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Smart Grid Standards for Operation in Sub-1 GHz Bands

An IEEE White Paper

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Contents

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Intended audience

This white paper is intended to provide information on the benefits and applications of IEEE 802® wireless standards operating in sub-1 GHz bands.[1] The intended audience is regulators, communication network planners for utilities, and users and developers of a variety of wireless Internet of Things (IoT) networks.

Why is sub-1 GHz of interest for Smart Grid?

In many of the deployment environments and scenarios for smart grid devices, the frequencies below 1 GHz provide superior propagation characteristics compared to higher frequencies. For example, using simple modulation, signals at 900 MHz will tend to penetrate foliage (e.g., trees, shrubs, other plants) more readily compared with 2.4 GHz, which is attenuated more by the water contained in plants and animals. Propagation through some building materials may also be improved at lower frequencies. The effective antenna aperture will be improved at lower frequencies as well (to a point). Bands in the 400 MHz to 900 MHz frequency range provide good tradeoffs.

In most regions of the world, there are license-exempt frequency allocations between 800 MHz and 1 GHz, and in many regions there are allocations in the 400 MHz to 500 MHz frequency ranges as well. IEEE 802 standards include operating modes to address these sometimes-limited allocations effectively, with simple and low-cost implementations.

At the end of the paper, calculations are presented to compare the link loss difference between a sub-1 GHz band at 902−928 MHz with the 2.4 GHz band, keeping all other variables equal. The parameters are typical of a commonly-available, moderately low data rate radio as is popular in many smart grid and IoT related applications such as metering and remote monitoring. It should be noted that other factors beyond propagation loss, including required data rate, would drive selection of a band. For example, the contiguous spectrum available at 2.4 GHz is much larger than what is available in sub-1 GHz bands in many regions; therefore, the maximum data rate achievable may limit the use of lower frequencies for applications that require high data volumes.

The example calculations are based on the NIST link budget calculator.[2] The "Small City" model was used since this approximates an urban environment. The results show, with all other factors equal, the link in the 915 MHz band provides a link reliability of 90% at 1.1 km. The same link at 2.4 GHz provides a link reliability of 90% at 0.589 km.

[1] IEEE and 802 are registered trademarks in the U.S. Patent & Trademark Office, owned by the Institute of Electrical and Electronics Engineers, Incorporated.
[2] NIST link budget calculator is at rfic.eecs.berkeley.edu/~niknejad/ee242/pdf-lock/NIST_LinkBudgetCalc_2_4_konglk.xls

Industrial, scientific, and medical (ISM) bands have many incumbents and existing users in the bands. The nature of these users depends on the regulatory domain. In North America, the 915 MHz band is less congested than the 2.4 GHz band, but it is still used by multiple services and devices. One notable user is the Progeny location service that operates in the 915 MHz ISM band under a license, and thus can transmit with much higher power levels.

In the TV White Space (TVWS) spectrum, the incumbents are TV broadcasters. TVWS operation is only permitted in areas and on channels that are unused. The status of unused is based on conservative rules intended to eliminate any possibility of interference with broadcasters. In many large metropolitan areas, there are no available channels. In rural areas, there are many. After the FCC auctions much of the 600 MHz band, there will be even less availability of TVWS channels.

Standards for regional sub-GHz channel plans

Figure 1 summarizes IEEE 802 wireless standards with channel plans specifying operation below 1 GHz.

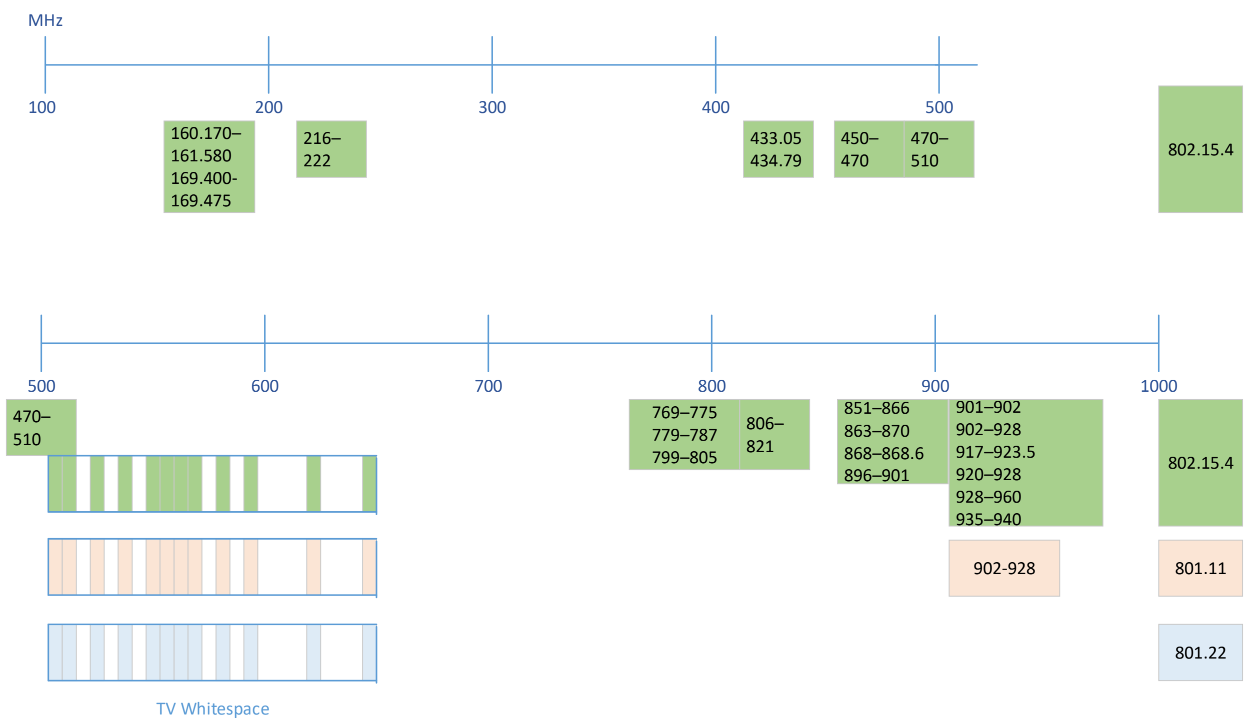

Figure 1 —Channel plans below 1 GHz

IEEE Std 802.15.4g (SUN)

IEEE Std 802.15.4g™ is a PHY amendment, published April 2012, built on the success of the IEEE 802.15.4™ standard for application to Smart Utility Networks in the field, neighborhood, and home area networking.[3] IEEE Std 802.15.4g provides three additional PHY layer definitions that support data rates from 2.4 kbps to 800 kbps. This amendment complements the short-range PHYs of IEEE Std 802.15.4-2011 with the capability to support large, geographically-diverse networks with minimal infrastructure, with a large number of participating devices.

The amendment includes the following three different PHY options:

— FSK PHY based on legacy AMI systems (part of which is used by Wi-SUN)
— Extension of the legacy IEEE 802.15.4 DSSS PHY
— OFDM PHY for higher data rates (50 kbps to 800 kbps)

The adoption of IEEE Std 802.15.4g together with some of MAC enhancements in IEEE Std 802.15.4e™ has been widespread in SUN and IoT applications. Conforming IEEE 802.15.4g based implementations are available from a large number of vendors, and has proven to be an effective basis for constructing large-scale outdoor wireless mesh networks. The proven technology standard enables interoperable products and addresses global market and has been adopted in many regions and markets.

The standard defines operation in license exempt and licensed bands in USA/Canada/EU/Japan/China/AU and other regions. Each PHY define multiple data rates to provide adaptability to the deployment environment.

IEEE Std 802.11ah (S1G)

IEEE Std 802.11ah™ is a MAC/PHY amendment of IEEE Std 802.11™ for potential applications such as Internet of everything (IoT), Smart Grid, Healthcare, Smart Appliances, Wearable consumer electronics.

This amendment defines an Orthogonal Frequency Division Multiplexing (OFDM) Physical layer (PHY) operating in the license-exempt bands below 1 GHz, e.g., 868−868.6 MHz (Europe), 950−958 MHz (Japan), 314−316 MHz, 430−434 MHz, 470−510 MHz, and 779−787 MHz (China), 917−923.5 MHz (Korea) and 902−928 MHz (USA), and enhancements to the IEEE 802.11 Medium Access Control (MAC) to support extended range (up to 1 km), higher power efficiency, and a large number of devices.

The data rates defined in this amendment optimize the rate vs. range performance of the specific channelization in a given band (see Figure 2).

[3]The IEEE standards or products referred to in this white paper are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

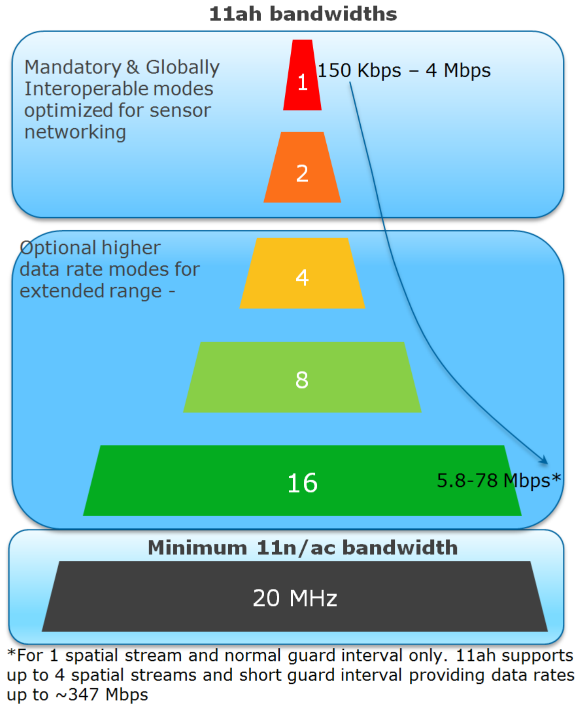

Figure 2 —IEEE 802.11ah channel bandwidths

PHY features of IEEE Std 802.11ah are summarized as the following:

- OFDM (FFT size 32 and 64)
- New reliable MCS working with larger delay spread and Doppler for outdoor
- Diverse data rates:150 Kbps−347 Mbps
- Range >1 km

MAC features of IEEE Std 802.11ah are summarized as follows:

- Scalability up to 8191 devices per AP (Hierarchical TIM structure)
- Efficient frames and transmissions (Short frame format, Short control/mgmt. frames)
- Reducing power consumption (Non-TIM operation, Target Wake Time mechanism)
- Relay operation

Standardization activity on this amendment began in November 2010. The IEEE 802.11ah amendment was approved Dec 7, 2016, and published on May 10, 2017.

Standards for TV White Space

Although TVWS standards have been available for several years, there has not been widespread commercialization and deployment. This may be partially due to the uncertainty around the outcome of the auctioning of 600 MHz spectrum by the FCC. The reduction of available channels will significantly curtail availably of vacant TV channels in metropolitan areas. Another aspect is the lack of maturity of database services that these IEEE 802 TVWS standards depend on for operation.

IEEE Std 802.15.4m (TVWS)

IEEE Std 802.15.4m™ is an amendment that specifies a physical layer definitions and MAC layer extensions for IEEE 802.15.4 enabling operation according to TV white space regulatory requirements in various regulatory domains. The standard enables operation in the VHF/UHF TV broadcast bands between 54 MHz and 862 MHz, supporting typical data rates in the 40 kbits per second to 2000 kbits per second range, to realize optimal and power efficient device command and control applications.

The alternate PHYs support principally outdoor, low-data-rate, wireless, TV white space (TVWS) network applications. The TVWS PHYs are as follows:

- Frequency Shift Keying (TVWS-FSK) PHY
- Orthogonal Frequency Division Multiplexing (TVWS-OFDM) PHY
- Narrow Band Orthogonal Frequency Division Multiplexing (TVWS-NB-OFDM) PHY

IEEE 802.15.4m TVWS devices are expected to operate indoors and outdoors at frequencies from 54 MHz to 862 MHz. Frequency availability varies by location and time. Frequency management is done using centralized coordination databases. Regulatory authorities have established operating and access rules in North America, EU, UK, parts of Asia, and other regions.

The frequency band and transmit power limits available in TVWS operation typically allow radio range up to several kilometers. IEEE Std 802.15.4m leverages features of IEEE Std 802.15.4, such as narrow band channelization, inherently low duty cycles, and favorable coexistence characteristics, which enable scalability to large network topologies. For example, in some regions the TVWS channel allocation is made in 6 MHz to 8 MHz per TVWS channels, which, by using IEEE 802.15.4m narrow band PHYs, allows for many PHY channels to be used in a single TVWS channel enabling support for high device density. The IEEE 802.15.4 MAC security features may be used to meet the confidentiality requirements imposed in some regulatory domains for exchange of channel availability information.

IEEE 802.15.4m PHYs provide features to improve link reliably such as forward error correction, multiple modulation, and coding schemes as well as existing features of the standard such as 32-bit frame check sequence, and acknowledged frame exchange with automatic retransmission.

IEEE Std 802.11af (TVHT)

With the global transition to Digital TV (DTV), sub-GHz RF spectrum is becoming available, much of it for unlicensed, license exempt and/or lightly licensed use. IEEE Std 802.11af™ made the necessary MAC and PHY changes to enable IEEE 802.11 products to take advantage of this additional spectrum. In the US, this represents a reconsideration of FCC regulations—the November 2008 FCC Part 15 Subpart H Television Band Devices rules; Ofcom (UK) is in the process of making this Digital Dividend band available, and the EU has conducted a consultation on the TV band. Other regulatory domains are expected to follow. The project will adapt to changes in the regulations as they progress. It is in the best interest of users and the industry to strive for a level of coexistence between wireless systems in the TVWS bands. IEEE Std 802.11af provides mechanisms for coexistence with other systems. One approach is a common coexistence mechanism (IEEE Std 802.19.1™) that may be used by other TVWS systems; other approaches are also possible.

- ## IEEE Std 802.22

The IEEE 802.22™ (Wi-FAR™) Standard on Cognitive Radio based Wireless Regional Area Networks (WRAN) takes advantage of the favorable transmission characteristics of the VHF and UHF TV bands to provide broadband wireless access over a large area with a range of 10−30 km from the transmitter. Hence each IEEE 802.22 Base Station can potentially provide a typical coverage over 300 km^2 and in some cases, up to 900 km^2.

IEEE 802.22-based wireless regional area networks take advantage of the favorable propagation characteristics in the VHF and low UHF TV bands, to provide broadband wireless access under both line-of-sight (LoS) and non-line-of-sight (NLoS) conditions. This occurs while operating on a strict non-interference basis in "TV white space" (TVWS)—spectrum that is assigned to, but unused by, incumbent licensed services. As a result, some industry trade associations, such as the WhiteSpace Alliance, have started referring to IEEE 802.22 standard as "Wi-FAR™". Each IEEE 802.22 network proposes to deliver up to 22 Mbps per 6 MHz channel and 28 Mbps per 8 MHz channel. This technology is especially useful for serving rural areas, and developing countries where most vacant TV channels can be found.

Use cases for IEEE 802.22-based devices include broadband access over large distances and NLoS conditions, broadband Internet access for remote and rural areas, IoT applications, cellular offload, monitoring of the rain forests, long-range backhaul, smart grid, critical infrastructure monitoring, defense, homeland security, healthcare, small office/home office (SoHo), and campus-wide broadband wireless access. The IEEE 802.22 Wireless Regional Area Networks Working Group is a winner of the IEEE Standards Association (IEEE-SA) Emerging Technology Award.

IEEE Std 802.22 incorporates advanced cognitive radio capabilities including dynamic spectrum access, incumbent database access, accurate geolocation techniques, spectrum sensing, regulatory domain dependent policies, spectrum etiquette, and coexistence for optimal use of the available spectrum. In addition, IEEE 802.22 systems have been incorporated with enhanced security features for both, traditional and cognitive functions.

IEEE Std 802.22b™ is an amendment to IEEE Std 802.22-2011. IEEE 802.22b-2015 is designed to double the throughput of devices based on the original IEEE 802.22 standard. The new amendment is intended also to serve more users per base station and enable relay capability for machine-to-machine (M2M) and IoT use cases.

- ## IEEE Std 802.19.1

IEEE Std 802.19.1™ began as a project to develop a standard for "TV White Space Coexistence Methods" and was initiated in December 2009 and published in June 2014. The standard provides coexistence solutions for different cognitive radio systems operating in TVWS frequency bands. It specifies radio technology-independent methods for coexistence among dissimilar or independently-operated TV band networks. IEEE Std 802.19.1 is designed to perform the following three key tasks required to solve coexistence problems between different TVWS radio networks:

— Discovery of WS radio systems that need to coexist with each other.
— Changing operating parameters of these WS radio systems to improve their performance.
— Providing a unified interface between different types of WS radio systems and a coexistence system.

As stated, the first task of a coexistence system is to discover WS radio systems that need to coexist with each other. To solve the first task, a logical entity called a Coexistence Discovery and Information Server (CDIS) is defined. Its key function is to support discovery of the neighbor WS radio systems. Two WS radio systems are neighbors if they are likely to cause one-way or mutual harmful interference to one another if they operate on the same frequency channel.

The second task of a coexistence system is to continuously update operating parameters of WS radio systems in a way that improves their performance. IEEE Std 802.19.1 provides two coexistence services to solve this task, namely, information service and management service.

Within the information service, the coexistence system provides neighbor discovery information to a WS radio system, and the WS radio system autonomously updates its operating parameters. Within the management service, the coexistence system manages the operating parameters of a WS radio system. To provide the management service, a logical entity called a coexistence manager (CM) is defined.

Once a coexistence system is deployed and in operation, it is intended to serve various types of white space radio systems. Correspondingly, there is a need to have a unified interface between different types of WS radio systems and a coexistence system. This task is solved by defining a logical entity called a coexistence enabler (CE). A CE provides a unified interface between a WS radio system and the IEEE 802.19.1 coexistence system. The interface between a CE and a WS radio system is outside of the scope of IEEE Std 802.19.1. In fact, the service access point is defined in an abstract manner in the standard, while exact implementation is left up to manufacturers. Such an approach is very beneficial, because it does not require any changes in already published and future standards in order to use coexistence services provided by the IEEE 802.19.1 coexistence system. A CE will serve as a translator of WS radio system specific messages to be exchanged between a CE and a CM.

Application-domain standards that build on IEEE 802 standards

The scope of IEEE 802 standards is limited to Layers 1 and 2 (MAC and PHY). In the application domain, additional standardization of higher layer functionality is often required to ensure interoperability. This can be accomplished by application-focused communication profiles.

Industry Alliances build upon IEEE 802 standards and integrate multiple standards at multiple layers.

One example is the Wi-SUN Alliance. The Wi-SUN FAN specification builds upon IEEE Std 802.15.4g, IEEE Std 802.15.4e, IEEE Std 802.15.4m, IEEE Std 802.1X, IEEE Std 802.15.9, security mechanisms from IEEE Std 802.11, and ANSI/TIA 4957 series. The specification also includes higher layer standards from IETF, defining operation up to the transport layer.

Applications

Smart grid applications can be divided into several broad categories related to the topologies and performance characteristics of both the individual devices and networks used to connect devices.

Field and neighborhood area networks endpoints may include applications such as the following:

- Electric meters
- Water and gas meters
- Distribution automation (grid control)
- Distributed energy resources
- Street lights, environmental sensors, and other “smart city” devices
- Plug-in vehicle charging

Many endpoints in the modern grid and/or smart city application share similar requirements from the network, such as moderate data rates, high device densities, very low energy consumption, and limited spectrum resources. IEEE 802 standards do a good job of addressing this type of device. For example, IEEE Std 802.15.4 includes PHY definitions and MAC features to specifically address these needs by offering low data rates with narrow bandwidth channelization, high spectral and special reuse factors, the ability to support very low power operation, and protocol options that enable adaptation to range/density trade-offs and varying environmental conditions. The standard includes the means to use nearly every conceivable type of spectrum allocation available around the world, with options to fit what regulations allow. In these types of applications, the low data rate requirements complement the limited amount of spectrum at sub-1 GHz frequencies, and the application of narrow band modulations in IEEE Std 802.15.4 optimizes use of the spectrum. Another common trait of many of these applications is low duty cycle for network access: communication is required infrequently. In some of these applications, energy available to run the device is limited. For example, a water meter or environmental sensor may be battery operated, with the need for the primary battery to last years. Features in the standard are optimized for such low duty cycle, “sleepy node” situations, enabling use of the communications link to be matched to the performance need (infrequent) saving energy by turning the radio off the rest of the time.

Other applications in the modern grid and/or smart city network have different trade-offs between energy, data rate, and spectrum utilization. IEEE 802® standards exist to address higher data rate applications such as network gateways, traffic aggregation points, data concentration (collectors), and inter-network routers. Where spectrum allocations allow the bandwidth for high data rates, standards such as IEEE Std 802.11, IEEE Std 802.16, and IEEE Std 802.22 provide spectral efficiency optimized for high data throughput appropriate for these kinds of applications.

Summary of characteristics and key comparisons

The SGIP PAP 2 committee developed a comprehensive matrix[4] that highlights key features and characteristics of wireless standards used for Smart Grid applications. A subset of that matrix including the sub-1 GHz standards is presented in Figure 3.

[4]This matrix publically available through NIST at: http://collaborate.nist.gov/twiki-sggrid/pub/SmartGrid/PAP02Wireless/Consolidated_Wireless_Characteristics_Matrix2_09-03-13.xlsx

Functionality/Characteristic	Measurement Unit	IEEE 802.11ah		802.15.4 and approved amendments	Wi-FAR IEEE 802.22
		Family Description + Indoor Model	Specific Operating Model + Outdoor Model		
Theoretical Range Limitations at Frequency	km, GHz	2km 0.9 GHz	2km 0.9 GHz	OFDM - 2k, 0.9GHz MR-FSK - 5k, 0.9GHz	Optimized for range up to 30 km in typical PMP environment, functional up to 100 km
Conditions for Theoretical Range Estimate	PtP, PMP, LoS, non-LoS	LoS	LoS	LoS	PtP, LoS for maximum range potential
Peak over the air uplink channel data rate	Mb/s	156	1.3	OFDM - 0.86 MR-FSK - 0.4	IEEE 802.22 Base Standard: 22 - 29 Mbps dependent upon the Channel Size of 6 MHz, 7
Peak over the air downlink channel data rate	Mb/s	156	1.3	OFDM - 0.86 MR-FSK - 0.4	IEEE 802.22 Base Standard: 22 - 29 Mbps dependent upon the Channel Size of 6 MHz, 7
Peak uplink channel data rate	Mb/s	109	0.91	OFDM - 0.86 MR-FSK - 0.4	IEEE 802.22 Base Standard: 18.72 - 24.67 Mbps dependent upon the Channel Size of 6 MHz, 7
Peak downlink channel data rate	Mb/s	109	0.91	OFDM - 0.86 MR-FSK - 0.4	IEEE 802.22 Base Standard: 18.72 - 24.67 Mbps dependent upon the Channel Size of 6 MHz, 7
Average uplink channel data rate	Mb/s	39	0.30303	OFDM - 0.86 MR-FSK - 0.4	IEEE 802.22 Base Standard: 9.36 - 12.33 Mbps dependent upon the Channel Size of 6 MHz, 7
Average downlink channel data rate	Mb/s	39	0.30303	OFDM - 0.86 MR-FSK - 0.4	IEEE 802.22 Base Standard: 9.36 - 12.33 Mbps dependent upon the Channel Size of 6 MHz, 7
Average uplink spectral efficiency	bit/s/Hz	2.4	0.65	OFDM - 1 MR-FSK - 0.5	1.56 bps/Hz
Average downlink spectral efficiency	bit/s/Hz	2.4	0.65	OFDM - 1 MR-FSK - 0.5	1.56 bps/Hz
Average uplink cell spectral efficiency	Mbps/Hz	2.4	0.65	OFDM - 1 MR-FSK - 0.5	1.56 bps/Hz
Average downlink cell spectral efficiency	Mbps/Hz	2.4	0.65	OFDM - 1 MR-FSK - 0.5	1.56 bps/Hz
Public radio standard operating in unlicensed bands	GHz DL/UL	0.9	0.9	0.169, 0.450-0.510, 0.779-0.787, 0.863-0.870, 0.902-	Essential use for Television (TV) Band frequencies from 54 MHz - 862 MHz. But this
Public radio standard operating in licensed bands	GHz DL/UL	0.9	0.9	0.22, 0.4-1, 1.427	Essential use for Television (TV) Band frequencies from 54 MHz - 862 MHz. But this
Duplex method	TDD/FDD/H-FDD	TDD	TDD	TDD	TDD
If TDD supported – provide details		alternate Tx & Rx on a selected channel	alternate Tx & Rx on a selected channel	alternate Tx & Rx on a selected channel	TDD includes adaptive and adjustable DL and UL allocation supported. Transport method is
Channel Bandwidths Supported	MHz	1,2,4,8,16	2	OFDM - Ranges from 0.2 to 1.2,	6, 7 and 8 MHz
Channel separation	MHz	1,2,4,8,16	2	OFDM - Ranges from 0.2 to 1.2,	Nominal Channel spacing = (BWChannel(1) + BWChannel(2))/2, where BWChannel(1) and
Number of non-overlapping channels in band of operation	Integer value	1/3/6/13/26 channels for 16/8/4/2/1MHz	13 channels for 2 MHz channel BW	OFDM - Ranges from 130 to 21,	Dependent on spectrum and available bandwidth
Frame duration	ms	Variable, up to 27ms	Variable, up to 27ms	OFDM - Ranges from 15ms to 120ms,	10 ms Frame
Maximum packet size	bytes	1500	1500	2047	2048 bytes
Segmentation support	Yes/No	Yes	Yes	Yes	Yes
Is Unicast, Multicast, Broadcast supported?	Yes/No	Yes	Yes	Yes	Yes, all
Encryption	Algorithms supported, AES Key length, etc	AES, 128,256	AES, 128,256	AES, 128	Yes. AES128 - CCM, ECC and TLS
Authentication	Yes/No (if Yes, please detail)	Yes	Yes	Yes	Yes. AES128 - CCM, ECC, EAP and TLS
Key exchange	Protocols supported	Yes	Yes	Yes	Security for Control and Management derived from PKMv2

Figure 3 —Excerpt from SGIP PAP 2 Wireless Characteristics Matrix for standards operating in sub-1 GHz spectrum

NOTES

1—IEEE Std 802.11ah uses a wider bandwidth and can provide a higher data rate.
2—IEEE Std 802.11ah is not generally deployed as a mesh, it is more suitable for star networks (although it does implement a multi-hop relay function for range extension).
3—IEEE Std 802.15.4g and IEEE Std 802.15.4m are typically combined with a meshing standard (at layer 2 or layer 3) to provide coverage over a broader area.
4—IEEE Std 802.22 is also a star topology.

Techniques for wide-area coverage

Due to the RF power limitations in ISM bands, ensuring adequate range and coverage is a technical challenge. Different techniques are used to extend range in different standards, based on receiving and forwarding packets to other devices within range so they will eventually reach their final destination.

Standards based on IEEE Std 802.15.4 are typically used with a meshing layer:

- Layer 3 mesh (RPL or similar)
- Layer 2 mesh (IEEE Std 802.15.10™)

IEEE Std 802.11ah provides relay operation with an unlimited number of hops.

Mesh vs. repeater

Mesh network topologies are used to extend the range of the network further than the range of the radios. With a simple star topology, it may be difficult or impossible to reach all endpoints. Adding a repeater can solve this in some situations. A repeater typically provides a static route: it can connect and act as a relay between one or more end points and the network coordinator, but it does not provide dynamic routing. This is typically a simple "1 hop" relay between static points.

A mesh network topology will support dynamic route determination, as well as redundant routing paths. When combined, these enable dynamic routing that is "self healing" in the event that a given path (radio link) is disrupted and/or a routing node in the network fails. The mesh more easily adapts to the environment and can be simpler to deploy, as the mesh protocol typically includes automatic route determination and adaptation.

A star with relay topology is simpler, and where flexibility and dynamic characteristics of the mesh are less important, may require fewer devices overall to support a given geographic area, especially where the area is large and the devices are sparsely deployed. In contrast, the mesh may be more cost efficient in high-density deployments where environmental conditions are changing and/or network configuration changes frequently. See also NIST draft paper.

Global regulatory environment

At the most basic level, spectrum usage is regulated by each and every country in the world, focused on those regulations that best support the individual country's strategic interests. The United Nations, recognizing the importance of a common forum to negotiate spectrum issues, created the International Telecommunications Union (ITU), and within the ITU, created the ITU Radio Communications Sector (ITU-R) focused on radio spectrum issues. The ITU-R operates on a consensus basis, with national bodies participating in the process of creating recommendations for spectrum usage, appropriate technologies, and coexistence methodologies. While the participating national bodies are the primary voting members in the ITU-R, industry and standards organizations are also permitted to participate as sector members. IEEE is a sector member of the ITU-R.

While each nation makes its own decisions about spectrum regulation, treaty obligations associated with participation in the United Nations process heavily influence the spectrum regulatory decision-making of national bodies. Other factors supporting cooperation in spectrum regulations include common economic interests, the value of economies of scale enabled by coordinated spectrum usage, and the need to avoid interference from services operating in border areas.

In addition to the activities of the ITU-R, national bodies within geographic regions have created regional bodies that are forums for regional cooperation. The following organizations focus on regional issues of spectrum regulations:

- CITEL: Inter-American Telecommunications Commission
- CENELEC: European Commission for Electrotechnical Standardization
- CEPT: European Conference of Postal and Telecommunications Administrations

National bodies that, by reason of their economic influence, have significant impact on world spectrum regulations are as follows:

- The Federal Communications Commission (FCC), which regulates commercial spectrum usage in the USA.
- OFCOM, which is the spectrum regulator for the United Kingdom.
- ARIB, which is the spectrum regulatory body in Japan.
- Industrie Canada, which is the spectrum regulatory body in Canada.
- MIIT, which is the spectrum regulatory body in the People's Republic of China.

Harmonized spectrum worldwide is the most valuable outcome of the cooperation between nations. Examples of harmonized spectrum with significant commercial value include the following:

- The 2.4 GHz, 5 GHz, and 60 GHz license-exempt bands.
- The worldwide allocation of the 700 MHz band for LTE operations.
- The wordwide regulatory support for GPS made possible by regulations that protect GPS spectrum from interference.

Smart Grid systems, especially for metering at customer premises, primarily use spectrum below 1 GHz. There is no worldwide coordination of spectrum for Smart Grid, i.e., no worldwide harmonized allocation of common bands across regional and national boundaries. The result are radio networks implemented in a hodgepodge of operational spectrum culled from regionally available allocations, including both licensed and license-exempt bands. Table 1 summarizes spectrum used by Smart Grid systems.

Table 1—Example of frequency bands used for wireless Power Grid Management Systems

Frequency (MHz)	Area/region	Comments related to the actual use
40–230 (part of), 470–694/698	North America, UK, Europe, Africa, and Japan	TV white space, rulemaking finished in USA and UK. Rulemaking is in process in Europe.
169.4–169.8125	Europe	Wireless MBUS
220–222	Some parts of ITU Region 2	In ITU Region 1 + Iran, this range is part of the band used for terrestrial broadcasting according to the GE06 agreement, not used for AMR/AMI
223–235	China	Licensed band
410–430	Parts of Europe	
450–470	North America, parts of Europe	
470–510	China	SRD band
470–698	North America and Europe	In ITU Region 1 + Iran, this range is part of the band used for terrestrial broadcasting according to the GE06 agreement, not used for AMR/AMI
779–787	China	

Frequency (MHz)	Area/region	Comments related to the actual use
868–870	Europe	ERC Recommendation 70-03
873–876	Parts of Europe	ERC Recommendation 70-03
896–901	North America	Licensed band, Part 90 in the USA.
901–902	North America	Licensed band, Part 24 in the USA.
902–928	North America, South America, Australia	License exempt ISM. In Australia and some countries in South America, only the upper half of the band is allocated
915–921	Parts of Europe	ERC Recommendation 70-03
917–923.5	Korea	
920–928	Japan	
928–960	North America	Licensed band, Part 22, 24, 90 and 101 in the USA.
950–958	Japan	Shared with passive RFID
1427–1518	United States and Canada	In parts of Region 1, namely in Europe: – The range 1452–1479.2 MHz is planned for use by terrestrial broadcasting according to the Ma02revCO07 agreement (registered in ITU as regional agreement) and by the Mobile service for supplemental downlink only according to relevant EC decision. – The range 1492–1518 MHz is used for wireless microphones according to ERC Recommendation 70-03, Annex 10. – Not used for AMR/AMI
2400–2483.5	Worldwide	
3550–3700	United States	Regionally licensed
5250–5350	North America, Europe, Japan	
5470–5725	North America Europe, Japan	
5725–5850	North America	License exempt, ISM band

The 3GPP2 cdma2000 Multi-Carrier family of technologies can also be used for power grid management applications. The applicable bands are defined in 3GPP2 C.S0057-E v1.0 Band Class Specification for cdma2000 Spread Spectrum Systems.

Conclusions

Unlicensed spectrum is valuable and beneficial for Smart Grid applications, due to the scarcity and cost of licensed spectrum in comparable frequency ranges. The sub-1 GHz spectrum offers superior propagation and penetration properties when compared to higher frequency ISM bands. TVWS spectrum can provide additional options for operation in rural areas with sufficient availability of unused TV channels. The sub-1 GHz standards implement coexistence mechanisms that make it possible to operate effectively in this shared spectrum.

Appendix: Example calculations for link range and reliability

Conditions:

Transmitter antenna height (m)	10.0
Receiver antenna height (m)	3.0
Center frequency in MHz	915
Environment	small city
Fading mode	shadowing and fading
Std. Deviation in dB	1.0
Percentage of time	90%
Desired link margin in dB	6.0
Transmit power	30 dBm
Receiver sensitivity	−97 dBm

Result:

Transmit power	30.0	dBm
Gains	10.0	dB
Losses	129.3	dB
Received power	−89.3	dBm
Noise + interference power	−120.9	dBm
Median received SNR	31.6	dB
Processing gain	0.0	dB
Median received EbNo	31.6	dB
Required EbNo	24.0	dB
Excess	7.6	dB
Margin	6.0	dB
SURPLUS	1.6	dB
Desired link reliability	90	%
Effective link reliability	62	%
Specified link distance	1.000	km
Distance for desired reliability	**1.100**	**km**

The second example uses exactly the same parameters, but changes the transmit frequency to use the 2.4 GHz license exempt band throughout the world. Changing only the frequency, the distance to achieve the same 6 dB link margin is reduced by nearly half:

Transmit power	30.0
Gains	10.0
Losses	139.8
Received power	−99.8

Noise + interference power	−120.9
Median received SNR	21.2
Processing gain	0.0
Median received EbNo	21.2
Required EbNo	24.0
Excess	−2.8
Margin	6.0
SURPLUS	−8.8
Desired link reliability	90
Effective link reliability	27
Specified link distance	1.000
Distance for desired reliability	**0.589**

Citations

[1] 3GPP2 C.S0057-E v1.0 Band Class Specification for cdma2000 Spread Spectrum Systems.

[2] ANSI/TIA 4957 series. Specifications for the Smart Utility Network

[3] ERC Recommendation 70-03, Relating to the Use of Short Range Devices (SRD).

[4] IEEE Std 802.1X, IEEE Standard for Local and metropolitan area networks—Port-Based Network Access Control.

[5] IEEE Std 802.11, IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

[6] IEEE Std 802.11af, IEEE Standard for Information technology—Telecommunications and information exchange between systems - Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 5: Television White Spaces (TVWS) Operation.

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[8] IEEE Std 802.15.4e, IEEE Standard for Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)—Amendment 1: MAC sublayer.

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[15] SGIP PAP 2 Wireless Characteristics Matrix, https://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless

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