

Presently, data transfers between the PC and printers, scanners, fax machines and modems, as well as communication between a laptop and a cellular phone, still require inconvenient cable interconnections and the time-consuming installation of drivers. Wouldn't it be nice if all your data-processing devices could independently converse with each other, with no need for cables or driver installation? This is now possible, thanks to Bluetooth, a short-range radio system that renders cables redundant and which should allow new applications to be developed.

By G. Kleine

Bluetooth

2.4-GHz data radio instead of computer cables



Nokia Mobile Phones, Ericsson Mobile Communications, IBM, Intel and Toshiba recognized the potential of this technology and founded the Bluetooth Special Interest Group (BSIG) [1,2] in May of 1998. Its objective is to define a universal standard for radio data communication between data-processing equipment. In the beginning, the main area of interest was data transfers between cellular phones and peripheral equipment, in order to eliminate annoying and inconvenient cables. Later, the area of interest was extended to include other applications, ranging from wireless connections between PCs and laptops and their peripheral equipment to the ad-hoc configuration of wireless networks.

Presently, more than 1100 firms are members of the Bluetooth Special Interest Group (BSIG) (see the box 'King Bluetooth and his friends'). They include not only all leading computer and communications technology firms, but also automobile and aeroplane manufacturers and representatives of the entertainment industry. The BSIG presented the provisional version of the Bluetooth 1.0 specification in the autumn of 1999. It has been made publicly available on the Internet [2], in order to promote the establishment of the Bluetooth system. This extensive specification fills more than 1500 pages. The primary objective of the Bluetooth project is the development of extremely inexpensive, compact modules that can be built into a variety of equipment. The tar-

geted unit price, given large-scale mass production (more than one million pieces), is less than five dollars.

Frequencies

When the BSIG was looking for licence-exempt frequency bands that are available worldwide, it came across the Industrial, Scientific and Medical (ISM) bands. These frequency bands may be used without any licence or fee for industrial, scientific and medical equipment with a limited radiated power. In addition to the available ISM bands listed in Table 1, there are other ISM bands at 5.8 GHz, 24.25 GHz and 122.5 GHz, but these cannot be utilized at a reasonable cost at the present time.

Since the possibility of interference from other unlicensed users of the ISM bands must always be taken into account, and given that Bluetooth should have a data transfer rate of around 1 Mb/s, the only suitable choice is the 2.4-GHz ISM band (2400 to 2483 MHz). This band is 83 MHz wide and thus provides enough room to avoid interfering signals coming from equipment that uses a particular frequency, such as a microwave oven. This frequency band is available worldwide, although its extent is somewhat reduced in Japan (2471 to 2497 MHz), France and Spain.

In order to avoid problems with anticipated interference signals, most of which have fixed frequencies, Bluetooth makes use of spread-spectrum techniques. This means that the frequency is changed rapidly (up to 1600 times per second) in a pseudo-random manner, with the result that enough interfer-

ence-free frequencies are available to allow the desired data transfer rate to be achieved, even with error protection (see **Figure 1**). This process is called Frequency-Hopping Spread Spectrum (FHSS). Bluetooth uses 79 frequencies in the range between 2.402 and 2.480 GHz, with a separation of 1 MHz. Due to the previously-mentioned reduction of the available frequency band, only 23 hop frequencies are used in France, Spain and Japan.

Piconets and scatter nets

A pair of devices equipped with Bluetooth modules can autonomously establish contact with each other, using the frequency-hopping technique. In order to prevent mutual interference with other Bluetooth equipment in the same vicinity that might use the same frequencies, the frequency sequence is determined by the address and clock rate of the device that initiates the connection. This device thus becomes the master device in this radio group, while all other participants are designated as slaves and must synchronize themselves to the master device.

Up to eight Bluetooth radios can use a single channel. Such a group forms a network that is called a *piconet* (see **Figure 2**). In this context, the term channel means that all members of the piconet employ the same hopping sequence, which means that they use the same series of frequencies. Since each Bluetooth device is assigned a unique 48-bit address by a central registration agency, it is not possible for two separate channels to have the same hopping sequence.

By independently setting up additional piconets in the same vicinity, it is possible to use more than eight Bluetooth devices in one location, such as an office, with high data transfer rates and without interference.

A slave transmit/receive device operating in a particular piconet is addressed by the master device in one time slot of a time-division multiplexed (TDM) protocol and may respond in the subsequent time slot. The slave is free to participate in another piconet in the remaining time slots. In order to do so, it sets its receiver to the frequency to which the other piconet has just hopped and synchronizes itself to the master device of that piconet. Multiple radio networks that are interconnected in this manner are referred to in Bluetooth terminology as *scatter nets* (see **Figure 2**). TDM collisions are avoided by the fact that the slave devices synchronize themselves to the clock rate of

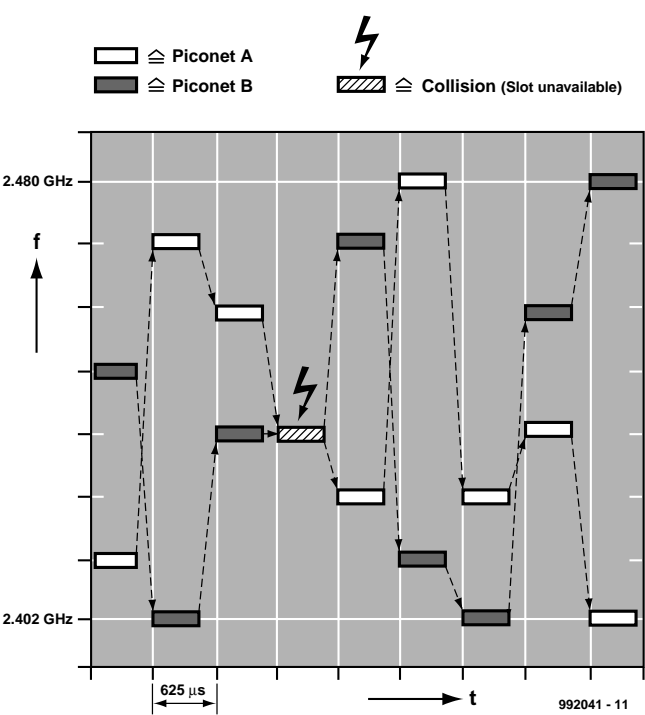


Figure 1. Frequency hopping (simplified representation)

Table 1. Some ISM frequency bands (not available in all countries)		
Frequency range ¹	Bandwidth	Shared with / Notes
26.957 MHz - 27.283 MHz	0.326 MHz	CB, cordless phones, ...
40.660 MHz - 40.700 MHz	0.040 MHz	small bandwidth
433.050 MHz - 434.790 MHz	1.74 MHz	Amateur radio
868 MHz - 870 MHz	2.00 MHz	little used, small bandwidth
2.400 GHz - 2.483 GHz	83.00 MHz	Microwave ovens, door openers

¹ Note: additional ISM Bands may be allocated around 5.8 GHz, 24.250 GHz and 122.5 GHz

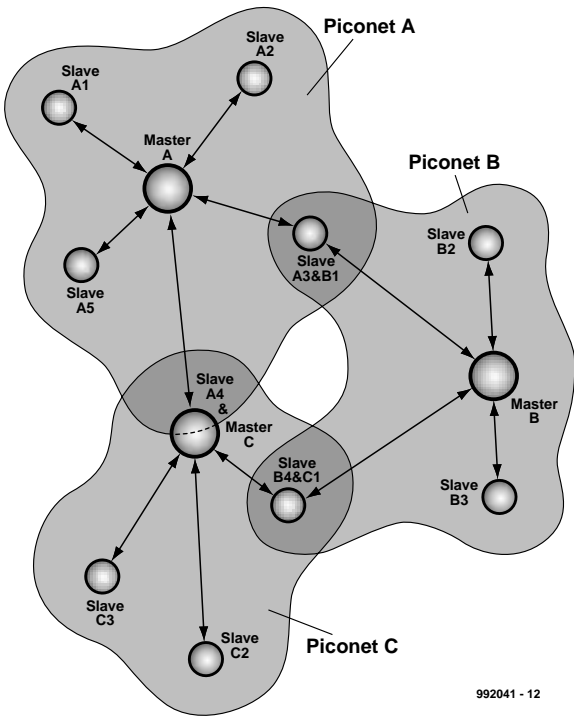


Figure 2. Piconets and scatter nets

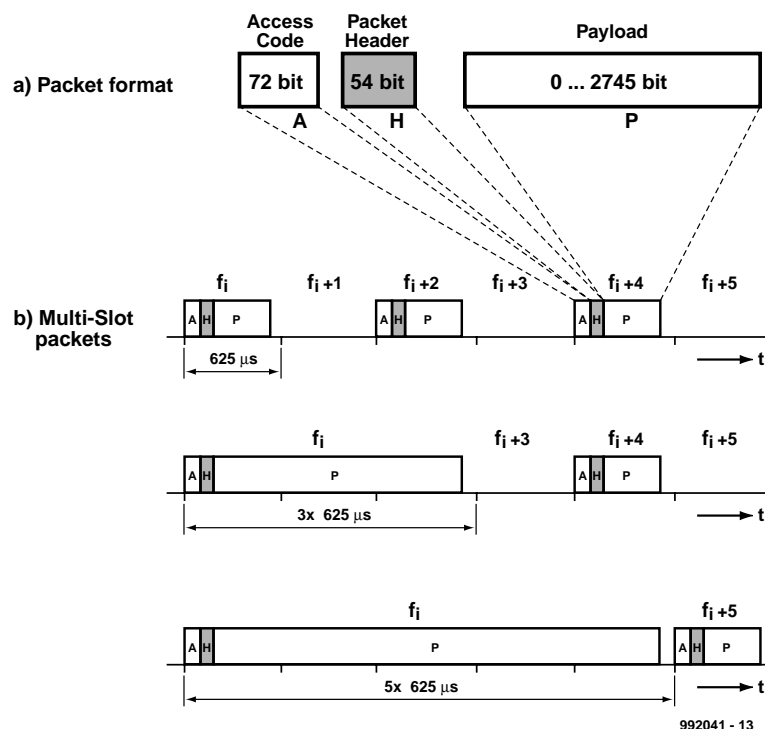


Figure 3. Packet format and multi-slot packets

the master.

As we have seen, up to eight devices are allowed in a single Bluetooth piconet. The higher-level scatter net can contain up to ten piconets, so that it is possible to configure systems containing up to 80 Bluetooth devices within a 10-metre radius. Even when a single device is a member of all ten piconets, the data transfer rate in any piconet is reduced by no more than around ten percent.

Modulation and error protection

Gaussian Frequency-Shift Keying (GFSK) modulation is employed for the frequency-hopping narrow-band carrier of each channel. With a frequency deviation of around 150 kHz, the 3-dB carrier bandwidth is 220 kHz. This fairly simple modulation scheme was chosen in order to keep the cost of the transceiver chips as low as possible. The

transmitted power, at 1 mW (0 dBm) nominal, allows for an effective range of at least ten metres under normal conditions. In certain special cases, the generation of higher field strengths (up to 100 mW transmitted power, or +20 dBm) is permitted with spread-spectrum transmissions, which enables effective ranges of up to 100 metres to be attained. The Bluetooth radio module can adapt its transmitted power to the transmission environment, within certain limits.

Error protection in the Bluetooth system is also adaptive, which means that error protection is dispensed with in favour of a higher data transfer rate if there is a very high-quality radio link. Two-stage Forward Error Correction (FEC) is only activated if interference occurs in the radio link. This naturally reduces the data transfer rate. In addition, the Automatic Retransmission Query (ARQ) technique is used, except for voice channels. ARQ allows re-transmission of a

packet to be requested. The header of every packet is always protected using FEC, so that even if FEC is switched off, re-transmission can always be instigated via ARQ if interference occurs.

SCO and ACL

The Bluetooth Baseband Protocol defines two types of data transfers: point-to-point and single-point to multiple-point.

Point-to-point transfers are referred to as *Synchronous Connection Oriented* (SCO). They are primarily intended to be used for voice data transmission. The link is thus symmetrical, which means that the data rate is the same in each direction. In practice, a full-duplex link is implemented by utilizing alternating time slots, with the data for one direction contained in one slot and the data for the other direction contained in the following slot. In contrast to data transfers, which are not time-critical, it is naturally not possible to use the ARQ technique for speech transmissions if interference occurs on certain frequencies. Instead, the *Continuous Variable-Slope Delta* (CVSD) method is used for voice encoding, since it exhibits good bit-error behaviour and produces only a slight increase in the background noise level in case of errors. The sampling rate for voice data transfers is 64 kb/s, the same as for ISDN.

Single-point to multiple-point transfers are asynchronous and connection-independent; they are based on data packets. Such links are referred to as *Asynchronous Connectionless* (ACL) in Bluetooth terminology. This type of transfer is used by a master device to communicate with several slave devices at the same time. In addition to being used for sending messages to all slave devices, this type of transfer is also used for sending data packets to a particular slave device. In order to increase the data transfer rate, a packet may use not only one 625-μs time slot, but also three or even five slots, as shown in **Figure 3**. To make this possible, frequency-hopping is suspended and the frequency at the start of the packet transfer (f_i) is maintained for the duration of the three or five slot intervals. This allows the 'holes' between successive slots, which are otherwise reserved for frequency hopping, to be used for the data transfer. In order to maintain overall synchronization, frequency hopping resumes on completion of the transfer with the frequency that would normally be used for the fourth slot (f_{i+4}) or the fifth slot (f_{i+5}), as appropriate.

Table 2. ACL link data rates

FEC	Slots	Data rate, symmetrical	Data rate, asymmetrical
none	1	2 x 172.8 kBit/s	172.8 kBit/s + 172.8 kBit/s
none	3	2 x 384.0 kBit/s	576.0 kBit/s + 86.4 kBit/s
none	5	2 x 432.6 kBit/s	721.0 kBit/s + 57.6 kBit/s
yes	1	2 x 108.8 kBit/s	108.8 kBit/s + 108.8 kBit/s
yes	3	2 x 256.0 kBit/s	384.0 kBit/s + 54.4 kBit/s
yes	5	2 x 286.7 kBit/s	477.8 kBit/s + 36.3 kBit/s

Data transfers from a slave device to a master, or from one slave to another slave via the master, require the permission of the master. For ACL links, the symmetry of the data rates in the two directions is controlled by the master. With asymmetric links, the data rate in one direction can be as high as 721 kb/s, in which case the rate in the other direction is only 57.6 kb/s. Both of these values are based on five-slot transfers without forward error correction (FEC). If FEC and the previously-mentioned ARQ procedure are employed, the data rate naturally drops. A 2/3-rate FEC is used. With a symmetrical link and no error protection, the maximum data rate is 432.6 kb/s in each direction. **Table 2** lists additional data rates for ACL links. With both types of links, ACL and SCO, there are 16 different types of packets that can be used for data transfers. Some of these are reserved for control functions. Every packet has a 72-bit identification field (Access Code), which is derived from the 48-bit master address and which is protected by FEC. Following this comes a 54-bit header field, which is also protected by 1/3-rate FEC. After this, in a normal packet, come up to 2745 bits of payload data (see **Figure 3**). Three-slot and five-slot packets can transfer correspondingly more payload data.

Bluetooth transfers can also be encrypted, using a 128-bit key for authentication. The user can determine whether he or she wants to use encryption in one direction or in both directions. This setting is saved. This allows the user to exactly specify the equipment with which a cellular phone (for example) is allowed to communicate. For example, you could allow your phone to access your own notebook, while denying any access to your colleagues.

With Bluetooth, it is possible to have either one asynchronous ACL channel or up to three simultaneous, synchronous SCO channels plus one asynchronous data channel with a parallel 64-kb/s speech channel.

Piconet states

Bluetooth modules that are not members of any piconet operate in the Standby mode, in which they search for possible transfers in their immediate environment every 1.28 seconds. They do this by testing 32 of the possible 79 frequencies, which are designated as wake-up carriers. In France, Spain and Japan there are 16 wake-up carriers among the total of 23 possible frequencies.

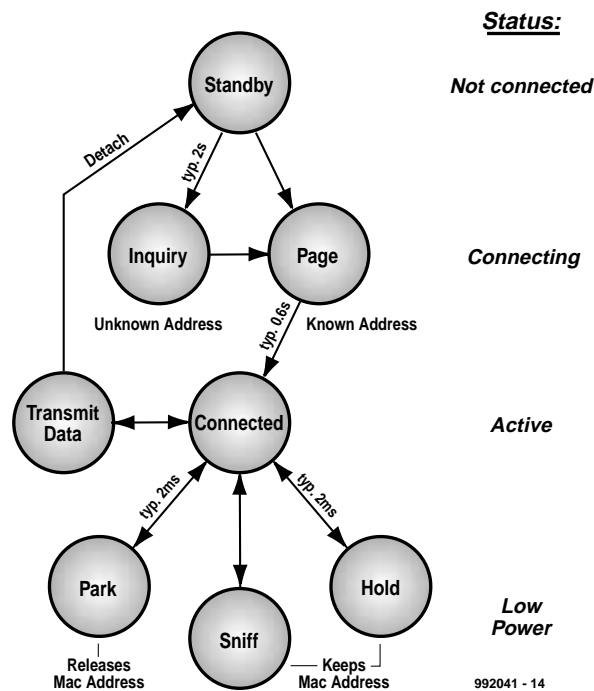


Figure 4. Bluetooth module state diagram

A Bluetooth module that is not yet connected transmits a call via the wake-up carriers, which is answered by any other nearby Bluetooth radio(s). After an introductory handshake, the two devices set up a piconet, in which the device that first issued the call takes on the role of master. Based on its address, it establishes the hopping sequence for this piconet. The slave device, and any other devices that later join this piconet, synchronize themselves to the clock rate of the master device.

Figure 4 shows the state diagram of a Bluetooth module. Starting from the Standby mode, it moves to the Inquiry state on detecting a second device. In this state, it transmits a general call followed by an address request. Once the address of the other device has been determined, or if this was already known in the Standby mode, the module transfers to the Page mode. After a typical delay of 0.6 second, the connection becomes active (Connected state). Data transmission can now take place (in the Transmit Data state). After a successful data transmission, the Bluetooth module can either return to the Standby mode or enter one of three low-power (energy-saving) modes.

The first low-power mode is the Hold mode, in which the device remains an active member of the piconet. When an internal timer in the slave device times out, the slave briefly makes itself known to the master before restarting the timer. If necessary, the slave can leave the

Hold mode immediately in order to transfer data. The master can force a slave into the Hold mode, but a slave can also voluntarily enter the Hold mode.

In the second low-power mode, the Sniff mode, the slave is programmed to periodically 'listen' to the piconet to determine whether there is a data transfer waiting for it.

The third low-power mode is the Park mode. In this mode, the slave drops out of the piconet and makes its Media Access Control (MAC) address free (each member of a piconet has a MAC address, with a value of 0 to 7). After this, it remains passive, and its only activity is to maintain synchronization with its piconet master at relatively long time intervals.

Interesting Bluetooth applications

In the first instance, Bluetooth should eliminate cables for connections between laptop or desktop computers and printers, scanners and fixed Local Area Networks (LANs). With it, even (wireless) keyboards, mice and joysticks or trackballs need not necessarily have a line-of-sight path to the computer. Other imaginable applications relate to laptop computers and cellular phones. For example, if you write your e-mail messages in the aeroplane using your laptop, you would no longer have to worry about how to send them. As soon as you leave the aeroplane and switch

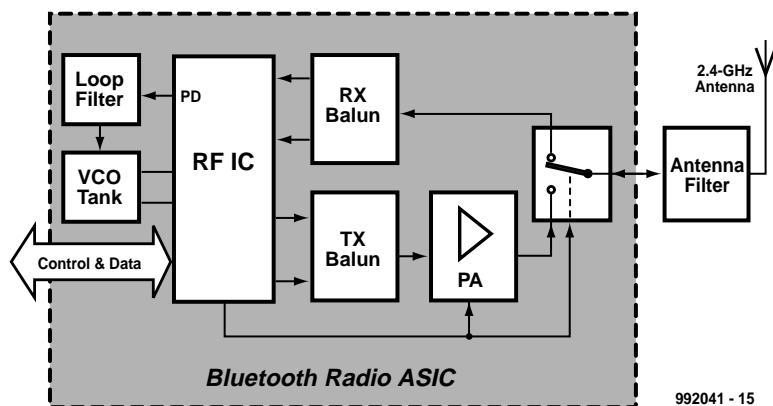


Figure 5. Block diagram of a Bluetooth radio module

on your cellular phone again, the laptop could make a Bluetooth connection and send the e-mail. The use of a Bluetooth radio module inside the aeroplane should also be allowed, due to its low transmitted power level (100 mW maximum).

In the future, you could also dispense with cables when using a cellular phone with a hands-free installation. You could leave your cellular phone switched on in your pocket and enjoy a wireless link to the headset of the hands-free unit. The use of a hands-free unit makes an important contribution to safety for commercial vehicles as well. Finally, you could equip your laptop with speakers and a microphone. The speech signal could be passed on to the cellular phone in your briefcase via a wireless Bluetooth link. This would make it possible to transfer speech, data and graphics using only one device, the laptop computer.

One very practical suggestion is to use Bluetooth for automatic file synchronization between a laptop computer, a desktop computer and a Personal Digital Assistant (PDA). Whenever these devices are located in the same vicinity,

they could independently exchange e-mail messages, appointments and addresses, in order to bring each other up to date. It would even be possible for a field-service technician (for example) to use a Bluetooth cellular phone to automatically update or modify his appointments calendar, based on information from the main office. In future conferences and meetings, the participants could bring along their laptops with Bluetooth interfaces and set up a spontaneous network. This would allow the exchange of graphics, texts and data, or the wireless remote control of a projector.

Wireless Internet access using Bluetooth should allow for more freedom of movement. Internet pages could reach your laptop via wireless links from a cellular phone, locally-installed modem or your firm's LAN. A Bluetooth cellular phone could automatically switch from GSM to DECT operation, both at home and in the office, as soon as it makes contact with a local cordless-phone base station. This would allow you to simply use the same unit for all your phone conversations.

From the world of entertainment elec-

tronics, there are suggestions for using Bluetooth as the basis for wireless connections to (for example) a video camera or a still camera. The camera could pass the image via a cellular phone to the mains network, or save it on a laptop, all via a wireless link. It would be possible to send still pictures as spontaneous 'electronic postcards' via Bluetooth to your cellular phone and thereby to their ultimate destinations. Remote control of television sets and stereo installations could also be implemented using Bluetooth, which would eliminate the annoying need to search for a line-of-sight path to the equipment.

The first Bluetooth components

Ericsson has developed a Bluetooth Development Kit in cooperation with Symbionics. It includes extensive documentation and design-support software. The baseband processor is provided by VLSI, and comes from the VWS26000 Bluetooth family [6]. The radio module (see Figure 5), which is a hybrid, is an Ericsson product (PBA 313) [4]. You can also obtain a Bluetooth Developer's Kit from Philips Semiconductors. The baseband portion is once again a VLSI ASIC, and the radio module contains the UAA-3558 Bluetooth transceiver. This kit contains two identical Bluetooth daughterboards that can be used to set up an initial radio link. Figure 6 shows the typical structure of a Bluetooth module. The firm Cambridge Silicon Radio [7] is working on single-chip Bluetooth components with integrated radio modules. The Bluecore™01, Bluecore™02 and Bluecore™03 ASICs are intended to incrementally incorporate additional Bluetooth functions. The size of a complete module should ultimately shrink to that of a postage stamp. Finally, numerous semiconductor manufacturers, such as Temic, Philips and Motorola, offer 2.4-GHz transceiver ICs especially for use in Bluetooth radio modules. All Bluetooth modules must pass a BSIG certification procedure in order to ensure compatibility.

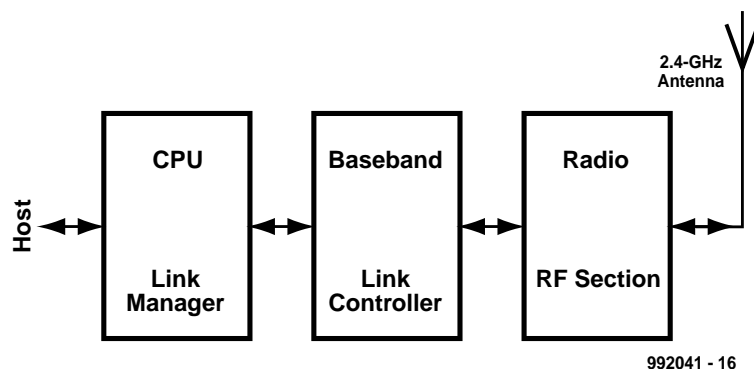


Figure 6. Block diagram of a Bluetooth module

Competition for Bluetooth

There is also competition for Bluetooth as a short-range radio networking technology. For some time now, it has been possible to transfer data between a PC and its peripheral equipment using an infrared-light interface that complies with the Infrared Data Association (IrDA) protocol. However, infrared links absolutely require free line-of sight

paths and can bridge a distance of a few metres at best, with viewing angles of only 60 degrees. The advantage of Bluetooth here is that it can even pass through walls into neighbouring rooms (see Reference 8 for a comparison of IrDA and Bluetooth). In the USA, several firms have joined forces to promote HomeRF [9] as a standard similar to Bluetooth. The Shared Access Working Protocol (SWAP), generated by the HomeRF Working Group (HRFWG), allows 127 devices per network with an effective range of 50 metres. Surprisingly enough, some of the founders of Bluetooth are also among the initiators of the HRFWG: Ericsson, IBM and Intel, along with Compaq, Hewlett-Packard, Microsoft, Motorola and Philips, play a decisive role. In any case, this group has only a few hundred members, while the BSIG can already boast of more than 1000 interested parties. In addition, if you want to obtain a copy of the HomeRF specification you must first pay a \$500 membership fee. The DECT standard for cordless phones is also a candidate for wireless LANs. It works in a dedicated frequency band around 1.8 GHz, and has a wider effective range (up to 500 meters) due to its greater transmitted power. DECT and Bluetooth perform equally well for wireless voice communications and for data transfers at low data rates (up to 64 kb/s), but Bluetooth can go beyond this to reach rates of up to 721 kb/s. A consortium based on 3Com, IBM, Intel, AMD, Compaq, Hewlett-Packard, Cisco and Lucent is promoting networking using telephone lines. They call themselves the Home Phonline Networking Alliance (HomePNA) [10], and their system will probably be used primarily in the USA, where it is common practice to provide every room with a telephone outlet. HomePNA uses the frequency region between 6 and 10 MHz, which lies above that reserved for the Asynchronous Digital Subscriber Line (ADSL) service [11]. Diverse powerline communications systems are also striving to be accepted for home networks. Their advantage is that mains outlets are present in every room. However, the high levels of interference on the mains wiring means that only quite limited data rates are possible.

Future prospect

Bluetooth has the best prospects of all the wireless LAN systems, which are quickly establishing themselves worldwide. In addition to extensive applications in the area of data communications, it should find areas of application

Literature and links:

- [1] www.bluetooth.com
- [2] www.bluetooth.net
- [3] www.zdnet.co.uk/news/specials/1999/04/bluetooth/
- [4] <http://bluetooth.ericsson.se/default.asp>
- [5] www.intel.com/mobile/bluetooth/
- [6] www.vlsi.com
- [7] www.cambridgesiliconradio.com/
- [8] *Comparison of IrDA and Bluetooth:*
www.countersys.com/tech/bluetooth.htm
- [9] HomeRF: www.homerf.org
- [10] HomePNA: www.homepna.org
- [11] *Fast Internet access by ADSL*, Elektor Electronics, November 1999
- [12] www.bluetooth.rsd.de/ and www.bluetooth-testing.com

in entertainment electronics and commercial transportation. Following the initial applications presented by Ericsson and Nokia, you can expect to see numerous other applications in the coming year. The CeBIT 2000 Trade Fair

should prove interesting in this regard, and you can look forward to being able to purchase the first Bluetooth systems in the near future.

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King Bluetooth and his friends

The name 'Bluetooth' was chosen in memory of the Danish king Harald Blaatand (Harold Bluetooth in English), who lived from 910 to 986 AD. He christianized and united large parts of Scandinavia. The illustration (courtesy of Rohde & Schwarz) shows a runic stone that was found in King Bluetooth's home city of Jelling in central Jutland. It clearly indicates that the king can be considered to be an early proponent of wireless communication between cellular phones and laptops.



The choice of name also naturally refers to the two main initiators of the system, Ericsson Mobile Communications of Sweden and Nokia Mobile Phones of Finland. As telephone manufacturers, they contributed preparatory work to the subject of wireless LANs.

In the meantime, King Bluetooth has found a lot of friends, as indicated by the following excerpt from the list of members of the Bluetooth SIG (see Reference 1 for the full list):

AKG Acoustics, Alcatel, Analog Devices, AMD, Bang & Olufsen, Boeing, Bosch, Casio, Compaq, Dell, Fujitsu, Grundig, Hagenuk, Hewlett-Packard, ICO, LEGO, LG Electronics,

Logitech, Lucent, Mitsubishi, Motorola,

NCR, National Semiconductor, Philips, Psion Computer, Qualcomm, Rohde & Schwarz, Samsung, Sennheiser, Seiko Epson, Sharp, Siemens, TDK, Telia, Temic, Texas Instruments, VLSI Technology, Volvo, 3Com.