Wireless Real-Time Communication Technologies: A Comparative Study

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Abstract – **Sometimes it is not convenient or even impossible to interconnect embedded systems by wire, in which case wireless connections are the solution for communication needs.**

It is difficult to choose the proper technology in the wide field of wireless communication technologies. This study gives an overview of the most important methods of wireless communication and compares the advantages and disadvantages in order to facilitate the design of wireless embedded systems.

Index Terms — embedded systems, real-time, wireless, communication, physical layer, comparative study.

1 INTRODUCTION

Embedded systems in particular are often used in mobile applications and thus benefit from wireless communication. There are several applications where communication by wire is not applicable (e. g. the control of moving objects, for short term usage, in buildings under monumental protection, or in dangerous areas, where no violation of the sealing jacket is acceptable). Aside from the elimination of the cabling effort, the replacement of the physical layer by a wireless connection galvanically isolates the sender and the receiver from each other which is important in high voltage environments. Additionally no special shielding is required.

Mechanical parts like plugs and sockets are susceptible for contact problems because of oxidation of contacts (especially in environments with high moisture or aggressive chemicals), mechanical stress, or wearout. Wireless connections are usually characterized by a high reliability, because there are no moving parts necessary.

The objective of this article is a comparison of the different technologies regarding the usability for real-time communication under various aspects like bandwidth, latency, attenuation in different mediae, and others.

One basic intention is that only technologies are considered where – beside acquisition costs – no additional costs arise. Therefore commonly used standards for cellular phones like GSM (Global System for Mobile Communication) or UMTS (Universal Mobile Telecommunications System) are disregarded.

The remainder of this article is organized as follows:

Section 2 deals with different types of optical links such as infrared or laser links.

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In Section 3, the special properties of acoustic links are treated.

Section 4 deals with different types of radio links.

This article is concluded with Section 5, where a short summary gives some recommendations for specific purposes.

2 OPTICAL LINKS

There are several possibilities for communicating through optical links. When light is used for communication the signal propagates with the highest possible velocity for a given distance and a given medium. Therefore it provides low latency compared with, e. g. acoustic links.

In addition no Federal Communications Commission (FCC) number is needed. Thus everyone is free to use some home made devices for communication.

2.1 Infrared Links

The usage of infrared light allows a reliable communication that is immune against radio emissions.

2.1.1 IrDA compliant Standards

The Infrared Data Association (IrDA)[1] was founded in 1993 as a non-profit trade association. Nowadays over 160 companies representing computer and telecommunications hardware, software, components and adapters are members of IrDA.

The IrDA standard uses directed infrared light for a bidirectional connection (semiduplex). Therefore the sender must be aligned with the receiver.

Two standards are presented by IrDA: IrDA DATA, which was published in 1994, and IrDA CONTROL, which was presented in 1998.

IrDA DATA: According to [PQT98] data exchange takes place through standard UART frames at 9600-115200 bit/s with Serial Infrared (SIR) and up to 4 Mbit/s with Fast Infrared (FIR). This standard was extended to 16 Mbit/s with Very Fast Infrared (VFIR) in 1999 (see [HPY99]).

The Communication is specified over a distance of one meter but most devices support distances greater than one meter (typically 2 meters can be reached).

Some optional protocols are specified as part of IrDA DATA including IrDA Lite, which provides methods for reducing the size of IrDA code while maintaining compatibility with full implementations.

[1] `http://www.irda.org/`

It is a widespread standard. Many notebooks, PDAs, printers, etc. have a built-in IrDA DATA compliant interface.

IrDA CONTROL: According to [CPC+98] data exchange takes place with 75 kbit/s coded with 16-pulse sequence modulation and multiplied by a 1.5 MHz subcarrier. It allows a host device to communicate with up to 8 peripheral devices with a fast response time (13.8 ms basic polling rate) and low latency thus providing features well suited for real-time communication.

Communication is specified over a distance of at least 5 m.

Since this standard was published recently it is not supported in older devices.

2.1.2 Wireless LAN (IEEE 802.11)

Although most hardware according to this standard uses radio waves (see Section 4.4) for communication, the standard (see [IEE99]) also specifies diffuse infrared light for the physical layer.

Communication is possible with line-of-sight infrared energy as well as with reflected infrared energy. It is usable for distances up to 20 m and allows data rates of 1 or 2 Mbit/s. The modulation schema is pulse position modulation (PPM).

In order to use it for real-time communication the same objections as in the radio version are valid.

2.2 Laser Links

Laser (mostly relative cheap laser-diodes are used) offers at least an order of magnitude longer distances than infrared LEDs. Depending on the equipment it is possible to bridge several kilometers at a data rate up to the Gigabit range. For a reliable operation the laser beam of the sender must be adjusted to the receiver exactly. Therefore it is best used as communication line between fixed objects.

In [GF97] a laser link for distances up to 500 km between two aircrafts was established at a data-rate of 1 GBit/s. Especially for long distances fog or rain can break the communication. In the given example the project benefits from the excellent optical conditions in the chosen altitude of about 13 km.

According to [Eng97] using the beam of an inexpensive, off-the-shelf laser pointer, usually provides only poor performance (about 9600 bit/s) because most laser modules have capacitors to filter power supply noise and switch glitches. These capacitors limit the switching speed of the laser module, but they are necessary to preserve the laser diode which is very thin-skinned and can be damaged easily. Using laser modules with an additional modulation input is expensive but allows using the full performance.

Although the IrDA standard is specified for infrared LEDs the respective interface integrated circuits may be used for a laser link also thus providing a cheap and reliable interface circuitry.

Eavesdropping is very difficult because the laser beam covers only a very small area compared to nondirected communication lines. At the receiver's side this may be detected as data loss.

Depending on the laser's intensity precautions may be necessary for preventing the direction of the laser beam in someones eyes because it may damage the retina permanently.

Because of its high bandwidth and its low latency it is well suited for the usage in real-time communication networks.

3 Acoustic Links

Solid materials like the steel framework of huge industrial buildings or ships conduct acoustic signals as well as liquids and - although with higher attenuation - air.

Dolphins and whales have been using this kind of communication over long distances for thousands of years. It is also used as communication link for scuba divers, submarines, etc.

In conjunction to the other technologies presented the velocity of propagation is slower by about 6 magnitudes (air: about 340 m/s, water: about 1500 m/s, the exact value depends on the media, temperature, etc.) and cannot be used in vacuum. Because of the slow velocity of propagation (compared to electromagnetic waves) the doppler-shift may vary the signal by a significant amount even for slow moving objects. Special care must be taken, because the parameters of the communication channel like attenuation and latency vary depending from temperature or the tides.

In addition, no FCC number is needed. Therefore everyone is free to use some home made devices for communication.

This method works like a narrow-band radio link except that the information is modulated on an acoustic carrier instead of a radio carrier. It is possible to use the same modulation schemes as for radio links.

The achievable data rate is constrained by negative effects like multi-path propagation. In [Nea00] an acoustic modem is described which is capable of sending data at a data rate of 20 kbits/s (up to 3 km) or 8 kbits/s (up to 10km) and 1 kbits/s (up to 50 km). Obviously the maximum bit rate is a function of range. Using lower frequencies allows lower attenuation (higher achievable range) but also lower bandwidth (lower data rate).

Because of the varying parameters (latency, noise, echo) its usability for real-time communication is limited.

Since sound waves cannot be focused to a beam, eavesdropping an acoustic link is no challenging task.

4 Radio Links

In general, this method uses a carrier frequency which is modulated by the information, e. g. amplitude modulation, frequency modulation, phase modulation, etc.

Radio waves propagate with the speed of light and thus provide low latency compared with, e. g. acoustic links. It is possible to establish a communication around the earth or to satellites.

Underwater electromagnetic waves suffer a high attenuation, which is even higher in sea water than in fresh water because sea water has a higher conductivity of about 4 Siemens. Table 1 depicts the attenuation of radio waves in sea water as stated in [Nav00]. Thus underwater radio communication may be used for short distances or at extreme low frequencies only. Low frequencies provide a very limited bandwidth and require huge antennas.

Frequency [MHz]	Attenuation [dB/m]
0.01	3
1.00	30
100	300

Table 1: Attenuation of electromagnetic radiation in sea water

The electromagnetic field is not only able to transport data but also energy for supplying a small embedded system with power. [LMRV00] describes a device called Radio Frequency IDentification (RFID) tag that can be read (and sometimes written) using a magnetic or electromagnetic field emitted by a fixed-position or mobile reader device over distances ranging from several centimeters up to a few meters. Since RFID tags collect the energy to operate from the field emitted by the reader device, they do not require an internal power source and can be produced both with very small form factor and at a very low price. These devices can be used as key in a access-control-system.

The available frequency spectrum is used by a multitude of services. Therefore a device may use radio waves only if it was reviewed by the FCC or another national authority in order to prevent the disturbance of other services. Therefore it is not permitted to use home made devices for radio communication except for the case, when a certified transceiver (a device which is capable of sending and receiving radio waves) is used.

It is in the nature of radio frequency that it penetrates walls. Thus it is subject to uncontrolled interference or eavesdropping.

A special type of a radio link is the *Directed Radio Link* which operates at high frequencies usually. Therefore a high bandwidth can be provided resulting in a high data-rate. In addition the propagation is quasi-optical and therefore requires a direct line of sight. Thus this type of communication is similar to a laser link, but less vulnerable to obstacles and usually tolerates fog or some trees. As the example of satellite communication shows, this technique can be used for distances of thousands of kilometers.

Because of its low latency it is well suited for the usage in real-time communication networks.

4.1 Analog Transceivers

These transceivers (devices capable of transmitting or receiving alternatively) usually provide an analog input, an analog output and some control inputs for selecting transmit- or receive-mode (sometimes specialized inputs/outputs for digital signals are provided).

Thus one has full control over the transceiver with respect to timing (when and how long the transmitter or receiver should be enabled or when it should be set idle for power saving), transmitter power, or communication speed. Additionally the device can be driven with different wave forms (some generate more harmonics but complicate clock recovery) or any desired protocol within the limits of the transceiver. Due to its flexibility by changing several parameters and the possibility of a very low latency it is well suited for the usage in real-time communication networks or for implementing a newly designed protocol. As a drawback this results in a higher complexity because the lowest layers of the protocol-stack have to be implemented too.

Although it is relatively easy to build such a device with the help of some specialized integrated circuits, in most countries it is forbidden to activate these devices without a prior certification.

Some manufacturers (for example micrel[2] or radiometrix[3]) provide such transceiver modules which are already certified and thus may be used in several countries (for information concerning a specific country the manufacturer or the local authorities should be contacted).

4.2 DECT-Standard

Based on the UK CT2 standard and the Swedish CT3 standard the first edition of the Digital Enhanced Cordless Telecommunications (DECT) - Standard was developed by the European Telecommunications Standards Institute (ETSI)[4] as well as European telecommunications equipment manufacturers, system operators and regulators.

After the first edition of the DECT standard was available in 1992, the DECT standardization work concentrated on the definition of the Generic Access Profile (GAP) and other interworking profiles (DECT/GSM, DECT/ISDN, DECT/Radio Local Loop, CTM and several data profiles).

This work and additional demands from the DECT market initiated several extensions and enhancements to the base standard and led to the 2^{nd} edition of the base standard being finalized by the end of 1995.

According to [ETS96] a DECT device operates at a given point in time on one out of 10 carrier frequencies in the range from 1880–1900 MHz using Gaussian Frequency Shift Keying (GFSK) modulation with a transmitter power of up to 250 mW. The radio interface is based on the Multi Carrier, Time Division Multiple Access, Time Division Duplex (MC/TDMA/TDD) radio access methodology. It can handle up to 12 simultaneous out of 120 possible full duplex channels with only one single radio transceiver which must be able to switch between the carrier frequencies within the given inter slot gaps. One slot lasts 417 μs resulting in 10 ms for a complete TDMA-round. Thus the usage in real-time embedded systems is quite possible.

Each channel provides a bitrate of 32 kbit/s. Higher bitrates can be achieved by combining several channels.

[2] `http://www.micrel.com/`
[3] `http://www.radiometrix.co.uk/`
[4] `http://www.etsi.org/`

In order to prevent eavesdropping the DECT standard supports encryption and authentication. An efficient addressing scheme in conjunction with seamless handover allow a reliable communication even for objects moving from one base station to another.

The jitter of a packet transmission is specified to be less than 1 μs. Therefore the distance between two communicating devices has to be less than 300 m. In buildings about 100 m can be reached because of the higher attenuation.

4.3 Bluetooth

According to [SIG01] Bluetooth devices use the Industrial, Scientific, Medicine (ISM) - band from 2400.0–2483.5 MHz which is subdivided into 79 channels and utilized by using Gaussian Frequency Shift Keying (GFSK). The channel is divided into time slots where each slot corresponds to an RF hop frequency and has a duration of 625 μs. The frequency hopping spread spectrum (FHSS) sequence is unique for each piconet (one master and up to seven active slaves) and is determined by the Bluetooth device address of the master. One slave may participate at different piconets therefore interconnecting them.

In order to use the best of the IR and radio, Bluetooth technology utilizes IrOBEX, a session protocol defined by IrDA (see Section 1). Thus the development of application programs that function well over both short-range RF and IR media is possible.

Bluetooth is specified for data rates of 1 Mbit/s over a distance of about 10 m with a transmitter power of 1 mW. It is expected that these values will be improved to 100 m with a transmitter power of 100 mW with Mega-Bluetooth.

It's small formfactor and low power consumption in conjunction with high bandwidth makes this technology suitable for real-time communication of embedded systems.

4.4 Wireless LAN (IEEE 802.11)

According to [IEE99], nowadays wireless ethernet cards mostly use DSSS and allow data rates up to 11 Mbit/s on the ISM-band at 2400.0–2483.5 MHz. A distance of up to 115 m can be bridged at a data rate of 1 Mbit/s. The modulation schema is differential binary phase shift keying (DBPSK) at 1 Mbit/s or differential quadrature phase shift keying (DQPSK) with a varying number of codes at higher data rates. Besides of spread spectrum techniques there exist 3 different subranges in the frequency range used.

In addition diffuse infrared light is defined as physical layer but rarely used (see Section 2.1.2).

In 1999 another physical layer was defined at 5 GHz allowing data rates up to 54 Mbit/s using orthogonal frequency division multiplexing (OFDM).

With directed antennas the communication over some kilometers is possible.

According to [NMG01], it is possible to use wireless LAN for real-time applications if a proper protocol is used.

A disadvantage is the effort required for controlling these devices (the complexity is like controlling a device for the PCI bus in nowadays personal computers). Usually a low-cost microcontroller cannot provide the number of required I/O-pins.

5 CONCLUSION

Small, battery driven embedded systems with the need for communication over a short distance of a few meters may use an infrared data link or Bluetooth. There are several ready to use integrated circuits which allow a fast communication link with a minimum of effort.

In applications with special requirements regarding latency or where a broadcast based protocol should be implemented and tested, it is recommended to use an analog radio transceiver. Then one can switch the receiver into a power-saving mode at each desired instant in time, use special wave forms, or use special receiving algorithms for enhanced quality. Especially for research in the area of real-time protocols or for battery driven devices this is very important.

For long-distance underwater applications the best choice will be establishing an acoustic link. All other possibilities are very limited in range.

If security is an important parameter (not all security-related risks can be avoided by using cryptographic methods) the usage of a directed link (laser or radio) or spread spectrum techniques is suggested because eavesdropping those links is hard to achieve.

For communication where low latencies are of utmost importance (e. g. control-loops) the usage of acoustic links should be avoided. Especially the propagation delay over long distances can reach a significant amount of time. Applications with the need for high bandwidth should also avoid acoustic links.

When a direct line of sight is not guaranteed the usage of an optical link is not suggested. Directed radio links can tolerate some obstacles. For massive obstacles radio communication at low frequencies may be used.

For amateurs, especially interested in building their home made devices optical or acoustic links are suggested because no certification is needed. Only amateur radio operators are equipped with the appropriate knowledge and thus allowed to use home made radio transmitters without certification.

For small projects using cheap microcontrollers the usage of Wireless LAN should be avoided because of its complexity.

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