration of buffer status in the Bluetooth module. Most likely buffer overflow occurs in the Bluetooth module. The result is that the communication between the module and the processor is halted.

To verify response time for different packet type configurations a Tektronix TLA 704 logic analyzer was used. Two PCs, both running a terminal program (Tera Term Pro v2.3), were connected via a Bluebus bridge. The test is simply conducted by sending one character from terminal A to terminal B. Two probes from the logic analyser are connected, one on the pin receiving data from the PC and another probe connected to the transmit pin sending the character to terminal B. The setup is sketched in figure 11.1.

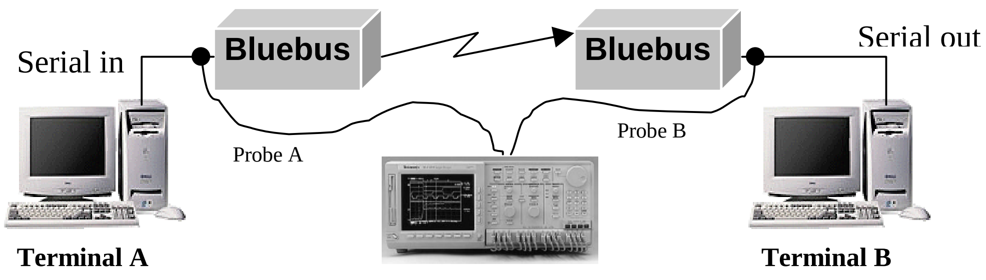


Figure 11.1. Response time test setup

When the first bit appears at the incoming serial port on Bluebus a timer in the logic analyser is triggered. The timer is stopped when the data ha propagated through and appears on the outgoing serial port of the receiving Bluebus unit. Hence, response time is measured. One such experiment is plotted in figure 11.2 below, where the status of the two lines is displayed. The lower of the two graphs show when a character is received from terminal A and the upper displays when the transmission from Bluebus to terminal B begins.

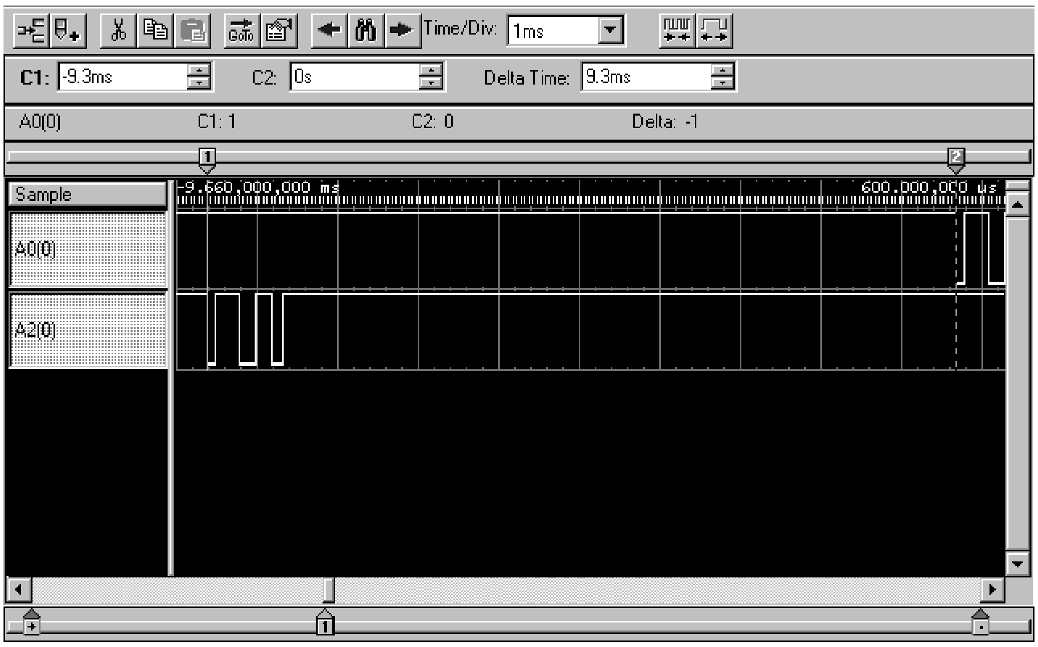


Figure 11.2. Response measured with logic analyzer (DM1).

The test was carried out for three cases with the packet type set to DM1, DM3 and DM5. During the test, the packet type was held constant. The DH packets were not tested since they cover the same amount of time over the air as the corresponding DM packet.

Theoretically the response time consists of mainly two components, the time for the UART to transfer the data from the host processor to the Bluetooth module, times two, taking the receiver into account and the time over the air. However, the time from that the byte is detected on the receive line until the data is entirely received by the processor has to be accounted for since the computer bit rate is only 9600 bps. Processor instruction time is considered insignificant and is not included in this estimation.

An excerpt from the *output_data* function shows how data is transmitted to the Bluetooth module. Each appearance of tx_char represents one byte sent.

```
tx_char((uint8) 0x02);
tx_char((uint8) Connection_Handle);
temp = (uint8)(Connection_Handle>>8) & 0x0f;
temp |= ((Packet_Boundary_Flag<<4) & 0x30);
temp |= ((Broadcast_Flag<<6) & 0xc0);
tx_char(temp);

tx_char((uint8) Length_HCI_Payload);
tx_char(((uint8)((Length_HCI_Payload)>>8)));

for(i=0; i < Length_HCI_Payload; i++)
    tx_char(Data[i]);
```

The transmitted data (`tx_char(Data[i])`) include the L2CAP header, which is 4 bytes long. Thus, the total number of bytes to be transmitted from the processor to the Bluetooth module is 10 bytes.

The serial interface between module and processor is operating at 57600 baud. 11 bits represent each byte: One start bit, eight data bits, one stop bit and one intermission bit. The DM1 packet is a one slotted packet. The corresponding time is 625 microseconds over the radio interface. In summary the response time when using the DM1 packet would be:

$$T_{response} = \underbrace{[(10 * 11)\text{ bits} * (1/\ 57600)\text{ s/bit}] *2}_{\text{Time elapsed for serial communication between processor and Bluetooth module.}} + \underbrace{(11/9600)}_{\text{Time elapsed from when the first bit enters Bluebus till the entire byte is received.}} + \underbrace{625\ \mu s}_{\text{Time over the air.}} = 5.59\text{ ms}$$

The exact same procedure applies for the other two cases, when DM3 and DM5 packets are used. Practically a series of at least thirty response measures were made. The response time was averaged and the result presented in table 11.1.

Packet Type	Theory	Practice (on average)
DM1	5.59ms	8.98 ms

Table 11.1. Response time result

The practical value show some deviation from the theoretical. The deviation probably depends on latency in the Bluetooth link, but this has not been verified. From these tests it is obvious that the response time suffers from the relatively slow serial interface. For a CAN implementation the bit rate would have to be increased. Using the an USB interface instead of the HCI UART transport layer would not add any particular value, since the Bluetooth radio will be the limiting factor. An even better solution would be to achieve a one-processor solution where both the implementation and the Bluetooth stack are handled by the same processor. As of now this solution is not supported by the Ericsson Bluetooth module.

12 Conclusions

The core of this thesis project was to understand and use the Bluetooth technology to enable data transfer between two networks over a wireless link. An essential part was to implement a working prototype, in both hardware and software. CAN, KWP-2000 and RS232 were investigated to find out if these standards are suitable for a wireless implementation. The serial protocols RS232 and KWP-2000 were found to be well suited to be incorporated in Bluebus. The CAN protocol is going to be more challenging to incorporate. It is considered possible. However, the CAN acknowledgement procedure makes it impossible to achieve full transparency. In an asymmetric configuration using the DH5 packet (723.2 kbps) a CAN bridge implementation operation at 500 kbps is achievable. Messages will be bridged, but with some delay. This configuration could be used for example for a log application where traffic is essentially traveling in one direction.

Initial work included choosing hardware and writing necessary parts of the Bluetooth software stack. In this project the parts of the L2CAP layer that handle segmentation and re-assembly were written. Large portions the Host Controller Interface and the entire UART transport layer were implemented, as described in the Bluetooth specification. It is recommended that data transfer be done in a generic packet format as proposed in this report. The idea of adding additional network standards by writing new driver routines will make the product conveniently expandable. As a result the product may be tailor made, with respect to hardware and drivers, to meet customer needs. The Bluebus prototype as of now consists of two development boards. The prototype is capable of creating a point-to point connection between two Bluebus units. The link is then used as a wireless serial interface, i.e. a virtual RS232 link. Schematics and a PCB layout for the production prototype have been designed and a circuit board has been manufactured, although lack of components has prevented testing so far. The product “shall” requirements, as stated in the specification, have consequently been satisfied. Low power consuming components have been chosen. Apart from that, all the “should requirements” are yet to be fulfilled.

Bluetooth is a technology that has great potential to become a recognized world wide standard. Major telecommunication companies such as Ericsson, Nokia, Toshiba and the software company Microsoft are supporting the technology. Bluetooth offers a flexibility that cables and for example infrared technology could never hope to achieve. Cable connections require connectors and sometimes a mishmash of harnesses. For example, IrDA is wireless and can even exchange data at a higher pace than Bluetooth, but only works well over short distances. It is also essential that there is a line of sight between the transmitter and the receiver. The Bluetooth specification 1.0B presents an impressive functionality. However at this point only portions of this functionality is available. For Bluetooth to succeed the manufacturers need to implement support for piconet configurations, service discovery possibilities where devices automatically can connect ad hoc and the essential software stack need to be made available for product developers. In a lot of applications the bit rate of 1 Mbit/s and range of 10 meters may not be enough. Even if all these shortcomings are overcome it is essential that modules are made available for large-scale production. The price for Bluetooth modules needs to decrease substantially for companies to adopt the technology and for end users to be able to afford Bluetooth products.

This thesis project involved lots of “hands on”, which made the time schedule most sensitive for problems with hardware and late deliveries of components. On the other hand the fact that the project was of a practical nature made the learning experience even more dramatic. A critical element was to acquire the Bluetooth module. After weeks of repeated phone calls to the supplier, urging them to deliver, the modules were delivered after twice the promised delivery time. Problems with delays of getting modules to the market seem to be a common difficulty for the Bluetooth module suppliers. Incorporating the RTOS, eCos, on the system proved to be a complicated task. Usually one would choose a processor and development board with support for the intended RTOS, or the other way around. For this project the chosen processor and evaluation board was found to be well suited for Bluebus, but was not ported for eCos. Therefore, effort was made to port eCos for the evaluation board. The attempt was partially successful, but we never made it all the way. Instead the program tasks had to be managed by Bluebus software. As always with software development lots of time was spent debugging, not only our on code but also figuring out shortcomings in the delivered hardware. Two major obstacles were first figuring out the fact that the Ericsson Bluetooth module could only send and receive data in L2CAP format, even though the standard suggested that data could be transmitted in HCI format. Secondly, the processor on the Atmel evaluation board turned out to contain an early version of the silicon, which contains bugs related to interrupt handling.

The development of Bluebus continues as a Tritech project. Additional software and hardware support will in a first step be added for CAN and KWP-2000 will be implemented upon customer request. Moreover, eCos needs to be ported for the AT91R40807 processor in order to handle more complicated matters than RS232 traffic. In conclusion this has been an interesting and successful thesis project.

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APPENDIX

APPENDIX A

Abbreviations

Abbreviations

ACK	Acknowledgement
ACL link	Asynchronous Connection-Less link
AM_ADDR	Active Member Address, 3-bit number to each active slave in a piconet
API	Application Programming Interface
ARQ	Automatic Repeat reQuest
BD_ADDR	Bluetooth Device Address
BER	Bit Error Rate
bps	Bits per second
BT	Bluetooth
CAC	Channel Access Code
CAN	Controller Area Network
COF	Ciphering Offset
CRC	Cyclic Redundancy Check
CTS	Clear To Send
DAC	Device Access Code
DH	Data High rate
DIAC	Dedicated Inquiry Access Code
DLC	Data Length Code
DM	Data Medium rate
ECU	Electrical Control Unit
FEC	Forward Error Correction code
FHS	Frequency Hop Synchronization
Flash	Non-volatile memory that is electrically erasable
FW	Firmware
GIAC	General Inquiry Access Code
GUI	Graphical User Interface
HEC	Header Error Check
HCI	Host Controller Interface
HID	Human Interface Device
HW	Hardware
IAC	Inquiry Access Code
IDE	Identifier Extension Bit

IEEE	Institute of Electronic and Electrical Engineering
ISM	Industrial, Scientific, Medical
JTAG	Joint Test Access Group. Commonly used name for IEEE 1149.1
KWP	Key Word Protocol
L2CAP	Logical Link Control and Adaptation Layer
LAP	Lower Address Part
LED	Light Emitting Diode
L_CH	Logical Channel
LC	Link Control
LM	Link Manager
LMP	Link Manager Protocol
LSB	Least Significant Bit
MAC	Medium Access Control (sub-layer of the data link layer)
MMI	Man Machine Interface
MSB	Most Significant Bit
NAK	Negative Acknowledgement
NAP	Non-significant Address Part
PCB	Printed Circuit Board
PIN	Personal Identification Number
RAND	Random number
REC	Receiver Error Counter
RF	Radio Frequency
RFCOMM	Serial Cable Emulation protocol based on ETSI TS 07.10.
RS-232	Standard for serial communication
RTR bit	Remote Transmission Request bit
RTS	Request To Send
RXD	Receive Data
SCO	Synchronous Connection-Oriented link
SEQN	Sequential Numbering scheme
SIG	Special Interest Group
SOF bit	Start Of Frame bit
SRR bit	Substitute Remote Request bit
SW	Software
TCP/IP	Transport Control Protocol/ Internet protocol
TDD	Time-Division Duplex

TEC	Transmitter Error Counter
TQFP	Thin Quad Flat Pack
TXD	Transmit Data
UA	User Asynchronous
UI	User Isochronous
UAP	Upper Address Part
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus

APPENDIX B

HCI COMMANDS AND EVENTS

Implemented HCI Commands and Events

A brief description is given of each HCI command and event used in this thesis project. A full definition is given in SIG 1999, part H:1. At the end of the appendix there is a list of error codes submitted, which is also extracted from the Bluetooth specification. This list gives a good idea of which the most essential commands are, in a Bluetooth implementation.

HCI Commands

Inquiry
The Inquiry command will cause the Bluetooth device to enter Inquiry Mode. Inquiry Mode is used to discovery other nearby Bluetooth devices.

Inquiry_Cancel
The Inquiry_Cancel command will cause the Blue-tooth device to stop the current Inquiry if the Bluetooth device is in Inquiry Mode.

Create_Connection
The Create_Connection command will cause the link manager to create an ACL connection to the Bluetooth device with the BD_ADDR specified by the command parameters.

Disconnect
The Disconnect command is used to terminate an existing connection.

Accept_Connection_Request
The Accept_Connection_Request command is used to accept a new incoming connection request.

Reject_Connection_Request
The Reject_Connection_Request command is used to decline a new incoming connection request.

Change_Connection_Packet_Type
The Change_Connection_Packet_Type command is used to change which packet types can be used for a connection that is currently established.

Remote_Name_Request
The Remote_Name_Request command is used to obtain the user-friendly name of another Bluetooth device.

Set_Event_Mask
The Set_Event_Mask command is used to control which events are generated by the HCI for the Host.

Reset
The Reset command will reset the Bluetooth Host Controller, Link Manager, and the radio module.

Set_Event_Filter
The Set_Event_Filter command is used by the Host to specify different event filters. The Host may issue this command multiple times to request various conditions for the same type of event filter and for different types of event filters.
Flush
The Flush command is used to discard all data that is currently pending for transmission in the Host Controller for the specified connection handle, even if there currently are chunks of data that belong to more than one L2CAP packet in the Host Controller.

Change_Local_Name
The Change_Local_Name command provides the ability to modify the user-friendly name for the Bluetooth device.

Write_Connection_Accept_Timeout
The Write_Connection_Accept_Timeout will write the value for the Connection_Accept_ Timeout configuration parameter, which allows the Bluetooth hardware to automatically deny a connection request after a specified period has occurred, and to refuse a new connection.

Write_Connection_Accept_Timeout
The Write_Connection_Accept_Timeout will write the value for the Connection_Accept_ Timeout configuration parameter, which allows the Bluetooth hardware to automatically deny a connection request after a specified period has occurred, and to refuse a new connection.

Write_Page_Timeout
The Write_Page_Timeout command will write the value for the Page_Reply_Timeout configuration parameter, which allows the Bluetooth hardware to define the amount of time a connection request will wait for the remote device to respond before the local device returns a connection failure.

Write_Scan_Enable
The Write_Scan_Enable command will write the value for the Scan_Enable configuration parameter, which controls whether or not the Bluetooth device will periodically scan for page attempts and/or inquiry requests from other Bluetooth devices.

Write_Page_Scan_Activity
The Write_Page_Scan_Activity command will write the value for Page_Scan_Interval and_ Page_Scan_Window configuration parameters. Page_Scan_Interval defines the amount of time between consecutive page scans. Page_Scan_Window defines the duration of the page scan.

Write_Inquiry_Scan_Activity
The Write_Inquiry_Scan_Activity command will write the value for Inquiry_Scan_Interval and Inquiry_Scan_Window configuration parameters. Inquiry_Scan_Interval defines the amount of time between consecutive inquiry scans. Inquiry_Scan_Window defines the amount of time for the duration of the inquiry scan.

Write_Inquiry_Scan_Activity
The Write_Inquiry_Scan_Activity command will write the value for Inquiry_Scan_Interval and Inquiry_Scan_Window configuration parameters. Inquiry_Scan_Interval defines the amount of time between consecutive inquiry scans. Inquiry_Scan_Window defines the amount of time for the duration of the inquiry scan.

Write_Authentication_Enable
The Write_Authentication_Enable command will write the value for the Authentication_Enable parameter, which controls whether the Bluetooth device will require authentication for each connection with other Bluetooth devices.

Read_Buffer_Size
The Read_Buffer_Size command returns the size of the HCI buffers. These buffers are used by the Host Controller to buffer data that is to be transmitted.

Read_BD_ADDR
The Read_BD_ADDR command will read the value for the BD_ADDR parameter. The BD_ADDR is a 48-bit unique identifier for a Bluetooth device. Inquiry Complete event The Inquiry Complete event indicates that the Inquiry is finished.

HCI Events

Inquiry Result event
The Inquiry Result event indicates that a Bluetooth device or multiple Bluetooth devices have responded so far during the current Inquiry process.

Connection Complete event
The Connection Complete event indicates to both of the Hosts forming the connection that a new connection has been established.

Connection Request event
The Connection Request event is used to indicate that a new incoming connection is trying to be established.

Disconnection Complete event
The Disconnection Complete event occurs when a connection has been terminated.

Remote Name Request Complete event
The Remote Name Request Complete event is used to indicate a remote name request has been completed. The Remote_Name event parameter is a UTF-8 encoded string with up to 248 bytes in length.

Command Complete event
The Command Complete event is used by the Host Controller to pass the return status of a command and the other event parameters for each HCI Command.

Command Status event
The Command Status event is used to indicate that the command described by the Command_Opcode parameter has been received and the Host Controller is currently performing the task for this command.

Hardware Error event
The Error event is used to indicate some type of hardware failure for the Bluetooth device.

Flush Occurred event
The Flush Occurred event is used to indicate that, for the specified Connection Handle, the current user data to be transmitted has been removed.

Number Of Completed Packets event
The Number Of Completed Packets event is used by the Host Controller to indicate to the Host how many HCI Data Packets have been completed for each Connection Handle since the previous Number Of Completed Packets event was sent.

Connection Packet Type Changed event
The Connection Packet Type Changed event is used to indicate the completion of the process of the Link Manager changing the Packet Types used for the specified Connection_Handle.