

Chapter 2

Radio-Frequency Technologies for WSNs

Abstract Many wireless monitoring and control applications are available for the industrial and home markets. Some hardware platforms are specialized for optimizing only one feature (e.g., high data rate, long transfer range, or low-power mode). However, the most restrictive parameters for WSNs are both power consumption and distance. This chapter briefly describes different radio-frequency technologies, although many of them are not appropriate or are not yet fully developed for WSNs. Therefore, only appropriate technologies are discussed in depth, and a brief overview of several integrated circuits from different manufacturers is included.

2.1 Bluetooth Technology (IEEE 802.15.1)

The Bluetooth wireless communications technology provides a personal area network (PAN) for exchanging data between Bluetooth-capable devices within a certain proximity.

Bluetooth technology has a low-power mode and high integrated devices and operates in the unlicensed 2.4-GHz band, but it is limited to short-distance communications. Therefore, this technology is not the most appropriate for developing a WSN. For this reason, Bluetooth is just mentioned and described as an existing technology (Bluetooth SIG).

2.2 Wi-Fi Technology (IEEE 802.11.a/b/h/g)

The Wi-Fi technology allows different devices like laptops, personal computers (PCs), cell phones, and personal digital assistants (PDAs) to communicate between one another or to connect to the Internet without needing a cable connection.

The Institute of Electrical and Electronics Engineers (IEEE) defined the Wi-Fi network protocols IEEE 802.11a, 802.11b, and 802.11g operating in the unlicensed radio bands of 2.4 and 5 GHz. Therefore, any kind of standard

Wi-Fi–certified device is able to operate all over the world with data rates of 11 Mbps for IEEE 802.11b or 54 Mbps for IEEE 802.11a. Of course, the greater the distance to the access point, the lower the performance.

Wi-Fi technology lacks a low-power mode and is also not very highly integrated. Thus, a low-powered and highly integrated WSN cannot use this technology, which is why we give just an overview of this existing technology (Wi-Fi Home Page).

2.3 UWB Technology (IEEE 802.15.3)

The Ultra Wideband (UWB) technology allows information to be transmitted at a large bandwidth in precise pulses that are typically 1 to 2 nanoseconds in length and occupy at least 25% of the center frequency, much more than other systems. The use of this technology is limited to the range of frequencies from 3.1 to 10.6 GHz. Another remarkable characteristic of UWB is its better behavior regarding interferences than other technologies due to the use of spread-spectrum modulation techniques.

Despite having a greater ratio of transmission velocity over power consumption than other similar technologies like Wi-Fi, UWB is limited to short-range applications. It is therefore appropriate for portable devices, to get long battery life, but not for WSNs requiring larger distances. This is the main reason for not going into further details on UWB technology (Intel UWB).

2.4 Wavenis Technology (EN300–220 and FCC15.247—Coronis Systems)

The Wavenis technology, developed by Coronis Systems, provides long-range data connections and services for autonomous devices with extremely limited battery resources and is intended for ultra low-power (ULP) and long-range wireless communications. Wavenis extends the industry standard Bluetooth protocol to provide robust wireless solutions for building ad hoc and fixed networks using autonomous, battery-powered devices.

2.4.1 Wavenis' Main Characteristics

Wavenis is a complete software and hardware solution for wireless communications in low-power devices. The core offer consists of an RF transceiver and a protocol stack, both specifically adapted to provide the optimal combination of secure and reliable connections, long range, and minimal power consumption. Highly resistant to interference and obstacles, Wavenis offers a means for including a wide variety of battery-powered products in PAN, LAN, and WAN

networks, particularly for low-data-rate domestic and industrial applications. Wavenis implements an advanced RF architecture and can serve as a means to extend Bluetooth applications toward applications for which no other solutions address real-world needs so directly. This extension not only ensures interoperability with existing networks, but also complements other protocols and avoids costly proprietary gateway solutions. The main features of Wavenis are

- Small footprint
- Low power consumption
- Low per-unit cost
- Line-of-sight connections up to 1 kilometer
- Completely programmable configurations
- Easy in-field installation
- Coexistence with other technologies; interference- and obstacle-resistant
- Point-to-point, broadcast, polling, repeater functions, mesh network topologies
- Ongoing QoS monitoring to have reliable communications

2.4.2 Wavenis' RF ASIC Solution

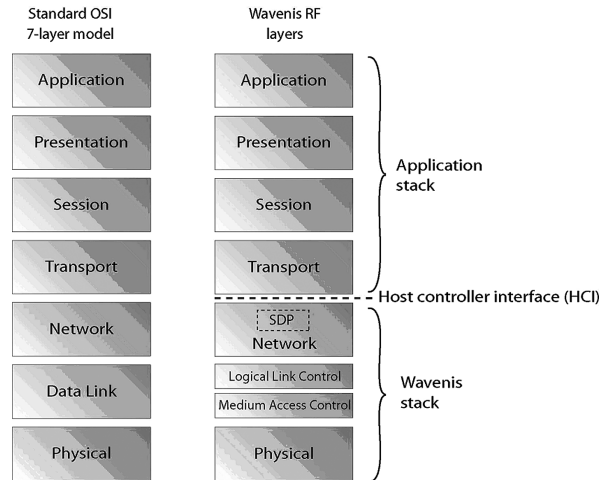
Wavenis licensees may benefit from the Wavenis ASIC, specific low-power baseband, and a full control over system design and RF integration to best meet the designer product goals. This offers the following features:

- It is a flexible solution for mass-produced products.
- Designers can build their own radio interface based on the Wavenis RF ASIC.
- Designers can run the Wavenis protocol stack in their own microcontroller.
- It has a low per-unit license cost.
- It has a small hardware and software footprint, for a low Bill of materials.
- It is stack-portable to many microcontrollers.
- The stack object code is available.

Figure 2.1 shows the structure of the Wavenis layers. The HCI interface offers a simple API to use Wavenis services. The designers can find services such as object code and APIs, Active X controls for Windows applications, and Wavenis' stack configuration tools.

Wavenis operates at frequency bands of 868, 915, and 433 MHz, with data rates between 2.4 and 100 kbps (typical 10 kbps), and uses different techniques for saving power and making the network robust, such as data interleaving, FHSS (frequency-hopping spread spectrum), forward error correction, and GFSK modulation. Wavenis has a high line-of-sight range of up to 1 kilometer and automatic frequency control (AFC) to guarantee high performance levels over the product's operating lifetime. Also, it is compliant with relevant European and U.S. electromagnetic compatibility regulations.

Fig. 2.1 Wavenis' protocol stack



Coronis is also currently developing its new system-on-chip ASIC. The new solution aims to offer unprecedented low-power consumption for large-scale wireless mesh networks and higher RF performance.

2.5 Wibree Technology (Nokia)

Wibree technology is a short-range wireless communications protocol intended to compliment Bluetooth by implementing most of the Bluetooth functions with less power consumption. The Wibree open standard is able to work in applications where reliable Bluetooth data transmission is not possible, although the maximum data transmission rate is three times lower than that of Bluetooth 2.0 (1 Mbps versus up to 3 Mbps).

The Wibree specifications are being defined by a group of important companies from different sectors such as semiconductor manufacturers, service providers, and vendors, with Nokia in the lead. (The list of such companies includes Broadcom, Casio, CSR, Epson, ItoM, Nordic Semiconductor, STMicroelectronics, Suunto, Taiyo Yuden, and Texas Instruments.)

This technology is designed to operate with either a standalone chip or a dual-mode chip. While the standalone chip is a small device able to operate with very low power consumption, the dual-mode Bluetooth Wibree is able to communicate with Bluetooth standard devices with less power consumption and at distances of 5 to 10 meters using the 2.5-GHz band.

The main characteristics of Wibree are the ultra low-power IDLE mode operation, power-saving technology, device discovery, reliable point-to-multipoint data transfer, and encrypted communications (Nokia, 2007).

Wibree is not explained here in more detail because it is not a long-distance technology, therefore being suited for low-power, small devices at limited distances (5–10 meters), not totally adequate for many typical WSN applications (Wibree Home Page).

2.6 ZigBee Technology

The ZigBee technology is a communications standard for systems with requirements such as long battery life, low data rates, secure communications, and less complexity compared with previous wireless standards. It is based on the IEEE 802.15.4 standard (IEEE, 2006) for wireless personal area networks (WPANs).

2.6.1 ZigBee’s Main Characteristics

IEEE 802.15.4 is a protocol for wireless networks aiming to achieve simplicity, low cost, low data rate, and low power consumption with the ability to operate months or even years with standard AA or AAA batteries (Freescale ZigBee Overview).

The IEEE 802.15.4 standard defines two layers, the MAC and the physical layer (PHY), as shown in Fig. 2.2, and uses the three license-free frequency bands. These license-free bands have a total of 27 channels divided into 16 channels at 2.4 GHz with data rates of 250 kbps, 10 channels at 902 to 928 MHz with data rates of 40 kbps, and one channel at 868 to 870 MHz with a data rate of 20 kbps. However, only the 2.4-GHz band operates worldwide; the others are regional bands. The 868–870-MHz band operates in Europe, while the 902–928-MHz band operates in North America, Australia, and other countries (ZigBee Home Page).

IEEE 802.15.4 has adopted the direct-sequence spread-spectrum (DSSS) technique in order to ensure coexistence and robustness against interference, and it uses more bandwidth than the signal transmitted without it. The standard 2.4-GHz band modulation is half-sine filtered offset quadrature phase-shift

User	Application Layer (APL)
ZigBee	Application (APS)
	Network/Security
IEEE 802.15.4	MAC
	PHY

Fig. 2.2. IEEE 802.15.4 stack

keying (OQPSK) and the 868/915-MHz bands use binary phase-shift keying (BPSK) (Maupin, 2007).

Another technique adopted for coexistence is frequency division multiple access (FDMA), which consists of dividing the 2.4-GHz band into 16 non-overlapping channels with a distance of 5 MHz between them, thus allowing devices operating in adjacent channels to coexist without problems.

In addition to the techniques described previously, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is also necessary in most networks without beacons because several devices may be working in the same channel. This technique basically consists of listening, looking for activity, and, if the channel is busy, waiting a certain amount of time and checking again, and then, if the channel is not busy, using it (ZigBee, 2007; IEEE, 2006).

2.6.2 *ZigBee Networks*

In addition to the MAC and Physical layers defined by IEEE 802.15.4 mentioned in Section 2.6.1, ZigBee defines two more layers: the Application Support layer (APS) and the Network/Security layer, shown in Fig. 2.2. The user is in charge of the Application layer on top of the Application Support layer.

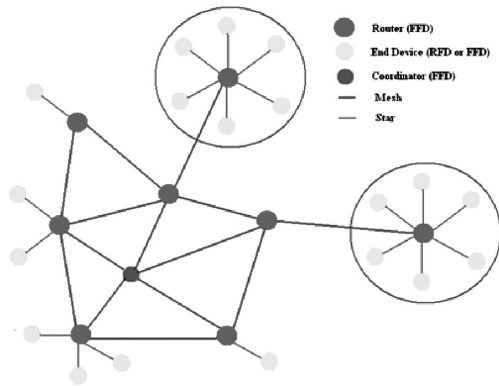
ZigBee network devices are able to communicate with data rates between 10 and 250 kbps over a 10- to 75-meter range. Depending on the memory requirements and the network size, IEEE short or long addressing can be used (Freescale ZigBee Overview).

Zigbee distinguishes among three types of network devices:

- Full-function device (FFD): FFDs have all the characteristics specified by the IEEE 802.15.4 standard and can work as a network router, end device, or both.
- Zigbee Coordinator (ZC): ZCs store all structure and node information in order to manage the network. For this task to run smoothly, good memory and computing power are fundamental.
- Reduced-function device (RFD): These devices are basically sensors and actuators with limited functionalities like send and/or receive; they know only their function, the location of the ZC, and the nearest router.

ZigBee supports star, mesh, and cluster-tree network topologies. Each has advantages over the others. Star topology networks are the most appropriate for very long battery-life applications and are formed by an FFD working as coordinator and a group of end devices. Mesh topologies provide more than one way through the network in order to increase reliability, and all the available paths are stored in the network routing table. Cluster-tree topologies are a combination of mesh and star topologies as shown in Fig. 2.3; therefore, they have the advantages of both high reliability and long battery life (Freescale ZigBee Overview).

Fig. 2.3. Cluster-tree topology



2.6.3 Zigbee Applications

Even though ZigBee is aimed at monitoring and controlling applications, it actually has a much wider range. The applications can be divided into three main groups:

- **Nonperiodical applications:** These kinds of systems can be developed so that most of their components are disconnected from the network. The devices will connect to the network only when communication is needed, thus consuming very little power. A wide variety of systems fit into this group, such as access control systems, lighting systems, remote control systems, interactive toys, etc.
- **Periodical applications:** The majority of the systems in this category are measurement systems for applications like patient or fitness monitoring or periodical process control systems. The device must be sleeping and should only wake up at the established time to perform its task; once the task is completed, the device returns to its sleeping mode.
- **Periodical low-latency applications:** There are also some periodical applications with important requirements like low latency. For these applications, beacon packets and a capability of ZigBee called Guaranteed Time Slots (GTS) need to be used in order to guarantee the time and duration of the communication without time delays (Craig).

2.6.4 ZigBee Promoters and Participants

ZigBee is a profitless alliance of more than 100 companies among semiconductor and electronic device manufacturers, with the goal of promoting this low-cost wireless technology. The ZigBee alliance has three classes of membership: promoters, participants, and adopters.

The promoters consist of semiconductor, software, and system providers and are the leaders of the alliance, representing a cross section of the wireless industry. The promoters of this alliance are BM Group, Ember, Freescale Semiconductor, Honeywell, Huawei, Mitsubishi Electric, Motorola, Philips (Lighting), Samsung, Schneider Electric, Siemens, ST Microelectronics, and Texas Instruments.

Participants play a less important role than promoters in ZigBee. Participants can attend the alliance meetings and have access to all preliminary specifications. Current participants, in alphabetical order, include Ad-Sol Nissin Corp., Airbee, Akita Electronics Systems, Alektrona, AMI Semiconductor, ArchRock, Arcom Solutions, Assa Abloy, Atalum, Atmel, Avocent, Betronic, Bubec, Cambridge Consultants, Certicom, Cirronet, Control 4, Crane Controls Group, Crossbow, Daintree Networks, Danfoss, Develco, Dust Networks, Eaton, eaZix, Eka Systems, Eldatl Embex, Epson, ETRI, Exegin, France Telecom, Fraunhofer, Frontline, Gigatek, Golden Power, Grundfos, Helicomm, Hitachi, Holley, IBBT, Innovative Wireless Technologies, Inovonics, Insta, Invensys, Integrations Associates, Itron, Jenninc, Johnson Controls, KDDI, KETI, Korwin, Legrand, LG, Marlin Controls, MaxStream, MeshNetics, Micrel, Microchip, Mikrokrets AS, Millennial Net, Mindteck, Mono Products, muRata, Nanotron, National ICT, National Instruments, NEC, Nice, Niko, NTS, OKI, Omron, One RF Technology, Orange Logic, OTSL, Radio Pulse, Renesas, RF Technologies, Rincon Research Corporation, Samsung, San Juan Software, SD System, Shinko, Silicon Laboratories, Software Technologies Group, Telecom Lab, Telegesis, Tendril, Trane TR Tech, TSC Systems, TTA, UbiquitousSystem Lab, UBIWave, Urmet Domus, Vantage Controls, Viconics, Vitelec, Winegard, Xanadu Wireless, Yamatake, Yaskawa, Yokogawa, and ZMD.

2.6.5 ZigBee System-on-Chip (SoC)

In most cases, solutions are formed by a transceiver plus a low-power microcontroller, enough to satisfy the wireless sensor's designer's needs. On other applications, a high scale of integration is required. For this purpose, some manufacturers have developed a System-on-Chip (SoC), integrating a microcontroller and a transceiver in the same package. With these integrated circuits (ICs), only a few external passive components are required to build a fully compliant ZigBee device in minimum space. Two examples are Chipcon and Freescale, whose main features are summarized as follows:

- The MC1320X family from Freescale integrates a 2.4-GHz transceiver and a powerful HCS08 processor with several memory combinations in a 5×5 -mm QFN package (Freescale Home Page; Freescale MC1320x).
- Chipcon also offers a wide variety of RF products and ZigBee solutions such as transceivers, transceivers and microcontrollers with USB, and others

(Chipcon). Interesting products from this manufacturer include the CC2430/CC2431 Systems-on-Chip, which feature an enhanced 8051 microcontroller and an IEEE802.15.4-compliant transceiver (TI, 2006).

2.6.6 Radio-Frequency Integrated Circuit Manufacturers

This section features a compilation of synthesized information from the main integrated circuit manufacturers and from some ZigBee alliance partners that developed embedded systems to evaluate the capacities of the transceivers, microcontrollers, or ZigBee software stacks instead of manufacturing a transceiver. The manufacturers that develop their own transceivers may use evaluation kits to test the effectiveness of their future radio-frequency ICs. The main features of the devices currently considered to be the most innovative and useful are shown below.

2.6.6.1 ZMD

ZMD has a great amount of experience manufacturing application-specific integrated circuits (ZMD Home Page) and focuses on applications for the electronics and automotive industries, medical technologies, and infrared interfaces. ZMD offers the ZM44102 transceiver for ZigBee and more recently developed the ZM44101 System-on-Chip. The advantages of each integrated circuit are described below.

The ZMD44101 is a fully integrated System-on-Chip CMOS transceiver that can operate in the 868.3-MHz European and in the 902-MHz to 928-MHz American ISM (industrial, scientific, and medical) bands. This transceiver has been optimized for low power and to handle data rates up to 40 kbps. In order to ensure reliable data transfers in hostile RF environments, it incorporates DSSS technology. Due to its high scale of integration, the number of external components is minimal (ZMD, 2004).

The ZMD44102 is a robust, fully integrated RF transceiver operating in the license-free European band of 868 to 870 MHz and in the American band of 902 to 928 MHz. ZMD44102 has been optimized for long range and for data rates of up to 40 kbps. DSSS technology is included, enabling ZMD44102 to operate in hostile RF environments (ZMD, 2006).

2.6.6.2 Chipcon

Chipcon, now Texas Instruments, offers a wide range of RF-IC products for short-range, low-power, low-cost, and high-integration wireless applications in the license-free sub-1-GHz and 2.4-GHz bands (Chipcon). The Chipcon ZigBee products are designed for different applications and requirements, such as

applications requiring pure transceivers (CC2420), standalone systems (CC2430), or sensor networking (CC2431) (TI, 2006).

The CC2420 is a low-cost, low-power transceiver designed to operate in the 2.4-GHz unlicensed ISM band. It supports AES encryption and authentication, together with cyclic redundancy checksum (CRC) among other features. In addition, we may find the CC2430, a System-on-Chip (SoC) solution for building ZigBee network standard nodes. It has an integrated 8051 microcontroller with a different size of flash memory depending on the version combined with the CC2420 transceiver. Chipcon also has the CC2431 SoC device with similar features to the CC2430, but engine location support is added in order to estimate the node's position in the network based on the signal strength (TI, 2006).

2.6.6.3 Atmel

Like many other silicon manufacturers, Atmel offers solutions for a wide area of wireless applications, including mobile phones, Bluetooth, or WiMAX (Atmel). The AVR-Z link platform is a ZigBee-certified and 802.15.4-compliant solution that allows wireless applications to be easily and quickly developed using free software and development kits. The use of AVR devices as the core of the systems allows the selection of a wide range of microcontrollers that support the porting of the ZigBee stack seamlessly (Atmel AVR). In addition, the AT86RF230 is one of the few transceivers developed by Atmel that is fully compliant with 802.15.4 and ZigBee applications working in the 2.4-GHz band. The AT86RF230 does not need external components to run apart from the antenna, crystal, and decoupling capacitors integrated on the chip, which leads to significant board space saving (Atmel, 2007).

2.6.6.4 Freescale

Freescale is the semiconductors division of Motorola (Freescale Home Page) that has inherited its wide experience in cable and radio communication chips. Freescale focuses on low-power wireless communications and protocols such as ZigBee in the semiconductors market. With this purpose in mind, Freescale has developed several transceiver products, like SoC devices and the MC13xxx family of transceivers (Freescale MC1320x).

The MC13203 is a 2.4-GHz band transceiver designed for wireless sensing and control applications. Like most 802.15.4-compatible devices working in this frequency band, these transceivers support data rates of 250 kbps with O-QPSK modulation and DSSS coding. Its internal architecture combines the reception and transmission circuitry necessary to reduce the number of discrete components needed for normal operation of the transceiver. Like other transceivers, the MC13203 uses the four-wire SPI interface to provide digital data connections with a microcontroller. The user must provide the low-level programming and interfacing to use the 802.15.4 MAC and ZigBee stack

supplied by Freescale. This software tool offers compatibility with the MC13xxx family of transceivers and several other microcontrollers from Freescale (Freescale MC13203).

2.6.6.5 Microchip

Microchip is a leader in the microcontroller market because of its PIC devices (Microchip Home Page). At the start of 2007, Microchip released the MRF24J40 (Microchip MRF24J40), its first low-power radio transceiver oriented toward 802.15.4 applications. Along with the release of the transceiver, Microchip announced the MiWi protocol, an 802.15.4-based protocol that is compatible with 802.15.4 devices. The main feature of MiWi is that fewer resources are needed while maintaining compatibility with other ZigBee devices. In addition, it is free, meaning that no royalties or certifications must be paid. This protocol has been designed for low-resource applications in which the number of nodes (1024), coordinators (8), chips per coordinator (127), or hops (4) is critical. One disadvantage is that the stack is designed to be used with Microchip PIC microcontrollers and with the MRF24J40 transceiver (Flowers and Yang, 2007).

Both the ZigBee and the MiWi stacks are fully compatible with the PICDEM Z demonstration board. This board allows easily developing and integrating of ZigBee applications using the Microchip MPLAB IDE as an environment and the MPLAB ICD 2 as an in-circuit programming and debugging tool. The kit includes two PICDEM Z boards with a PIC18LF4620 microcontroller, some push buttons, temperature measurement, I/O interfacing, and a daughter board with the radio chip. The initial versions of this kit prior to the release of the MRF24J40 had a third-party transceiver mounted on the RF daughter board. Finally, the kit includes the ZigBee stack supporting various functionalities (Microchip PICDEM Z).

2.6.6.6 Renesas

Renesas is an emerging corporation that sells silicon devices (Renesas Home Page). Among many integrated circuits, Renesas offers several solutions for the market of ZigBee applications. One of them is the ZigBee Development Kit, which has the necessary items to start building low-power wireless applications immediately. This kit is comprised of the hardware platform, software stack, and development environment. The hardware platform is based on the M16C Renesas microcontroller together with several peripherals like a character LCD, analog, I/O, and radio. The radio is currently only available at 2.4 GHz, but future products will support 900-MHz frequency bands. The software that runs on the M16C microcontroller is a limited version of the ZigBee and 802.15.4 MAC layers. Motes come preprogrammed with an additional demo application that acts as a packet sniffer. This software is useful in

order to track packets and data transactions between other nodes when their firmware is being debugged. The development environment is completed with a serial interface that is used to program the platform and to debug user applications through a demo version of the ZigBee Demo Kit ZDK for M16C software (Renesas ZDK).

2.6.6.7 Silicon Laboratories

The IC-specialty firm Silicon Labs offers several solutions for the ZigBee and 802.15.4 protocols (SiLabs Home Page). The microcontrollers of the 8051 family from Silicon Labs are optimal for low-power wireless applications like ZigBee. Silicon Labs has developed microcontroller kits that are available in order to test the platforms and implement future applications. As an example, the ZigBee-2.4-DK is a development kit that allows the user to create ZigBee applications from scratch. It has six target boards and the necessary accessories and software to make it work; each board consists of a Chipcon CC2420 transceiver connected to a C8051F121 microcontroller including USB and JTAG interfaces (SiLabs ZDK; SiLabs AN222). The software tool also consists of an integrated development environment based on the Keil C compiler and software stack, including the ZigBee and 802.15.4 MAC layers. It also includes an application programming interface (API) for personal computers, which has the necessary network primitives to build applications that can manage a ZigBee-based network (SiLabs AN241; SiLabs AN242).

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Problem Solving for Wireless Sensor Networks

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