White Paper

Which radio data transmission protocol matches to my application?

802.15.4 based radio standards by comparision

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July 2012
Abstract

Meanwhile a number of protocols for wireless data transmission and the structure of networks based on 802.15.4 are established. To the most important ones belong 802.15.4 MAC, 6LoWPAN, ZigBee PRO and RF4CE. They differ from each other not only in the setup of the network structure but also in their performance. Depending on the actual requirements in the specific case of application the developer has to choose the matching protocol. The protocol determines the structure of the network and the performance as well as the development effort.

This document gives an overview of the most important 802.15.4 based protocols and compares them with respect to their most important features and typical fields of application. This helps the reader to choose the matching protocol for his application.
## Glossary

The glossary gives an overview of the terms and definitions used in this white paper.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.15.4</td>
<td>IEEE 802.15.4-standard, applicable to low-rate wireless Personal Area Network (WPAN)</td>
</tr>
<tr>
<td>6LoWPAN</td>
<td>IPv6 over Low power Wireless Personal Area Networks</td>
</tr>
<tr>
<td>Hop</td>
<td>Stopover of a route as well as the way from one network node to the next</td>
</tr>
<tr>
<td>IETF</td>
<td>Internet Engineering Task Force</td>
</tr>
<tr>
<td>IPSO</td>
<td>Internet Protocol for Smart Objects (Alliance)</td>
</tr>
<tr>
<td>IPv6</td>
<td>Internet protocol version 6, version of the Internet Protocol (IP) intended to succeed IPv4 which is the protocol currently used to direct almost all internet traffic.</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control ... layer, address etc.</td>
</tr>
<tr>
<td>MPDU</td>
<td>MAC Protocol Data Unit</td>
</tr>
<tr>
<td>MTU</td>
<td>Maximum Transmission Unit</td>
</tr>
<tr>
<td>NWK</td>
<td>Network</td>
</tr>
<tr>
<td>OSI</td>
<td>Open Systems Interconnection (OSI) model, a prescription of characterizing and standardizing the functions of a communications system in terms of abstraction layers</td>
</tr>
<tr>
<td>PAN</td>
<td>Personal Area Network</td>
</tr>
<tr>
<td>PHY</td>
<td>OSI model layer 1: The physical layer defines electrical and physical specifications for devices. It defines the relationship between a device and a transmission medium including the layout of all hardware components.</td>
</tr>
<tr>
<td>RPL</td>
<td>Routing Protocol for low power and Lossy networks</td>
</tr>
<tr>
<td>ROLL</td>
<td>Routing Over Low power and Lossy networks</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>uIP</td>
<td>Micro IP stack</td>
</tr>
<tr>
<td>MPDU</td>
<td>MAC Protocol Data Unit</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td>ZigBee</td>
<td>Low-cost, low-power wireless mesh network standard. The ZigBee Alliance is a group of companies that maintain and publish the ZigBee standard.</td>
</tr>
</tbody>
</table>
802.15.4 MAC

Amongst all presented protocols this one embodies the simplest execution. All other – 6LoWPAN, ZigBee und RF4CE – use 802.15.4 MAC as subjacent protocol layer, see Figure 1. The bottommost layer (PHY) as well as the MAC layer is the same at all protocols. Here it is only defined by which method the data are transmitted. For example it is declared which frequencies, modulation- and encoding procedures are used. The following figure compares the structure of the different protocol layers according the OSI model:

<table>
<thead>
<tr>
<th>OSI layer</th>
<th>802.15.4 MAC</th>
<th>6LoWPAN</th>
<th>ZigBee</th>
<th>RF4CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>User defined</td>
<td>User defined</td>
<td>Standardized and user defined ZigBee profiles</td>
<td>Public or proprietary application profile</td>
</tr>
<tr>
<td>Presentation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td></td>
<td>e.g. UDP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Network</td>
<td></td>
<td>IPv6</td>
<td>ZigBee NWK layer</td>
<td>ZigBee RF4CE NWK layer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6LoWPAN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data link</td>
<td>802.15.4 MAC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical</td>
<td>802.15.4 PHY</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: Classification of different protocols in the OSI model

Higher layers such as the network layer are responsible for the organization of the network. They are different from protocol to protocol, or rather not existing. According to this network structure and complexity are differing. As you can see in Figure 1 all other protocols are established on the 802.15.4 MAC. It is linguistically as well as conceptual used as synonym for the binary transmission and safety layer.

As the MAC is lacking in a real network layer it only provides basic functions; thus there are a number of advantages. The memory requirements for example are very low: This allows the application of low cost 8-bit controllers with small flash size (32 to 128 kB). If large lot sizes are targeted it results in a cost advantage by low part costs. Moreover this gives the developer an ample scope concerning the implementation of own protocols. Depending on the complexity of the application and an appropriate implementation very short switch-on times (and long stand-by times respectively) of the nodes can be accomplished. Thereby the current consumption can be reduced to a minimum. This predestinates the pure MAC layer for energy harvesting applications as well as for devices whereby a very long battery change cycle shall be reached. Furthermore, bottom-up on the proprietary protocol extensions of the MAC layer, by far higher data rates can be reached compared to e.g. ZigBee or 6LoWPAN. The minimalist architecture of 802.15.4 additionally contributes to the ability to reach very low network laten-
cies. This of course is only possible if the nodes in between of which the latency is measured are not sleeping and the data transmission is not executed via several hops.

The implementation based on the MAC layer can confront the developer with some hurdles that have to be considered. For example routing is not designed. In other words, if the application requires the development of a network structure going beyond static addressing, routing schemes possibly have to be implemented “by hand”. For smaller networks <10 nodes it is still manageable, with increasing complexity however it can mean considerable additional effort for implementation and test. For this reason the MAC layer is especially adapted for connection types not requiring routing, e.g. star topologies or point-to-point connections. Especially simple designed radio networks can use peer-to-peer connections where a coordinator is not necessary. The nodes can e.g. address itself directly or they can send broadcast telegrams.

Implementations

Basically all manufacturers of 802.15.4 transceivers offer appropriate 802.15.4 MAC software together with their chips (e.g. Atmel's IEEE 802.15.4 MAC). An exception is ZMDi: here the MAC is integrated into the hardware of the transceiver.

Preferred fields of application

- Is especially suitable for simple point-to-point connections (“wire substitute”)
- Implementation of proprietary protocol layers
- In extreme resource-limited systems, e.g. in energy harvesting solutions or very long battery change cycles

6LoWPAN

6LoWPAN is an acronym for IPv6 over Low Power Wireless Personal Area Networks (with low energy consumption). 6LoWPAN is the name of the IETF task group which is responsible for this standard; at the same time it is used as synonym for the above mentioned communication protocol. Although 6LoWPAN is commonly classed among the protocols, it only represents an adaption layer in the strict sense; the real used network protocol is called IPv6. So 6LoWPAN offers a smart possibility to apply IPv6 on 802.15.4 based nodes. The idea behind this approach is to create an option to integrate sensor networks into the already existing IP infrastructure. Indeed this is also possible using other protocols such as e.g. ZigBee, but in case of 6LoWPAN the effort of gateways (which execute the protocol implementation) is omitted.

The standard 6LoWPAN comprises among others header compression procedures which make it possible to transmit IPv6 packets via IEEE 802.15.4 based networks without the need of transmitting the complete IPv6 header. The functional principle of these procedures is based on the fact that particular information of the IP header can be gained from the subjacent 802.15.4 layer. 6LoWPAN is
aimed at integrating wireless PANs with the lowest possible effort into existing nets. A typical setup of a 6LoWPAN net shows the figure below:

**Figure 2: Multiple WSNs connected to the internet or IP infrastructure by border router** (source: IPSO Alliance [1])

Significant at this are the border routers which act as 6LoWPAN gateway; they connect the WSNs to the global IP infrastructure.

6LoWPAN introduces a fragmentation scheme as the maximal size of the MPDU of 802.15.4 is only 127 bytes. This corresponds less than 10% of the so called Maximum Transmission Unit (MTU) of an IPv6 frame. In other words, if a data packet of a size greater than the permissible 127 bytes is to be transferred this mechanism is used to subdivide the data into several individual packets.

Beside fragmentation the header compression is an important element of 6LoWPAN: Thereby the protocol overhead is partial greatly decreased. The IPv6 header has a fixed length of 40 bytes. Together with the smallest possible 802.15.4 header this would result in a minimum overhead of 45 bytes which corresponds approx. 35% of the maximum possible frame length of 802.15.4. In **Figure 3** the length of the headers dependent on the addressed network segment is illustrated. For the by means of 6LoWPAN compressed header the resulting length is between 7 and 31 bytes.
Figure 3: Header structure of 802.15.4 and 6LoWPAN

The WSN’s nodes use a complete IPv6 stack; but caused by using IPv6 the emerging overhead is decreased by application of the header compression. For the application on resource-limited devices (e.g. 8-bit microcontroller) especially compact stacks are used, such as e.g. uIP. That implies that when using 6LoWPAN, protocols such e.g. UDP can be applied. Therewith 6LoWPAN leaves the implementation of higher layers (of the OSI reference model) up to the application layer open.

To organize the network different approaches exist, e.g. route over or mesh under. Another IETF task group (Routing Protocol for Low power and Lossy Networks - ROLL) deals with dynamic routing procedures which are better adapted to the conditions of WSNs. One preliminary result out of it is the RPL (Routing Protocol for Low power and Lossy Networks). It connects demands of an efficient energy management (long power-down phases) with the advantages of IPv6. Currently it is applied e.g. in ContikiRPL.

Preferred fields of application

By using IPv6 6LoWPAN is optimally suited to embed radio link and sensor networks respectively into an existing IP infrastructure, to link e.g. individual sensor nodes or even networks to the internet. 6LoWPAN is also applied in the field of machine-to-machine communication; for example it is used by SP100.11. Hence 6LoWPAN is interesting in the field of industrial automation, too.
ZigBee

The ZigBee specifications are published and maintained by the ZigBee Alliance; currently there are ZigBee PRO and ZigBee RF4CE (see section RF4CE). This industrial alliance consists of several large enterprises that develop the standards and specifications, carry out the certification of their products and are involved in financing the alliance. The BitCloud stack for example has been published by Atmel. This ZigBee Pro is exemplary used in this section for a ZigBee stack. Meanwhile there are a great number of further implementations beyond that by other manufacturers. The certification of completed products by accredited institutes as well as ZigBee implementations by the alliance itself plays an important role in the process: Thus interoperability of ZigBee devices of different manufacturers is ensured.

From the developer’s view ZigBee offers a couple of advances compared to the 802.15.4 MAC. A number of different functions are already implemented; for example the mechanisms for over-the-air firmware update, channel agility, low-power operation, the application of safety certificates as well as different prefabricated application profiles. Thereby development time is effectively saved; the developer is dispensed from the implementation effort for the network layer. A comparably low network latency, high data rates as well as low power consumption are of course possible with ZigBee. A more hardware-close and application specific implementation based on 802.15.4 MAC can however often result in a considerably better performance concerning these parameters. Especially important when applying ZigBee is the formation of so called mesh networks (meshed network topology). Due to the high number of possible packet routes and by high redundancy the transmission reliability is enhanced compared to other network topologies. Figure 4 shows the structure of such a net as an example.

![Figure 4: Structure of a ZigBee mesh network](source: ZigBee Alliance [2])
ZigBee is equipped with a highly-developed powerful data link layer. For the user this means high transmission reliability. By using acknowledgements (ACKs) the successful transmission of a telegram is confirmed. In case of transmission interference this can be detected and the data are sent again at a later date.

Additionally ZigBee offers the developer certain scalability. The fitting stack is available in different expansion stages. And ZigBee provides the basic network functions. Based on this it is also possible to use different application profiles such as e.g. smart energy or home automation. These profiles access the ZigBee Cluster Library; they are e.g. included in the BitCloud Profile Suite. Depending on the application they allow the developer to access already predefined functions. Thereby the implementation efforts as well as the development effort decrease. Additionally the interoperability among each other is ensured by using unified application profiles inside of ZigBee devices of different manufacturers. The consequence out of it is that devices can be smoothly integrated into existing installations. Thus it is possible to combine a switch of company X together with a device of company Y (e.g. a ZigBee-capable ceiling lamp or a jalousie).

In Figure 5 below the architecture of the BitCloud Profile Suite is outlined. The red marked areas are responsible for processing the hardware-close functionalities. They are equivalent to the commonly called ZigBee stack. The green marked parts are profile-specific and represent the standardized interfaces of the application. The area marked in dark grey is the part that has to be implemented by the developer; it corresponds to the real application.

It has already been mentioned that Atmel’s ZigBee PRO represents an exemplary implementation of a ZigBee stack. Thereover Atmel’s Bitcloud Profile Suite is available, too; it contains the following standards:

- ZigBee Smart Energy 1.1 (ZSE 1.1)
- ZigBee Home Automation (ZHA)
- ZigBee Building Automation (ZBA)
Preferred fields of application

BitCloud Pro:
- Complex networks with large spatial dimensions
- Multi-hop networks
- Proprietary measurement and automation solutions

BitCloud Profil Suite:

The ZigBee Smart Energy (ZSE) standard provides a complete solution for **smart metering** applications with predefined device and application profiles such as e.g. gas, water and electric meters, thermostats as well as monitoring displays. Numerous features implemented beforehand support the developer.

With the ZHA standard ZigBee is also present in the field of **home automation**. Applications are available with a group of predefined device types and functions as e.g. light switches, air conditioning technology, door closer and alarm systems. Moreover in the profiles a number of different sensor types are defined. Altogether a broad base on which home automation solutions can be developed is generated.

Furthermore ZigBee offers a standardized profile for **building automation**, too. For the developer building automation tools with predefined functions for illumination and safety technology as well as occupancy monitoring are available. This profile additionally offers the advantage of compatibility with BACnet. Thus an easy and smooth integration into already existing building automation systems can be carried out. Just like with other abovementioned profiles a number of different predefined sensors and devices are available, too.
More ZigBee application profiles:

RF4CE

Another 802.15.4 based protocol is RF4CE (Radio Frequency for Consumer Electronics). The focus however here is clearly set on remote control, especially in the field of consumer electronics. Infrared remote control units are increasingly replaced by radio-based solutions. They feature the crucial advantage that no line of sight visibility is required to transmit signals.

In case of RF4CE it is basically distinguished between two different types of nodes: target und controller. The target node or device (the terminal device to be controlled) acts as PAN coordinator and can thereby start networks (WPANs) independently. Respective radio remote control units are called controller nodes. In order that a controller can connect to the network or to the belonging target node the so called “pairing” has to be executed; in doing so a remote control unit can be paired with several targets. This is illustrated in Figure 6; the controller in the center of the picture controls three different targets: TV, DVD und CD.

![Figure 6: Typical RF4CE network [3]](image)

Altogether RF4CE uses only three different channels in the 2.4 GHz band. Between them can be switched automatically, if required by the situation. Thus the coexistence with other participants in the 2.4 GHz band (typically WiFi und Bluetooth) can be ensured. Thereto the so called target device determines the own channel automatically based on the reception conditions when booting. If there are interferences with other devices during operation, the target device can switch the channel dynamically. The respective controllers find the new channel autonomously then [4].
Preferred fields of application

- Remote control of devices in the field of consumer electronics
- Replacement of infrared remote control units
- Wireless input devices for PCs and games consoles
Comparison of the protocols

Comparison according to features
The following table shows the functionality of the individual standards. However the developer is free to enhance this standardized range of functions: He could for example implement the multi-hop functionality for 802.15.4 MAC himself.

<table>
<thead>
<tr>
<th>Feature</th>
<th>802.15.4 MAC</th>
<th>6LoWPAN</th>
<th>ZigBee Pro</th>
<th>RF4CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible network topologies</td>
<td>Star</td>
<td>Tree, mesh</td>
<td>Mesh</td>
<td>Star</td>
</tr>
<tr>
<td>Multi-hop capable</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Over-the-air update</td>
<td>No</td>
<td>No</td>
<td>in ZigBee Smart Energy standardized</td>
<td>No</td>
</tr>
<tr>
<td>IPv6 compatible</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Automated channel change</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Possible frequency bands</td>
<td>2.4 and sub-GHz</td>
<td>2.4 and sub-GHz</td>
<td>2.4 and sub-GHz</td>
<td>2.4 and sub-GHz</td>
</tr>
<tr>
<td>Maximal number of nodes</td>
<td>Implementation dependent</td>
<td>&gt; 64000</td>
<td>&gt; 64000 nodes per network</td>
<td>N/A</td>
</tr>
<tr>
<td>Stand-by modi</td>
<td>Have to be implemented</td>
<td>Available depending on implementation¹</td>
<td>Already available</td>
<td>Already available</td>
</tr>
<tr>
<td>Network security</td>
<td>AES-128 possible</td>
<td>AES-128 possible</td>
<td>AES-128 possible</td>
<td>AES-128 possible</td>
</tr>
<tr>
<td>End-to-end encryption</td>
<td>None</td>
<td>IPSec scheduled²</td>
<td>Application link keys</td>
<td>None</td>
</tr>
<tr>
<td>Preferred field of application</td>
<td>Point-to-point connections, networks with small number of nodes</td>
<td>WPANs with IP connectivity</td>
<td>Smart energy und home automation applications</td>
<td>Remote controls for consumer electronics</td>
</tr>
</tbody>
</table>

¹ Realized e.g. in Contiki by using RPL/CoAP. For more information thereto see [5].
² So far, in not any 6LoWPAN implementation available, possible concepts are currently discussed by the IETF [6].
Comparison according to memory requirements

In the end, when choosing the appropriate radio protocol, not only the desired functionalities are of great interest but also the available memory consumption (flash memory and RAM) on the target system. Of course, often an identically constructed controller with a larger flash can be acquired, too, but this may not always be feasible for different reasons (cost factor, incompatibility, market conditions etc.). As a rule of thumb it can then be stated, the larger the required space in the flash the larger the whole stack is structured. Thus the network latencies extend necessarily. Furthermore this causes an increased need for RAM memory. Figure 7 gives an overview of some implementations presented in this white paper; please note that these numbers stand for the stack including a minimal application. If ambitious applications are implemented by the developer the memory requirements can increase considerably. An example: in case of the BitCloud Profil Suite and the use of a deRFmega128 module the only available memory flash is 28 kB, more than 78% of the memory space is a priori already occupied. Likewise obvious is the minimalist approach of the 802.15.4 MAC; with not more than 16 kB it indeed needs a fractional amount of the “big” protocols.

![Figure 7: Memory requirements of different protocols by comparison](image)

Summary and outlook

Due to the variety of available protocols the developer of wireless technology solutions is given a broad scope for action which ranges from using 802.15.4 MAC for minimalist networks to the BitCloud Profile Suite providing already predefined device classes with typical functions included.

Most freedom of implementation allows 802.15.4 MAC: Here the developer is theoretically free to implement his own protocol. Furthermore mechanisms or application specific time regimes can be used that allow getting along with a minimum of electric power.
The other protocols discussed here slightly ease developer’s work beforehand by providing the pre-made mechanisms for network and energy saving functions. But they are more complex and do not achieve the energy and memory efficiency of 802.15.4 MAC.

The major criteria to choose the appropriate protocol are:

- Required data rate
- Available electrical power supply
- Number of network nodes
- Need of IP connectivity

As already mentioned the use of a certain protocol is always dependent on the application to be implemented. However to give a rough guidance the following can be assumed:

**802.15.4 MAC**

- Simple to simplest network design
- Small number of nodes (usually 2 - 10 nodes, but much more possible)
- High net data rate necessary
- Minimal energy consumption desired (e.g. for energy harvesting or extreme long battery durability)

**6LoWPAN**

- The radio network shall provide IP connectivity
- High complexity of the network (>10 nodes)
- Latency and data rates subordinate, but data rate higher than ZigBee
- Longer range and multi-hops necessary

**ZigBee**

- Compatibility to devices of other manufacturers is desired and the application has to fit in one of the given profiles
- High complexity of the network (>10 nodes)
- An appropriate controller with enough memory is available
- Safe delivery of packets required
- Multi-hops

**RF4CE**

- For remote control units
- Consumer electronics
References


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