

Zigbee

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Zigbee is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. Hence, Zigbee is a low-power, low data rate, and close proximity (i.e., personal area) wireless ad hoc network.

The technology defined by the Zigbee specification is intended to be simpler and less expensive than other wireless personal area networks (WPANs), such as Bluetooth or more general wireless networking such as Wi-Fi. Applications include wireless light switches, home energy monitors, traffic management systems, and other consumer and industrial equipment that requires short-range low-rate wireless data transfer.

Its low power consumption limits transmission distances to 10–100 meters line-of-sight, depending on power output and environmental characteristics.^[1] Zigbee devices can transmit data over long distances by passing data through a mesh network of intermediate devices to reach more distant ones. Zigbee is typically used in low data rate applications that require long battery life and secure networking (Zigbee networks are secured by 128 bit symmetric encryption keys.) Zigbee has a defined rate of 250 kbit/s, best suited for intermittent data transmissions from a sensor or input device.

Zigbee was conceived in 1998, standardized in 2003, and revised in 2006. The name refers to the waggle dance of honey bees after their return to the beehive.^[2]

Zigbee



A Zigbee module	
International standard	IEEE 802.15.4
Developed by	Zigbee Alliance
Industry	Industrial, scientific and medical
Physical range	10 to 20 meters (approx)

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Overview

Zigbee is a low-cost, low-power, wireless mesh network standard targeted at the wide development of long battery life devices in wireless control and monitoring applications. Zigbee devices have low latency, which further reduces average current. Zigbee chips are typically integrated with radios and with microcontrollers that have between 60-256 KB of flash memory. Zigbee operates in the industrial, scientific and medical (ISM) radio bands: 2.4 GHz in most jurisdictions worldwide; though some devices also use 784 MHz in China, 868 MHz in Europe and 915 MHz in the USA and Australia, however even those regions and countries still use 2.4 GHz for most commercial Zigbee devices for home use. Data rates vary from 20 kbit/s (868 MHz band) to 250 kbit/s (2.4 GHz band).

The Zigbee network layer natively supports both star and tree networks, and generic mesh networking. Every network must have one coordinator device, tasked with its creation, the control of its parameters and basic maintenance. Within star networks, the coordinator must be the central node. Both trees and meshes allow the use of Zigbee routers to extend communication at the network level.

Zigbee builds on the physical layer and media access control defined in IEEE standard 802.15.4 for low-rate WPANs. The specification includes four additional key components: network layer, application layer, *Zigbee Device Objects* (ZDOs) and manufacturer-defined application objects which allow for customization and favor total integration. ZDOs are responsible for some tasks, including keeping track of device roles, managing requests to join a network, as well as device discovery and security.

Zigbee is one of the global standards of communication protocol formulated by the significant task force under the IEEE 802.15 working group. The fourth in the series, WPAN Low Rate/Zigbee is the newest and provides specifications for devices that have low data rates, consume very low power and are thus characterized by long battery life. Other standards like Bluetooth and IrDA address high data rate applications such as voice,^[3] video and LAN communications.

Zigbee provides the ability to run for years on inexpensive batteries for a host of monitoring and control applications. The Zigbee network layer ensures that networks remain operable in the conditions of a constantly changing quality between communication nodes. The Zigbee advantage is the Zigbee protocol which is designed to communicate data through hostile RF environment that are common in commercial and industrial application. Its protocol features include support for multiple network topologies such as; point to point and mesh network, collision avoidance and retries, and low latency. Another defining feature of Zigbee is facilities for carrying out secure communications, protecting establishment and transport of cryptographic keys, cyphering frames, and controlling device. It builds on the basic security framework defined in IEEE 802.15.4.

History

Zigbee-style self-organizing ad-hoc digital radio networks were conceived in the 1990s. The IEEE 802.15.4-2003 Zigbee specification was ratified on December 14, 2004.^[4] The Zigbee Alliance announced availability of Specification 1.0 on June 13, 2005, known as the *Zigbee 2004 Specification*.

Cluster Library

In September 2006, the *Zigbee 2006 Specification* was announced, obsoleting the 2004 stack^[5] (2006 mainly replaces the Message/Key Value Pair structure used in 2004 with a "cluster library").

The library is a set of standardised commands, organised under groups known as clusters with names such as *Smart Energy*, *Home Automation*, *Zigbee Light Link*.^[6]

In January 2017 they renamed it to Dotdot and announced it as a new protocol to be represented by an emoticon ||; they also announced it will now additionally run over other network types using Internet Protocol^[7] and will interconnect with other standards such as Thread^[8]

Zigbee PRO

Zigbee PRO, also known as Zigbee 2007, the enhanced *Zigbee Pro Specification*, was posted on 31 October 2007, and was finalized that same year. Zigbee PRO is fully backward-compatible with Zigbee 2006 devices. A Zigbee 2007 device may join and operate on a Zigbee 2006 network and vice versa. Due to differences in routing options, Zigbee PRO devices must become non-routing Zigbee End-Devices (ZEDs) on a Zigbee 2006 network, and Zigbee 2006 devices must become ZEDs on a Zigbee PRO network. The applications running on those devices work the same, regardless of the stack profile beneath them. The first Zigbee Application Profile, Home Automation, was announced November 2, 2007.

Use cases

Zigbee protocols are intended for embedded applications requiring **low power consumption** and tolerating **low data rates**. Zig-Bee is not for situations with high mobility among nodes. Hence, it is not suitable for tactical ad hoc radio networks in the battlefield, where high data rate and high mobility is present and needed. The resulting network will use very small amounts of power — individual devices must have a battery life of at least two years to pass Zigbee certification.^[9]

Typical application areas include:^[10]

- Home Entertainment and Control — Home automation such as in QIVICON,^[11] smart lighting,^[12] advanced temperature control, safety and security, movies and music
- Wireless sensor networks — Starting with individual sensors like Telosb/Tmote and Iris from Memsic
- Industrial control
- Embedded sensing
- Medical data collection
- Smoke and intruder warning
- Building automation
- Remote wireless microphone configuration, in Shure Wireless Microphone Systems^[13]

Standard and profiles

Established in 2002, the Zigbee Alliance is a group of companies that maintain and publish the Zigbee standard.^[14] The term **Zigbee** is a registered trademark of this group, not a single technical standard. The Alliance publishes application profiles that allow multiple OEM vendors to create interoperable products. The relationship between IEEE 802.15.4 and >igbee^[15] is similar to that between IEEE 802.11 and the Wi-Fi Alliance.

Zigbee Alliance Membership

The Zigbee Alliance has three levels of membership: Adopter, Participant, and Promoter.^[16] The Adopter members are allowed access to completed Zigbee specifications and standards, and the Participant members have voting rights, play a role in Zigbee development, and have early access to specifications and standards for product development.

The requirements for membership in the Zigbee alliance cause problems for Free Software developers because the annual fee conflicts with the GNU General Public Licence.^[17] The requirement for the developer to join the Zigbee Alliance similarly conflicts with most other free software licenses.^[18]

The Zigbee Alliance board has been asked to make their license compatible with GPL, but refused.^[19] Bluetooth has GPL licensed implementations.^[20]

Application profiles

The current list of application profiles either published, or in development are:

Released specifications

- Home Automation 1.2
- Smart Energy 1.1b
- Smart Energy 1.2
- Smart Energy 1.2a
- Smart Energy 1.2b
- Telecommunication Services 1.0
- Health Care 1.0
- RF4CE – Remote Control 1.0
- RF4CE – Input Device 1.0
- Remote Control 2.0
- Light Link 1.0
- IP 1.0
- Commercial Building Automation 1.0
- Gateway 1.0
- Green Power 1.0 (Optional battery-less remote control feature of Zigbee 2012)
- Retail Services

Specifications under development

- Zigbee Smart Energy 2.0
- Smart Energy 1.3 (not released)
- Smart Energy 1.4
- Light Link 1.1
- Home Automation 1.3

The **Zigbee Smart Energy V2.0** specifications define an Internet protocol to monitor, control, inform and automate the delivery and use of energy and water. It is an enhancement of the Zigbee Smart Energy version 1 specifications.^[21] It adds services for plug-in electric vehicle charging, installation, configuration and firmware download, prepay services, user information and messaging, load control, demand response and common information and application profile interfaces for wired and wireless networks. It is being developed by partners including:

- HomeGrid Forum responsible for marketing and certifying ITU-T G.hn technology and products
- HomePlug Powerline Alliance
- International Society of Automotive Engineers SAE International
- IPSO Alliance
- SunSpec Alliance
- Wi-Fi Alliance.

Zigbee Smart Energy relies on Zigbee IP, a network layer that routes standard IPv6 traffic over IEEE 802.15.4 using 6LoWPAN header compression.^{[22][23]}

In 2009, the RF4CE (Radio Frequency for Consumer Electronics) Consortium and Zigbee Alliance agreed to deliver jointly a standard for radio frequency remote controls. Zigbee RF4CE is designed for a broad range of consumer electronics products, such as TVs and set-top boxes. It promised many advantages over existing remote control solutions, including richer communication and increased reliability, enhanced features and flexibility, interoperability, and no line-of-sight barrier.^[24] The Zigbee RF4CE specification lifts off some networking weight and does not support all the mesh features, which is traded for smaller memory configurations for lower cost devices, such as remote control of consumer electronics.

With the introduction of the second Zigbee RF4CE application profile in 2012 and increased momentum in MSO market, the Zigbee RF4CE team provides an overview on current status of the standard, applications, and future of the technology.^{[25][26]}

Radio hardware

The radio design used by Zigbee has been carefully optimized for low cost in large scale production. It has few analog stages and uses digital circuits wherever possible.

Though the radios themselves are inexpensive, the Zigbee Qualification Process involves a full validation of the requirements of the physical layer. All radios derived from the same validated semiconductor mask set would enjoy the same RF characteristics. An uncertified physical layer that malfunctions could cripple the battery lifespan of other devices on a Zigbee network. Zigbee radios have very tight constraints on power and bandwidth. Thus, radios are tested with guidance given by Clause 6 of the 802.15.4-2006 Standard. Most vendors plan to integrate the radio and microcontroller onto a single chip^[27] getting smaller devices.^[28]

This standard specifies operation in the unlicensed 2.4 to 2.4835 ^[29]GHz (worldwide), 902 to 928 MHz (Americas and Australia) and 868 to 868.6 MHz (Europe) ISM bands. Sixteen channels are allocated in the 2.4 GHz band, with each channel spaced 5 MHz apart, though using only 2 MHz of bandwidth. The radios use direct-sequence spread spectrum coding, which is managed by the digital stream into the modulator. Binary phase-shift keying (BPSK) is used in the 868 and 915 MHz bands, and offset quadrature phase-shift keying (OQPSK) that transmits two bits per symbol is used in the 2.4 GHz band.

The raw, over-the-air data rate is 250 kbit/s per channel in the 2.4 GHz band, 40 kbit/s per channel in the 915 MHz band, and 20 kbit/s in the 868 MHz band. The actual data throughput will be less than the maximum specified bit rate due to the packet overhead and processing delays. For indoor applications at 2.4 GHz transmission distance may be 10–20 m, depending on the construction materials, the number of walls to be penetrated and the output power permitted in that geographical location.^[30] Outdoors with line-of-sight, range may be up to 1500 m depending on power output and environmental characteristics^[1]. The output power of the radios is generally 0-20 dBm (1-100 mW).

Device types and operating modes

Zigbee devices are of three kinds:

- *Zigbee Coordinator (ZC)*: The most capable device, the Coordinator forms the root of the network tree and might bridge to other networks. There is precisely one Zigbee Coordinator in each network since it is the device that started the network originally (the Zigbee LightLink specification also allows operation without a Zigbee Coordinator, making it more usable for off-the-shelf home products). It stores information about the network, including acting as the Trust Center & repository for security keys.^{[31][32]}
- *Zigbee Router (ZR)*: As well as running an application function, a Router can act as an intermediate router, passing on data from other devices.
- *Zigbee End Device (ZED)*: Contains just enough functionality to talk to the parent node (either the Coordinator or a Router); it cannot relay data from other devices. This relationship allows the node to be asleep a significant amount of the time thereby giving long battery life. A ZED requires the least amount of memory, and, therefore, can be less expensive to manufacture than a ZR or ZC.

The current Zigbee protocols support beacon and non-beacon enabled networks. In non-beacon-enabled networks, an unslotted CSMA/CA channel access mechanism is used. In this type of network, Zigbee Routers typically have their receivers continuously active, requiring a more robust power supply. However, this allows for heterogeneous networks in which some devices receive continuously while others only transmit when an external stimulus is detected. The typical example of a heterogeneous network is a wireless light switch: The Zigbee node at the lamp may constantly receive, since it is connected to the mains supply, while a battery-powered light switch would remain asleep until the switch is thrown. The switch then wakes up, sends a command to the lamp, receives an acknowledgment, and returns to sleep. In such a network the lamp node will be at least a Zigbee Router, if not the Zigbee Coordinator; the switch node is typically a Zigbee End Device.

In beacon-enabled networks, the special network nodes called Zigbee Routers transmit periodic beacons to confirm their presence to other network nodes. Nodes may sleep between beacons, thus lowering their duty cycle and extending their battery life. Beacon intervals depend on data rate; they may range from 15.36 milliseconds to 251.65824 seconds at 250 kbit/s, from 24 milliseconds to 393.216 seconds at 40 kbit/s and from 48 milliseconds to 786.432 seconds at 20 kbit/s. However, low duty cycle operation with long beacon intervals requires precise timing, which can conflict with the need for low product cost.

In general, the Zigbee protocols minimize the time the radio is on, so as to reduce power use. In beaconing networks, nodes only need to be active while a beacon is being transmitted. In non-beacon-enabled networks, power consumption is decidedly asymmetrical: Some devices are always active while others spend most of their time sleeping.

Except for the Smart Energy Profile 2.0, Zigbee devices are required to conform to the IEEE 802.15.4-2003 Low-Rate Wireless Personal Area Network (LR-WPAN) standard. The standard specifies the lower protocol layers—the physical layer (PHY), and the Media Access Control portion of the data link layer (DLL). The basic channel access mode is "carrier sense, multiple access/collision avoidance" (CSMA/CA). That is, the nodes talk in the same way that humans converse; they briefly check to see that no one is talking before he or she starts, with three notable exceptions. Beacons are sent on a fixed timing schedule and do not use CSMA. Message acknowledgments also do not use CSMA. Finally, devices in beacon-enabled networks that have low latency real-time requirements may also use Guaranteed Time Slots (GTS), which by definition do not use CSMA.

Software

The software is designed to be easy to develop on small, inexpensive microprocessors. For more detail, please use one or more of the sources listed in the References section below, or go directly to the Zigbee Alliance web site using the External links provided below.

Network layer

The main functions of the network layer are to enable the correct use of the MAC sublayer and provide a suitable interface for use by the next upper layer, namely the application layer. Its capabilities and structure are those typically associated to such network layers, including routing. The Network Layer's function is exactly as it sounds. It deals with network functions such as connecting, disconnecting, and setting up networks. It will add a network, allocate addresses, and add/remove certain devices. This layer makes use of star, mesh and tree topologies. It adds an interface to the application layer.

On the one hand, the *data entity* creates and manages network layer data units from the payload of the application-layer and performs routing according to the current topology. On the other hand, there is the layer *control*, which is used to handle configuration of new devices and establish new networks: it can determine whether a neighboring device belongs to the network and discovers new neighbors and routers. The control can also detect the presence of a receiver, which allows direct communication and MAC synchronization.

The routing protocol used by the network layer is AODV, which has similar properties to Associativity-based Routing^[33] (ABR). Unlike AODV, ABR was a patented routing protocol invented in 1994 at Cambridge University, England. AODV was a working IETF draft, which consistently added features from a variety of suggestions and sources over time. In AODV, to find the destination device, AODV broadcasts out a route request to all of its neighbors. The neighbors then broadcast the request to their neighbors and onward until the destination is reached. Once the destination is reached, it sends its route reply via unicast transmission following the lowest cost path back to the source. This approach of route discovery is **exactly similar** to those of Associativity-based Routing,^[34] except that ABR does not use sequence number or distance vectors. Once the source receives the reply, it will update its routing table for the destination address of the next hop in the path and the path cost.

Application layer

The application layer is the highest-level layer defined by the specification and is the effective interface of the Zigbee system to its end users. It comprises the majority of components added by the Zigbee specification: both ZDO and its management procedures, together with application objects defined by the manufacturer, are considered part of this layer. This layer binds tables, sends messages between bound devices, manages group addresses, reassembles packets and also transports data. It is responsible for providing service to Zigbee device profiles.

Main components

The *ZDO* (Zigbee Device Object), a protocol in the Zigbee protocol stack, is responsible for overall device management, security keys, and policies. It is responsible for defining the role of a device as either coordinator or end device, as mentioned above, but also for the discovery of new (one-hop) devices on the network and the identification of their offered services. It may then go on to establish secure links with external devices and reply to binding requests accordingly.

The *application support sublayer* (APS) is the other main standard component of the layer, and as such it offers a well-defined interface and control services. It works as a bridge between the network layer and the other elements of the application layer: it keeps up-to-date binding tables in the form of a database, which can be used to find appropriate devices depending on the services that are needed and those the different devices offer. As the union between both specified layers, it also routes messages across the layers of the protocol stack.

Communication models

An application may consist of communicating objects which cooperate to carry out the desired tasks. The focus of Zigbee is to distribute work among many different devices which reside within individual Zigbee nodes which in turn form a network (said work will typically be largely local to each device, for instance, the control of each household appliance).

The collection of objects that form the network communicates using the facilities provided by APS, supervised by ZDO interfaces. The application layer data service follows a typical request-confirm/indication-response structure. Within a single device, up to 240 application objects can exist, numbered in the range 1-240. 0 is reserved for the ZDO data interface and 255 for broadcast; the 241-254 range is not currently in use but may be in the future.

Two services are available for application objects to use (in Zigbee 1.0):

- The *key-value pair service* (KVP) is meant for configuration purposes. It enables description, request and modification of object attribute through a simple interface based on getting/set and event primitives, some allowing a request for a response. Configuration uses compressed XML (full XML can be used) to provide an adaptable and elegant solution.
- The *message service* is designed to offer a general approach to information treatment, avoiding the necessity to adapt application protocols and potential overhead incurred on by KVP. It allows arbitrary

payloads to be transmitted over APS frames.

Addressing is also part of the application layer. A network node consists of an 802.15.4-conformant radio transceiver and one or more device descriptions (basically collections of attributes which can be polled or set, or which can be monitored through events). The transceiver is the base for addressing, and devices within a node are specified by an *endpoint identifier* in the range 1-240.

Communication and device discovery

For applications to communicate, their comprising devices must use a common application protocol (types of messages, formats and so on); these sets of conventions are grouped in *profiles*. Furthermore, binding is decided upon by matching input and output cluster identifiers, unique within the context of a given profile and associated to an incoming or outgoing data flow in a device. Binding tables contain source and destination pairs.

Depending on the available information, device discovery may follow different methods. When the network address is known, the IEEE address can be requested using unicast communication. When it is not, petitions are broadcast (the IEEE address being part of the response payload). End devices will simply respond with the requested address while a network coordinator or a router will also send the addresses of all the devices associated with it.

This extended discovery protocol permits external devices to find out about devices in a network and the services that they offer, which endpoints can report when queried by the discovering device (which has previously obtained their addresses). Matching services can also be used.

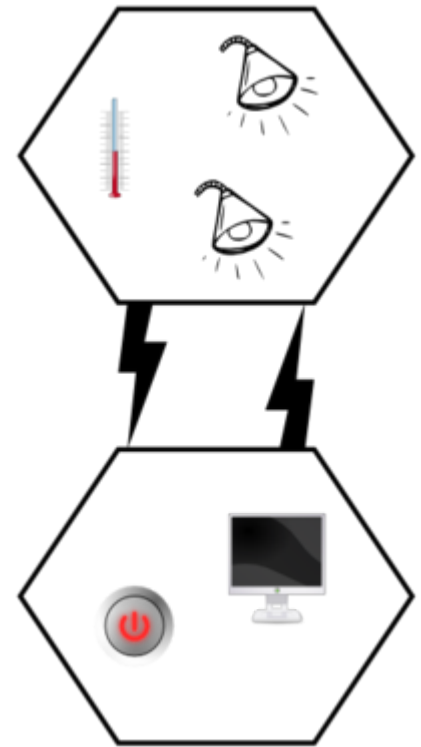
The use of cluster identifiers enforces the binding of complementary entities using the binding tables, which are maintained by Zigbee coordinators, as the table must always be available within a network and coordinators are most likely to have a permanent power supply. Backups, managed by higher-level layers, may be needed by some applications. Binding requires an established communication link; after it exists, whether to add a new node to the network is decided, according to the application and security policies.

Communication can happen right after the association. *Direct addressing* uses both radio address and endpoint identifier, whereas indirect addressing uses every relevant field (address, endpoint, cluster, and attribute) and requires that they are sent to the network coordinator, which maintains associations and translates requests for communication. *Indirect addressing* is particularly useful to keep some devices very simple and minimize their need for storage. Besides these two methods, *broadcast* to all endpoints in a device is available, and *group addressing* is used to communicate with groups of endpoints belonging to a set of devices.

Security services

As one of its defining features, Zigbee provides facilities for carrying out secure communications, protecting establishment and transport of cryptographic keys, cyphering frames, and controlling devices. It builds on the basic security framework defined in IEEE 802.15.4. This part of the architecture relies on the correct management of symmetric keys and the correct implementation of methods and security policies.

Basic security model



Zigbee, high-level communication model

The basic mechanism to ensure confidentiality is the adequate protection of all keying material. Trust must be assumed in the initial installation of the keys, as well as in the processing of security information. For an implementation to globally work, its general conformance to specified behaviors is assumed.

Keys are the cornerstone of the security architecture; as such their protection is of paramount importance, and keys are never supposed to be transported through an insecure channel. A momentary exception to this rule occurs during the initial phase of the addition to the network of a previously unconfigured device. The Zigbee network model must take particular care of security considerations, as ad hoc networks may be physically accessible to external devices. Also the state of the working environment cannot be predicted.

Within the protocol stack, different network layers are not cryptographically separated, so access policies are needed, and conventional design assumed. The open trust model within a device allows for key sharing, which notably decreases potential cost. Nevertheless, the layer which creates a frame is responsible for its security. If malicious devices may exist, every network layer payload must be ciphered, so unauthorized traffic can be immediately cut off. The exception, again, is the transmission of the network key, which confers a unified security layer to the grid, to a new connecting device.

Security architecture

Zigbee uses 128-bit keys to implement its security mechanisms. A key can be associated either to a network, being usable by both Zigbee layers and the MAC sublayer, or to a link, acquired through pre-installation, agreement or transport. Establishment of link keys is based on a master key which controls link key correspondence. Ultimately, at least, the initial master key must be obtained through a secure medium (transport or pre-installation), as the security of the whole network depends on it. Link and master keys are only visible to the application layer. Different services use different one-way variations of the link key to avoid leaks and security risks.

Key distribution is one of the most important security functions of the network. A secure network will designate one special device which other devices trust for the distribution of security keys: the trust center. Ideally, devices will have the center trust address and initial master key preloaded; if a momentary vulnerability is allowed, it will be sent as described above. Typical applications without special security needs will use a network key provided by the trust center (through the initially insecure channel) to communicate.

Thus, the trust center maintains both the network key and provides point-to-point security. Devices will only accept communications originating from a key supplied by the trust center, except for the initial master key. The security architecture is distributed among the network layers as follows:

- The MAC sublayer is capable of single-hop reliable communications. As a rule, the security level it is to use is specified by the upper layers.
- The network layer manages routing, processing received messages and being capable of broadcasting requests. Outgoing frames will use the adequate link key according to the routing if it is available; otherwise, the network key will be used to protect the payload from external devices.
- The application layer offers key establishment and transport services to both ZDO and applications.

The security levels infrastructure is based on CCM*, which adds encryption- and integrity-only features to CCM.

According to a German computer magazine website, Zigbee Home Automation 1.2 is using fallback keys for encryption negotiation which are known and cannot be changed. This makes the encryption highly vulnerable.^[35]

Simulation of Zigbee networks

Network simulators, like NS2, OPNET, and NetSim can be used to simulate IEEE 802.15.4 Zigbee networks.

These simulators come with open source C or C++ libraries for users to modify. This way users can determine the validity of new algorithms before hardware implementation.

See also

- Wireless ad hoc networks
- Mobile ad hoc networks
- Bluetooth mesh networking
- HaLow
- DASH7
- Z-Wave – RF mesh technology
- Thread (network protocol)
- 6LoWPAN
- INSTEON – dual-mesh (RF and Powerline) technology
- EnOcean
- LoRaWAN
- Comparison of 802.15.4 radio modules
- Comparison of wireless data standards

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External links

- [Official website](#)

- Smart Energy Documents (V2.0)
- Alliance Documents
 - "ZigBee RF4CE: A Quiet Revolution is Underway" (PDF). December 2012. Archived from the original (PDF) on 2013-01-18.
- What does ZigBee Pro mean for your application? by Jack Shandle, 27 November 2007
- The ZigBee PRO Feature Set: More of a good thing by Bob Gohn, 18 December 2007
- ZBOSS ZigBee Open Source Stack, (Certified by Zigbee alliance)
- Zigbee for M2M Technology Find out how Zigbee can be used for M2M communications
- FreakZ open source Zigbee project, Project homepage, and Zigbee/802.15.4 chip comparison
- ZigBee wants to be the Bluetooth of the internet of things. Too bad everyone hates it.

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