**IEEE P802.15**

**Wireless Personal Area Networks**

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| Abstract | [This document provides background information behind the development of the IEEE 802.15.4q standard. The information includes motivations, applications and the benefits of having ULP PHYs. Comprison of ULP PHYs to Bluetooth Smart is also provides.] | |
| Purpose | [To provides background information behind the development of the IEEE 802.15.4q standard] | |
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# Motivations and applications of ULP PHYs

For over a decade the IEEE 802.15 working group successfully developed wireless PAN standards (15.4) with low energy consumption in mind. However, further reduction in energy consumption is desired to address emerging markets like wearable devices, electronic shelf labeling and building automation where the energy sources, driven by size and cost constrains, are limited to coin cell batteries or energy harvesting devices. These energy sources have substantial less capacity and peak power ratings than traditional batteries (e.g. AA or AAA size). This calls for an amendment which aims for further reduction in energy consumption and peak power. In addition the more traditional markets, already successfully addressed by IEEE802.15.4, may benefit from such amendment by getting a prolonged battery life.

* 1. **Example application scenario for ULP TOOK**

Among several short-range, ULP communication-based application scenarios that find ULP-TOOK as the suitable choice, one important application scenario is the wearable devices (ex: mobile healthcare.). Typically, wearable devices involve a set of medical/non-medical devices, coordinating with each other, monitoring the essential medical conditions of the host such as heart beat rate, blood pressure, sugar level, etc. These parameters are reported to the coordinator for further required processing, which is, typically, a PDA/smartphone of the user. The wearable devices are tiny devices powered with coin-cell batteries, and are required to transmit with low transmit power. On the other hand, the coordinator, albeit with a requirement of low-power consumption, can afford moderate circuit complexity and power consumption requirements are not as stringent those required for the sensors. The intra-communication range of sensors is often very small (< 5 m) when compared to the sensor-to-coordinator communication range (~5-10 m). A way to exploit this asymmetry in the links is to employ low-complexity, ULP TOOK non-coherent receivers at the sensors and sophisticated ULP TOOK coherent receivers at the coordinator. This task can be achieved due to the fact that ULP-TOOK supports ULP communication in both coherent and non-coherent mode simultaneously.

* 1. **Example application scenario for ULP GFSK**

Shelf label and real-time inventory systems share a similar topology; usually there are many low complexity end-devices and one central coordinator. This results in a traditional star-topology network. While the end-devices are limited in terms of computing capabilities and power source, the concentrator has virtually no constraints in this regards. Amongst other techniques this network structure is leveraged in this amendment to further decrease energy and power consumption. In these systems battery lifetime is crucial as it is probably the most important system parameter that decides upon the commercial success of such systems. These systems are good examples for the ULP GFSK physical layer.

1. **Comparison of 802.15.4 (DSSS) with ULP-TOOK PHY**

In this section, the features in ULP-TOOK PHY are compared with those in standard 802.15.4 (DSSS) PHY.

* 1. **Modulation and spreading**

In PHY of 802.15.4 (DSSS), the data-symbols are spread using binary spreading sequences whose chips are drawn from a bipolar alphabet. The resultant chip-stream is modulated using OQPSK modulation. Therefore, the receiver needs to perform quadrature processing and coherent demodulation.

In ULP-TOOK PHY the data-symbols are modulated using TOOK (ternary on-off keying) whose features and benefits are discussed in Annex A of the spec.

* 1. **Error control mechanism**

There is no error control mechanism used in the PHY of 802.15.4 (DSSS), whereas ULP-TOOK PHY employs

* Shortened BCH (63, 51, 2) codes with bit-level interleaving
* Non-binary single parity check codes (SPC)

Use of FEC mechanism in ULP-TOOKPHY contributes to approximately an SNR gain of 3 dB in the link margin. Simpler encoding and decoding algorithms have been explored which support low-complexity implementation. It should be specifically noted that, for a BCH code with an error correcting capability of 2, many variants of low-complexity implementations are available in the literature.

* 1. **Comparison of system parameters**

Comparison of power consumption figures of 802.15.4 (DSSS) with ULP-TOOKPHY is given in the Table 1.

**Table 1—Comparison of power consumptions of 802.15.4 (DSSS) and TOOK PHY**

|  |  |  |
| --- | --- | --- |
| **System parameters** | **802.15.4(DSSS)** | **ULP-TOOKPHY** |
| **Transmitter power consumption** | 12 mW | 6.3 mW |
| **Receiver power consumption** | 15 mW | 3.1 mW |
| **Data rate** | 250 kbps | 126 kbps-1 Mbps |

Comparison of energy consumption between 802.15.4 (DSSS) and ULP-TOOK is given in Table 2. A single super-frame was considered that consists of one beacon interval and one PPDU with a given data rate, followed by the ACK. For this super-frame, total energy consumption is evaluated for ULP-TOOK PHY as well as for other existing PHYs. The following are the assumptions made in carrying out the analysis:

* Sleep current =
* Data rate of the beacon frame = 126.25 Kbps.
* Beacon size = bytes.
* Transmitted packet size = 10 bytes.
* ACK size = 5 bytes.

**Table 2—Comparison energy consumption of 802.15.4 (DSSS) and TOOK-PHY**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| PHYs | Datarate (in Kbps) | Beacon Order | Beacon Interval (in milliseconds) | Energy required/ beacon interval (in micro joules) |
| OQPSK-DSSS | 250 | 0 | 15.36 | 44.2 |
| ULP-TOOK | 126.25 | 0 | 15.36 | 16.9 |
| ULP-TOOK | 1000 | 0 | 15.36 | 10.4 |
| OQPSK-DSSS | 250 | 8 | 3932.160 | 56.04 |
| ULP-TOOK | 126.25 | 8 | 3932.160 | 28.67 |
| ULP-TOOK | 1000 | 8 | 3932.160 | 22.28 |

1. **Comparison of ULP-GFSK PHY with existing PHYs:**

The ULP GFSK PHY in this amendment achieves the power and energy saving by several means:

Increased data rate to minimize on-time

Reduced overhead to minimize wasted on-time

Leverage asymmetric links to minimize both transmit and receive power consumption in the end nodes

Optional transmit power control

In a network where the optional transmit power control is implemented, the receiver can measure the signal quality and/or RSSI. For example, when the signal is 40dB above the sensitivity, the receiver may request the transmitter to back-off its transmit power by 10dB. In a point to point communication this method may save transmit power in both ends of the link.

While IEEE 802.15.4 already has some FSK based PHYs in several amendments, this combination of features is unique to 4q and cannot be found in any other amendment. A comparison between different amendments is provided by Table 3.

**Table 3—Comparing ULP GFSK to other 802.15.4 PHYs**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **802.15.4-2011 DSSS** | **802.15.4g MR-FSK** | **802.15.4f**  **MSK** | **802.15.4k**  **FSK** | **802.15.4q ULP GFSK** |
| **Min. Preamble Length** | 4 octets | 4 octets | 4 octets | 4 octets | 2 octets |
| **PHR Length** | 1 octet | 2 octets | 1 octet | 2 octets | 2/1/0 octets |
| **Max. Datarate** | 250 kbps | 200 kbps | 250 kbps | 37.5 kbps | 1000 kbps |
| **Datarate doubling** | No | Between frames with mode switch | No | No | Seamless within one frame |
| **FEC Support** | No | Yes, K=4 | No | Yes, K=7 | Yes, K=7 |
| **Power control IE** | No | No | No | No | Yes |

The possibility to leverage asymmetric links is especially powerful in star-topology networks. In these networks the topology properties can be used to further reduce power and energy consumption in the end-devices. This is accomplished by having a convolutional encoder and a MSK precoder in the end device, both effectively for free in terms of power consumption and cost, combined with a trellis decoder in the central node. While the trellis decoder may add to the power budget and the cost this is considered less of an issue at the central node. The configuration described allows for a significant improvement in receive sensitivity in the central node which can be leverage by reducing transmit power in the end devices prolonging their battery life. The trellis decoder can be avoided in the end devices by having more transmit power in the central device. A more detailed description on how this mechanism works is provided in the spec of IEEE 802.15.4q, Annex B.

* 1. **Energy efficiency for 15.4q**

Energy efficiency is a major concern in an ULP centered approach. The mechanisms in ULP GFSK address this issue with a high maximum data rate which helps to reduce the on-time during transmitting and receiving. In addition, overhead in the SHR and PHR is reduced considerably. These improvements result in a very short on-time that greatly reduces consumed energy.

In a comparison of the PSDU efficiency and on-time is shown. The PPDU efficiency is calculated as follows:

As an example a PSDU of 5 octets, i.e. one ACK frame, has been chosen. Additionally the relative energy consumption is calculated by the following equation:

The comparison in Table 4 shows that the ULP GFSK PHY has the highest PPDU efficiency. It can be further increased by using the ULP PPDU Mode (see 3.3) for transmission (). However this special mode is not suitable for all situations. If the data rate is taken into account the relative energy consumption shows the advantage of the ULP GFSK PHY compared to the other amendments. The MSK PHY from the 4f amendment is closest in terms of relative energy consumption. However it still consumes 4.4 times more energy than the ULP GFSK PHY. This clearly shows the potential of the ULP GFSK PHY contributed to its dual strategy to reduce overhead and increase data rate.

**Table 4—Comparison on energy efficiency**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **PHY** | **min preamble**  **[octets]** | **SFD**  **[octets]** | **PHR**  **[octets]** | **PSDU**  **[octets]** | **PPDU efficiency** | **data rate**  **[kpbs]** | **on-time**  **[µs]** | **relative energy consumption** |
| **4**  **(DSSS)** | 4 | 1 | 1 | 5 | 0.45 | 250 | 352 | **4.4** |
| **4f**  **(MSK)** |
| **4g**  **(MR-FSK)** | 4 | 2 | 2 | 5 | 0.38 | 200 | 520 | **6.5** |
| **4k**  **(FSK)** | 4 | 3 | 2 | 5 | 0.36 | 37.5 | 2987 | **37.3** |
| **4q**  **(ULP GFSK)** | 2 | 2 | 1 | 5 | 0.50 | 1000 | 80 | **1.00** |

* 1. **Battery life estimation example**

To illustrate the energy saving potential of the ULP GFSK PHY an exemplary calculation has been conducted to estimate battery lifetime of such system. For comparison the same calculations have been done for a 4f (MSK PHY) and a 4g (MR-FSK) system.

The communication scenario used for the calculation can be described as follows: A star topology network is assumed for a shelf label system. The central coordinator builds a beacon-enabled network and updates the shelf labels with information announced in the beacons. Each shelf label receives information every n-th beacon and requests the data. Communication schedule from the perspective of an end-device is as follows:

1. Receive Beacon from central node (PSDU = 30 Octets)
2. If there is data announced the shelf label send data request command frame to central node (PSDU = 11 Octets)
3. Central node responds with ACK (PSDU = 5 Octets)
4. Central node sends secured data frame with new pricing. (PSDU = 30 Octets)
5. Shelf label responds with ACK (PSDU = 5 Octets)
6. Set device to sleep state

For the battery life estimation the following values have been assumed:

* A 90 mAh CR2016 coin cell battery with approx. 110 nA self-discharge current
* 5 mA current consumption in RX/TX state
* 1 µA current consumption in sleep state

**Table 5—Comparison on battery lifetime**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Amendment** | **BO** | **Beacon interval [s]** | **Data rate**  **[kpbs]** | **Data n-th beacon** | **Battery lifetime [years]** |
| 4  (DSSS) | 8 | 0,98 | 250 | 1000 | 1,47 |
| 4f  (MSK) |
| 4g  (MR-FSK) | 8 | 1,22 | 200 | 800 | 1,41 |
| 4q  (ULP GFSK) | 10 | 0,98 | 1000 | 1000 | 4,05 |

The advantage of the ULP GFSK becomes obvious when looking at Table 5, where the ULP GFSK achieves an approx. three times higher battery lifetime than the other PHYs.

*NOTE: Due to an asymmetric link setup the ULP GFSK would usually have a lower TX power than other PHYs in the same scenario. However for easier comparison the RX/TX current consumption has been assumed constant for all PHYs.*

* 1. **ULP PPDU**

In a number of ULP application where the transmitted packets are short, frame related parameters rarely change. As such it is not necessary to send all the packet fields. For these applications the existing 802.15.4 PPDU formats are inefficient and are not the right fit. The ULP PPDU eliminates the explicit transmission of information contained in the PHY header such as modulation, coding and packet length. The approach fits nicely with the asymmetric link feature of the standard. The end result is a low power PPDU format suited for many ULP wireless sensor applications.

1. **IEEE 802.15.4q vs. Bluetooth Smart**

IEEE 802.15.4q has the following advantages, comparing to Bluetooth Smart™:

* A wireless communication device operating in sub-GHz bands requires far less power compared to devices operating in 2.4 GHz. Power efficiency is equivalent to longer battery life. Bluetooth Smart, also known as Bluetooth LE, only operates in 2.4 GHz. In contrast, IEEE 802.15.4q PHY operates in both 2.4 GHz as well as sub-GHz bands. In fact, IEEE 802.15.4q could operate in a frequency band as low as 169 MHz. As such, IEEE 802.15.4q enables longer battery life compared to Bluetooth Smart when operating in Sub-GHz bands.
* IEEE 802.15.4q introduces support to asymmetric links. This feature is extremely helpful in a point to multi-point communication. In these applications the sensor nodes would have to operate with extremely low-power. However, the concentrator (PAN Coordinator) does not have this restriction. This new feature relieves the complexity from the end nodes. Unlike IEEE 802.15.4q, Bluetooth Smart does not have such a feature to enable extremely low power operation of sensor nodes.
* IEEE 802.15.4q utilizes 802.15.4 MAC with some minor modifications to accommodate new PHYs. As such, mesh networking is fully supported. Bluetooth Smart on the other hand does not support mesh networking in a native way.