**IEEE P802.19**

**Wireless Coexistence**

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| Abstract | This document is the proposed overview of the Sub-1 GHz frequency band systems for P802.19.3. | |
| Purpose | To respond 802.19.3 Task Group’s call for proposal. | |
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**Overview of the Sub-1 GHz Frequency Band Systems**

Many Internet of Things (IoT) applications require low bandwidth communications over a long distance at low cost and low power. IEEE 802.11ah, IEEE 802.15.4g, LoRa and SigFox are the emerging Low Power Wide Area Network (LPWAN) technologies that fulfill these requirement by using the Sub-1 GHz (S1G) frequency bands to achieve communication range from 1 km up to 50 km. Using these technologies, an access point (AP)/base station (BS)/Gateway can support thousands of connected devices. In terms of the coexistence, 802.11ah provides coexistence mechanism with other non-802.11 systems, 802.15.4g only provides the method for coexistence among 802.15.4g devices that use different 802.15.4g PHY protocols. LoRa and SigFox do not address the coexistence.

In addition, IEEE 802.15.4w Task Group is developing a LPWAN extension to the IEEE 802.15.4 LECIM PHY layer to cover network cell radii of typically 10-15km in rural areas and deep in-building penetration in urban areas. It extends the frequency bands to additional Sub-GHz unlicensed and licensed frequency bands to cover the market demand.

**IEEE 802.11ah**

IEEE 802.11ah standard, marketed as Wi-Fi HaLow, is a wireless communication

PHY and MAC layer standard that operates in the unlicensed Sub-1 GHz frequency bands. 802.11ah defines a narrow band orthogonal frequency division multiplexing (OFDM) PHY to make it suitable for IoT applications such as smart city, smart appliances and wearables.

Frequency band allocation is region dependent, e.g., 902-928 MHz band in United States, 863-868 MHz band in Europe and 915-928 MHz band in Japan. 802.11ah supports a wide range of bandwidths with mandatory 1 MHz channel and 2 MHz channel and optional 4 MHz channel, 8 MHz channel and 16 MHz channel. Modulation and coding schemes such as binary convolutional codes (BCC) and low density parity check (LDPC) encoding make it a highly flexible technology. 802.11ah specifies same data rate for uplink traffic and downlink traffic. With 1 spatial stream, 802.11ah enables a data rate up to 78 mbps at short ranges and 150 kbps up to 1 km. With 4 spatial streams, 802.11ah enables a data rate up to 346 mbps at short ranges. Support for 1 MHz channel and 2 MHz channel with 1 spatial stream is mandatory. Support for 1 MHz channel and 2 MHz channel with 2, 3 or 4 spatial streams is optional. Support for 4 MHz channel, 8 MHz channel, and 16 MHz channel with 1, 2, 3 or 4 spatial streams is optional. The maximum allowed transmission power is region dependent and ranges from 3 mW to 1000 mW, e.g., 1000 mW in United States, 250 mW in Japan and 25.12 mW in Europe. 802.11ah network can be organized in start topology or tree topology.

In order to support large numbers of stations, the 802.11ah extends the range of

Association IDs (AIDs), i.e., the number of associated stations, from 2048 up to

8192 per AP, and organizes stations in a four level hierarchical structure to improve station management scalability. Stations are grouped together based on their similarities. Each station is assigned a four level AID structure encompassing page, block, sub-blocks and station fields.

In terms of channel access, 802.11ah typically applies carrier sense multiple access/with collision avoidance (CSMA/CA) specified via Enhanced Distributed Channel Access (EDCA) function, which implements service differentiation by classifying the traffic into four different access categories with different priorities. As such, the different backoff parameter set is specified for different access category (AC). The time division multiple access (TDMA) based channel access is also possible through HCF Controlled Channel Access (HCCA) function, which uses polling mechanism to assign transmission opportunity (TXOP) to QoS enabled stations.

In addition, 802.11ah has introduced bi-directional TXOP (BDT) that can help non-AP stations to minimize energy consumption. This technique allows the combination of transmission and reception of frames within a single TXOP, where the reduction in the required frame exchange enables stations to extend their battery life time. This mechanism also assists in efficient use of contention based channel accesses.

Furthermore, 802.11ah specifies several features for spectrum efficiency and power efficiency. The restricted access window (RAW) mechanism reduces contention by clustering stations into RAW groups and slots, only allowing the stations in one group to contend for the channel at any time slot. As such, it effectively combines the efficiency of CSMA/CA and the determinism of TDMA into a dynamically adaptable MAC scheduler. RAW has been shown to significantly reduce collision probability and interference in dense networks, resulting in a potential throughput increase of 50% or more.

The S1G stations that are associated with a S1G AP transmit and receive on the channel or channels that are indicated by the AP as the enabled operating channels for the basic service set (BSS). Subchannel selective transmission (SST) is a feature specified by 802.11ah to allow stations to rapidly select and switch to different channels between transmissions to counter fading over narrow subchannels.

Traditional 802.11 stations need to wake up for every beacon frame, resulting in high power consumption. 802.11ah circumvents this by splitting the target information map

(TIM) into segments, each transmitted with another beacon. As a result, stations only need to listen for beacons carrying the delivery traffic indication map (DTIM), which notifies the stations which beacon will carry their TIM segment. Subsequently, they only wake up to listen for that specific beacon, rather than all of beacons.

The target wake time (TWT) feature further reduces power consumption for stations transmitting data only occasionally, by letting stations negotiate with the AP when they should wake up. The TWT feature is realized by specifying TWT service period (SP) and TWT SP start time. The TWT allows a sleep interval from seconds up to years.

From coexistence perspective, 802.11ah is only S1G frequency band standard that addresses the coexistence with other non-802.11 systems including IEEE 802.15.4 and IEEE 802.15.4g. An S1G station (STA) uses energy detection (ED) based CCA with a threshold of –75 dBm per MHz to improve coexistence with other S1G systems. If a S1G STA detects energy above that threshold on its channel, then the following mechanisms might be used to mitigate interference:

* Change of operating channel
* Sectorized beamforming
* Change the schedule of RAW(s), TWT SP(s), or SST operating channels
* Defer transmission for a particular interval

However, the features such as sectorization, beamforming, RAW, TWT and SST are optional in 802.11ah standard.

**IEEE 802.15.4g**

IEEE 802.15.4g, marketed as Wi-SUN (Wireless Smart Utility Network), is a PHY amendment to the IEEE Std 802.15.4-2011. 802.15.4g is specifically designed for long range communication. In other words, it is a long range extension of the popular 802.15.4 standard family, arguably the most popular network solution for IoT applications.

It was originally designed for smart metering applications but is getting more and more popular in long range IoT applications. 802.15.4g can operate both on the Sub-1 GHz frequency bands and the 2.4 GHz frequency bands. The star topology and mesh topology are typical network architectures for 802.15.4g network organization.

802.15.4g specifies alternate PHYs in addition to those of IEEE Std 802.15.4-2011. The alternate PHYs support principally outdoor, low-data-rate, wireless, smart utility network (SUN) applications under multiple regulatory domains. Three SUN PHYs are defined:

* Multi-rate and multi-regional frequency shift keying (MR-FSK) PHY
* Multi-rate and multi-regional orthogonal frequency division multiplexing (MR-OFDM) PHY
* Multi-rate and multi-regional offset quadrature phase-shift keying (MR-O-QPSK) PHY

Even 802.15.4g primarily defines new PHYs, it also specifies the MAC modifications needed to support new PHY implementation. Besides baseline 802.15.4-2011 MAC, 802.15.4e is used as additional MAC. The CSMA/CA is main channel access mechanism specified in 802.15.4-2011, where different backoff processes take place depending on the beacon-enabled network or nonbeacon-enabled network. In beacon-enabled network, TDMA based channel access is specified in the contention free period (CFP) via guaranteed time slot (GTS) mechanism. In nonbeacon-enabled network or contention access period (CAP) of the beacon-enable network, CSMA/CA based channel access is employed.

802.15.4e was published in 2012 as an amendment to the MAC protocol defined by IEEE Std 802.15.4-2011, mainly for improving the adoption of sensor node communication for industrial applications. One of the most promising new features in 802.15.4e is time-slotted channel hopping (TSCH), which is a TDMA based channel access mechanism and designed specifically to provide deterministic performance, ultra-low power consumption and network robustness, minimizing the impact of wireless unreliability. In TSCH mode, the slotframe replaces conventional superframe, and therefore, no beacon is required. Instead, nodes are synchronized by obtaining synchronization information from enhanced beacon and communicate by following a TDMA schedule called TSCH schedule.

In addition, as 802.15.4g supports PHY packet size up to 1500 bytes, it is able to deliver IP packets without fragmentation and therefore, increases bandwidth efficiency and reduces energy consumption.

The maximum transmission power is region dependent, e.g., 1000 mW in United States, 25 mW in Europe and 250 mW in Japan. The transmission range is up to 1 km. Its inherent multihop capabilities give it a unique edge to other LPWAN solutions.

The frequency band allocation is also region dependent, e.g., for the S1G frequency band, 902-928 MHz in United States, 169 MHz in Europe and 920-928 MHz in Japan. Depending on the PHY configuration, the bandwidth of channels ranges from 200 kHz to 1200 kHz and the data rate ranges from 6.25 kbps to 800 kbps.

In terms of the coexistence, 802.15.4g does not address the coexistence with other non-802.15.4g systems. However, it provides method to facilitate inter-PHY coexistence. In order to mitigate interference among different 802.15.4g PHYs, a multi-PHY management (MPM) scheme is specified. For this purpose, the MPM scheme facilitates interoperability and negotiation among potential coordinators with different PHYs by permitting a potential coordinator to detect an operating network during its discovery phase using the common signaling mode (CSM) appropriate to the band being used. The CSM mechanism can be used in conjunction with the clear channel assessment (CCA) mechanism to provide coexistence control. The CSM is a common PHY mode that uses the Filtered 2FSK modulation with the 200 kHz channel and the 50 kbps data rate. An 802.15.4g device acting as a coordinator and with a duty cycle greater than 1% shall support CSM.

In a beacon-enabled network, an existing coordinator shall transmit an enhanced beacon (EB) at a fixed interval by using CSM. Any intending coordinator shall first scan for an EB until the expiration of the enhanced beacon interval or until an EB is detected, whichever occurs first. If an intending coordinator detects an EB, it shall either occupy another channel, achieve synchronization with the existing network, or stop communication.

In a nonbeacon-enabled network, an existing coordinator should transmit an enhanced beacon (EB) periodically using the CSM. Any intending coordinator shall first scan for an EB until the expiration of the enhanced beacon interval for nonbeacon-enabled network or until an EB is detected, whichever occurs first.

**LoRa**

Long Range (LoRa) is a physical layer technology for creating long range communication links. It makes use of a novel radio modulation technique, chirp spread spectrum (CSS) that has a very high sensitivity and thus increased communication range. The Long Range Wide Area Network (LoRaWAN) defines the communication MAC protocol and system architecture for the network, on top of the LoRa PHY layer.

The star network architecture defined by LoRaWAN. It is designed to allow low power devices to communicate with Internet connected applications over long range wireless connections. LoRaWAN can be mapped to the second and third layer of the OSI model. It is implemented on top of LoRa or FSK modulation in industrial, scientific and medical (ISM) radio bands. The LoRaWAN protocols are defined by the LoRa Alliance and formalized in the LoRaWAN specification.

The frequency band allocation is region dependent. In Europe, LoRaWAN operates in the 863-870 MHz frequency band with a duty cycle as low as 1% or even 0.1%. In the United States, LoRaWAN operates in the 902-928 MHz frequency band. Unlike the European band, the United States band has dedicated uplink and downlink channels. In Japan, LoRaWAN operates in 920-923 MHz frequency band. LoRaWAN can use channels with a bandwidth of either 125 kHz, 250 kHz or 500 kHz, depending on the region or the frequency plan.

In Europe, LoRaWAN defines ten channels. Eight of them are 125 kHz LoRa channels that, depending on the used spreading factor, offer data rates from 250 bps to 5.5 kbps. By dynamically adapting the spreading factor, a trade-off between data rate and range can be achieved. In addition, there is also a single high data rate 250 kHz LoRa channel at 11 kbps and a single FSK channel at 50 kbps.

In the United States, the LoRa band has dedicated uplink and downlink channels. The band is divided into 8 sub-bands that each have 8x125 kHz uplink channels, 1x500 kHz uplink channel and 1x500 kHz downlink channel.

By default the maximum transmission power is considered to be 1000 mW. In Europe, the maximum uplink transmission power is 25 mW and the maximum downlink transmission power is 500 mW.

LoRa data rate ranges from 250 bps to 50 kbps. The communication range is up to 15 km. Both end device and gateway use same radio.

Uplink data originating from end devices is received by one or multiple gateways. These gateways act as transparent (non-intelligent) bridges, relaying the data to a cloud-based network server. In case downlink traffic is available, the cloud server decides which gateway has the best connectivity with the end device, and the downlink traffic is transmitted from this gateway. As a result, all intelligence resides in this network server, which manages the network, filters redundant received packets, performs security checks, schedules acknowledgments through the optimal gateway, performs adaptive data rate, etc.

Three devices classes have been defined: Class A, Class B and Class C. All LoRaWAN devices must implement Class A, whereas Class B and Class C are extensions to the specification of Class A.

Class A devices support bi-directional communication between a device and a gateway and allow download traffic right after an upload slot. Uplink transmission from the end device to the network server can be sent at any time (randomly), i.e., ALOHA channel access. The end device then opens two receive windows at specified times after an uplink transmission. If the server does not respond in either of these receive windows, the next opportunity will be after the next uplink transmission from the device. The server can respond either in the first receive window or in the second receive window, but should not use both windows.

Class B devices extend Class A by adding scheduled receive windows for downlink traffic from the server. Using time-synchronized beacons transmitted by the gateway, the devices periodically open receive windows. As a result, Class B schedules separate upload windows.

Class C devices extend Class A by keeping the receive windows open unless they are transmitting. This allows for low latency communication but is many times more energy consuming than Class A devices, thereby trading in battery lifetime for lower downlink communication latency.

There is no coexistence mechanism provided by LoRa. It uses ALOHA channel access mechanism.

**SigFox**

SigFox is a proprietary technology for long range IoT applications. It is an ultra-narrowband technology. It uses different radio for uplink and downlink. The standard radio transmission method called binary phase shift keying (BPSK) is used for uplink and Gaussian Frequency Shift Keying (GFSK) is used for downlink. It takes very narrow chunks of spectrum and changes the phase of the carrier radio wave to encode the data. The bandwidth of uplink channel is region dependent, e.g., 100Hz in Europe and 600 Hz in United States. The downlink channel is 1.5 kHz. This allows the receiver to only listen in a tiny slice of spectrum that mitigates the effect of noise. This results in great sensitivity, which allows for long-range communication up to 50 km in rural areas and up to 10 km in urban areas, provided there is no interference. The uplink data rate is 100 bps in Europe and 600 bps in United States. The downlink data rate is 600 bps worldwide. The SigFox network is typically in star topology.

The low bitrate means that sending a SigFox packet requires a transmission time in the order of seconds, making it likely to collide with other technologies. Since

SigFox does not employ any collision-avoidance techniques, and since such narrowband transmissions are the worst type of interferers for other systems, a single SigFox device can easily interfere with wideband Sub-1 GHz frequency band technologies such as LoRa, 802.11ah and 802.15.4g.

The frequency band allocation for SigFox is region dependent, e.g., 915 MHz in United States, 868 MHz in Europe and 433 MHz in Asia. The maximum transmission power is also region dependent, e.g., 25 mW uplink power in Europe and 158 mW uplink in United States, 500 mW downlink power in Europe and 4000 mW downlink power in United States. Europe also requires 1% uplink duty cycle and 10% downlink duty cycle.

In contrast to the inexpensive radio of the end devices, the base stations use a sophisticated software-defined radio platform to simultaneously monitor the full frequency spectrum and look for SigFox signals, e.g., full 192 kHz spectrum in Europe. The random access is a key feature to achieve a high quality of service. The transmission is unsynchronized between the base station and the device. To guarantee 99.9% reliability, the device emits a message on a random frequency and then sends 2 replicas on different frequencies and time, which is called “time and frequency diversity”, to ensure it will correctly be received by at least one of the base stations in range.

The SigFox technology is suitable for very specific, very low data rate uplink IoT applications. Due to its popularity, it must be taken into account as a potentially harmful interferer for the other low power technologies.

There is no coexistence mechanism provided by SigFox. It uses ALOHA channel access mechanism.

**802.15.4w**

IEEE 802.15.4w Task Group is defining a LPWAN extension to the IEEE Std 802.15.4 LECIM PHY layer to cover network cell radii of typically 10-15km in rural areas and deep in-building penetration in urban areas. It uses the LECIM FSK PHY modulation schemes with extensions to lower bitrates, e.g. payload bitrate typically < 30 kb/s. It extends the frequency bands to additional Sub-GHz unlicensed and licensed frequency bands to cover the market demand. For improved robustness in channels with high levels of interference, it defines mechanisms for the fragmented transmission of Forward Error Correction (FEC) code-words, as well as time and frequency patterns for the transmission of the fragments. Furthermore, it defines lower code rates of the FEC in addition to the K=7 R=1/2 convolutional code. Modifications to the MAC layer, needed to support this PHY extension, are defined.

This standard is still under development. It considers coexistence with other 802.15.4 systems and 802.11ah system.

**Table 1 Summary of Sub-1 GHz frequency band technologies**

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| Technology | PHY Modulation | Channel  Bandwidth | PHY Data Rate | TX Range | Maximum TX Power | Channel Access | Coexistence Mechanism |
| IEEE 802.11ah | OFDM | 1/2/4/8/16 MHz | 150 kbps – 78 mbps | 1 km | 1000 mW | CSMA/CA  &TDMA | Inter-system coexistence |
| IEEE 802.15.4g | FSK/  OFDM/  O-QPSK | 200 kHz – 1.2 MHz | 6.25 kbps – 800 kbps | 1 km | 1000 mW | CSMA/CA  &TDMA | Intra-systeem coexistence |
| LoRa | CSS/FSK | 125 kHz/  250 kHz 500 kHz | 250 bps – 50 kbps | 15 km | 1000 mW | ALOHA | No |
| SigFox | BPSK(up),  QFSK(down) | 100 Hz – 1.6 kHz | 100 bps – 600 bps | 50 km | 4000 mW | ALOHA | No |