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A Review of Wireless and Satellite-Based M2M/IoT Services in Support of Smart Grids

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Abstract The Smart Grid (SG) is an evolution of the electricity network that dynamically integrates the activities and energy control of power consumers, power generators, distribution systems, and devices connected to the grid (e.g., substations, transformers, and so on). The goal of the SG is to economically and efficiently deliver a sustainable, reliable, and secure electricity supply. Machine-to-Machine (M2M) technology is designed for automated data exchange between devices, and thus has applicability to SGs. With M2M technology, organizations track and manage assets; inventories; transportation fleets; oil and gas pipelines; mines; wide-spread infrastructure; natural phenomena such as weather conditions, crop production, forestry condition, and water flows; and, as noted, SGs. Wireless communication is a staple of M2M. These wireless technologies range from unlicensed local connectivity, to licensed 3G/4G/5G cellular, to Low Earth Orbit (LEO) satellites. All of these technologies are relevant to the SG. Utilities have started to gradually support M2M and Supervisory Control And Data Acquisition (SCADA) systems over satellite links. This article focuses on wireless and satellite-based M2M services, as applicable to the Smart Grid, including the use of Internet of Things (IoT), particularly for the transmission and distribution (T&D) space sector; some comparisons to wireline solutions are also discussed.

Keywords Smart grid · Wireless · Very small aperture terminals (VSATs) · High throughput satellites · Ka-band · Machine-to-machine (M2M) · Device-to-device (D2D) · Supervisory control and data acquisition (SCADA)

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1 Introduction

The intelligent integration of information from actions of users connected to the electricity grid – consumers, generators, and the distribution grid – are performed by the Smart Grid (SG). Efficient, sustainable, economical and secure delivery of electricity supplies is the main goal of SG, as described by the European Technology Platform for Electricity Networks for the Future. Thus, a SG encompasses the various stages of power generation, distribution, and consumption. SGs are an evolution of a traditional power system; their goal is to exploit the power of automation to better control distribution, green efficiency, and consumption. Looking at a traditional power system, the initial step entails converting power from a generation source, such as steam-, hydroelectric-, or renewable-based generation systems, into a high voltage electrical signal that can be transmitted utilizing the power grid. Often, but not always, the power is generated at some distance from the consumption point; this is particularly the case for hydroelectric and wind-generated power. The next stage occurs where the high-voltage power is stepped up for long-distance transmission and then "stepped-down" for distribution to consumers utilizing switchgear and transformers; the power flow is then controlled downstream using circuit breakers and arresters. At that juncture, the resulting medium-voltage electrical power is distributed to the users after additional step-down transformers. It should be noted that, due to long distance transmission loss, even with high voltage lines, about 40% of the generated power is lost; thus, any technology that, in some way, can reduce these losses is highly desired, especially as there is a societal drive to affect a greening of the environment. Fig. 1 provides a pictorial view. Systems in countries with large or remote regions (e.g., Canada, Brazil, China, Philippines, Australia) can greatly benefit from wireless and satellite based systems for grid control.

Currently, the transmission and distribution systems are facing multiple change drivers, including the emergence of distributed renewable energy generation and the increasing electrical energy demand of businesses and consumers. SG management technologies are needed to address these and related issues. The power industry is increasingly seeking to incorporate Information and Communication Technologies (ICT) into its operations, including at the edges. The thus-enhanced grids are known as SGs.

An extensive body of literature and research on the topic of SG is available, e.g., see [1, 2]. SGs typically entail the following disciplines: Advanced Distribution Network Architectures, Smart Metering, Demand Response, Integration of Renewable Sources, Smart Cities, Home Intelligence, Market Integration, Storage, Privacy and Data Security. SGs' control requires wide-area network coverage that spans the generation, transmission, distribution, and consumer portions. For this purpose, cost-optimized communications networks are needed. Attempts at controlling parts of the grid, for example, using Automated Meter Readers (AMRs), go back several decades; one application of Integrated Services Digital Networks (ISDN) developed in the mid-1980s was intended to be for AMR and for telemetry; unfortunately, ISDN turned out to be too expensive and achieved limited penetration. Although wireline-based solutions have evolved and are now available, wireless communication technologies will become increasingly important in the broad-based deployment of SGs. Specifically, power line carrier-based communications have been deployed, however, currently few of these technologies have been broadly adopted in terms of level of practicality, scalability, and cost-effectiveness. These attributes are critical to enable the industry to institutionalize them as a viable final solution, particularly in rural environments, supporting the long-distance portion of the transmission grid. Wireless automatic meter reading is of particular interest to utilities for both urban and suburban environments.

Fortunately, evolving Machine to Machine (M2M) services under the rubric of Internet of Things (IoT) are seen as increasingly applicable to SG applications [3–10]. M2M communications takes place between two or more mechanistic entities that routinely omit direct human intervention. These devices appear in a large set of operational devices, such as SG

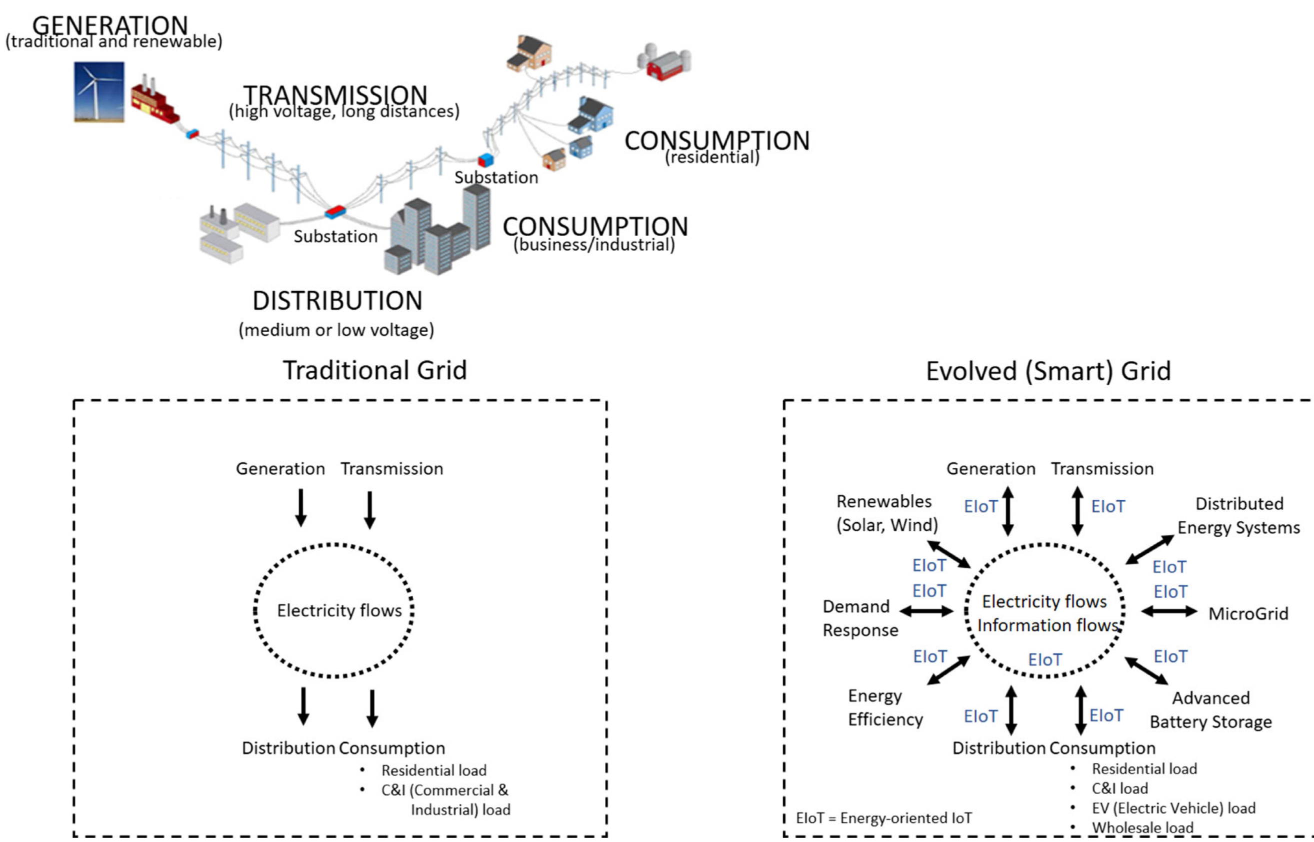

Fig. 1 Transmission and distribution grid structure

controllers, AMRs, surveillance cameras, alarm systems, and automotive equipment, and many more. M2M is defined extensively by ETSI standards. For example, ETSI TD 102690 V1.1.1 (October 2011) defines a High-Level M2M System Architecture (HLSA). In addition, a number of use cases were published by ETSI for several applications including ETSI TR 102691: "*M2M: Smart Metering Use Cases*". The expectation is that M2M communication will be an important component for the implementation of the next-generation SG.

As shown in Fig. 2, a Radio Access Network (RAN) is often used in M2M environments. A RAN can be a cellular network, a satellite network, or a number of other evolving wireless edge-area networks [12]. The RAN can be utilized to support SG applications. Enhancement, modernization, and extension of SCADA functionality has been supported by M2M-based solutions. M2M, on the other hand, is not intended to connect directly SCADA-based devices but to provide interoperation with the use of proxies and/or gateways [13]. IPv6 and Mobile IPv6 (MIPv6) may play an important role in SG systems' future.

Wireless-based M2M solutions based on a plethora of technologies have been sought in the recent past. As a specific example, cellular telephony solutions may be utilized, but both the modem cost and the service availability outside of major urban centers remain a challenge, especially in developing countries. Hence, satellite-based M2M services may be increasingly applicable to SGs, particularly for rural environments. Satellite-based M2M supports transmission of small data quantities in a wide geographic area. For example, many M2M and SCADA applications are gradually enhanced over satellite links. In addition to SG, satellite-based M2M include applications for connectivity such as data collection for monitoring the environment and climate analysis, law enforcement and Coast Guard applications, and off-shore oil drilling. Other wireless technologies may be appropriate for urban environments, where, for example, access to individual meters – often located in closed environments, such as basements – is needed. Regardless of which wireless link technology is used, cost-effectiveness, appropriate geographic coverage, and security, are key desiderata [3, 4, 14–16].

This review article focuses on wireless and satellite-based M2M services, as applicable to the SG applications, particularly for the transmission and distribution (T&D) space sector. Section II discusses some key SG requirements. Section III discusses relevant wireless technologies that can be employed in the SG/IoT/M2M environment, including satellite-based M2M systems.

2 Smart grid requirements

Power companies are increasingly injecting ICT technology in general, and M2M principles in particular, into their operations in support of modernization efforts to improve reliability and efficiency, including cybersecurity mandates. SG

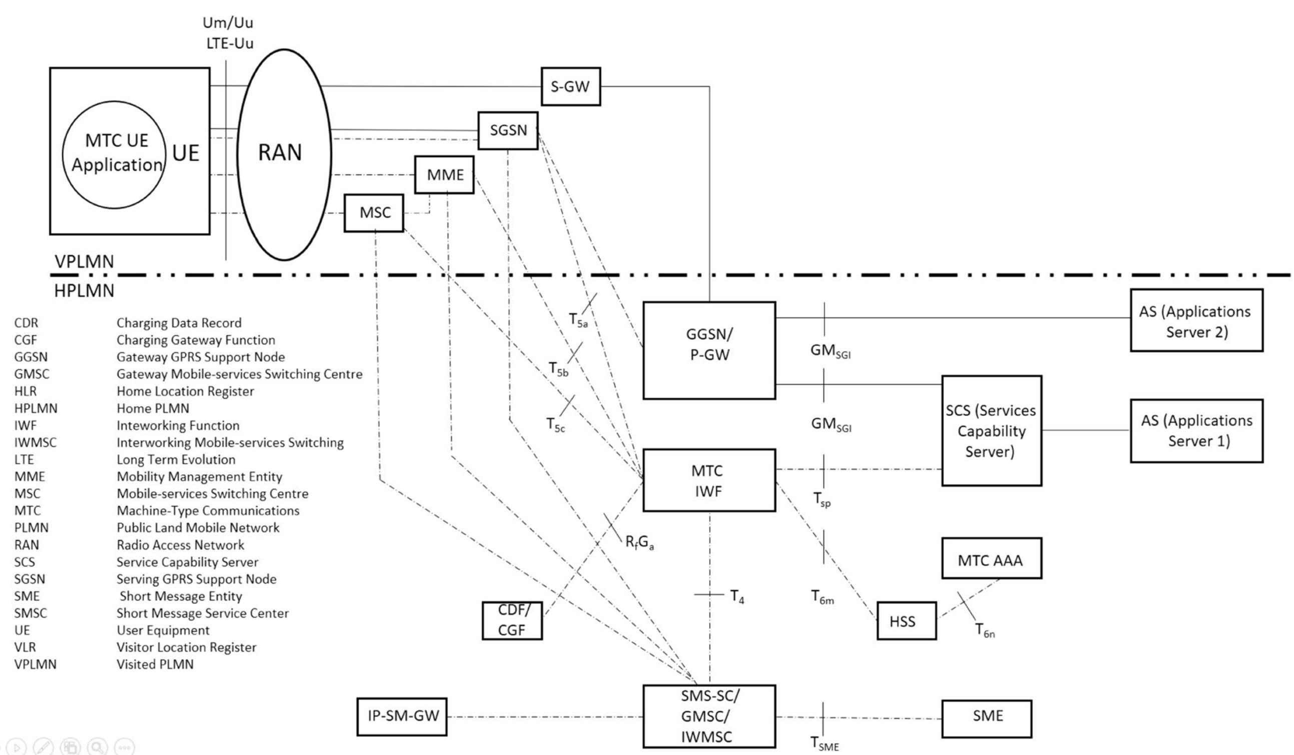

Fig. 2 ETSI M2M architecture

requirements for wireless and satellite-based M2M services include the following [17]:

- Wireless Channels

– Two-way channels
– Widespread coverage
– Adequate throughput for a range of applications, including Variable Link Capacity
– Adequate Quality of Service (QoS), e.g., Packet Loss, Packet Errors
– Interoperability
– Scalability
– Scalable internetworking with overlay networks
– Low cost
– Flexibility
– Reliability and self-healing capability, especially for backbone applications
– Intrinsic security and privacy

- Remote sensing devices

– Ruggedness
– Long lasting batteries (if not energized from the line)
– Ability to support multiple protocols (Multi-Radio Support and Spectrum Efficiency)
– Self-Configuration and Self-Organization

- Gateways to core networks

– Ability to support many different physical links and protocol stacks
– Addressing, Routing, Network address translation (NAT), firewalling/security, authentication, interworking proxy
– Resource (channel) management
– Remote entity management
– History and data retention, transaction management
– Compensation brokerage

- Domicile/In-Home devices

– Ability to support a large number of devices and appliances
– Low power consumption
– Ability to support many different physical links (e.g., Ethernet, 802.15.4, Wi-Fi, Bluetooth, power line communications [PLC[1]] and cellular).

[1] PLC is a wireline technology for data exchange over power lines by using advanced modulation methods.

As the SG evolves there is a need to continue to support existing SCADA-based systems and applications. A SCADA system collects operational information and transfers the information to a centralized processing center for decision making. The processed and analyzed event data alerts management that an event of interest has occurred, and that some action is needed. Thus, a SCADA system transfers information between a centralized system and a constellation of Remote Terminal Units (RTUs) and/or Programmable Logic Controllers (PLCs) [13]. SCADA systems traditionally used Public Switched Telephone Network (PSTN) for securing the connectivity needed to support the intended monitoring; wireless technologies are now being increasingly applied to SCADA applications.

There are a number of SCADA-related protocols; the most common being:

- International Electrotechnical Commission (IEC) 60,870–5 series, specifically IEC 60870–5-101. In particular, IEC 60870–5-1 specifies the data link and physical layers for application control. Other standards in this family support important functionality including mapping application data units to transmission frames and rules for defining data and information elements.
- Distributed Network Protocol version 3 (DNP3). This protocol works in serial communications mode for point-to-point data exchange. It facilitates inter-device communication for SCADA RTUs. Specifically, the RTU-to-Intelligent Electronic Device (IED) communication protocol and also master-to-RTU/IED communication protocol is included (an IED is an intelligent controller of power system equipment; examples include circuit transformers and breakers.)

In the U.S., responsibilities for coordinating the development and adoption of SG standards and related guidelines due to the Energy Independence and Security Act of 2007 (EISA) is granted to the Federal Energy Regulatory Commission (FERC) and the National Institute of Standards and Technology (NIST). Industry experts note that the SG:

- Must be cyber secure;
- Must be a national integrated grid with several command and control centers, not just with local/regional grids;
- Must manage distributed energy from solar and wind and store and manage net metering and the production of renewable sources;
- Must manage loads at the plug level; and,
- Must be resilient and redundant rerouting transmission in real time.

The Advanced Metering Infrastructure (AMI) is one example of this modernization effort. The AMI is the ICT mechanism that is put in place between the consumer and the power utility. In the aggregate, it is an integrated assembly of smart meters, networks, and data processing systems that supports two-way communication between the utilities and the consumers [14, 18]. AMI is a significant component of the overall approach for implementing the SG, and the main component for achieving Demand Response (DR). SG devices and smart appliances are increasingly designed to be "Demand Response-enabled". To realize efficiency and load-management goals utility companies are adopting two-way networking connectivity to enable consumers to monitor and possibly reduce their energy usage [19, 20]. A centralized entity will poll or inform the meter to gather appropriate consumption information. The goal is to improve the efficiency of the distribution of energy by utilizing detailed real-time information about the end user's (consumer or business) consumption, especially in conjunction with incentivized billing plans.

As noted, many grid-related functions have been supported utilizing SCADA-based mechanisms, which have traditionally been wireline oriented. The migration to wireless thus entails supporting the SCADA mechanisms along with improved cybersecurity over said media.

As alluded to above, a key element of a SG is a cost-effective communications network (e.g., as supported by the AMI), that enables automated metering capabilities. Specifically, such a network collecting power consumption data allows the utility to automatically control customer loads, especially during peak demand periods. Additionally, it enables the utility to remotely and automatically update the grid configuration, and control supply of power to certain customers. Among other benefits of smart metering are the ease of site access, power usage information, and statement accuracy, monetary savings associated with DR and management of power demand. Fig. 3 depicts the AMI environment graphically.

A growing number of utility companies are planning to roll out intelligent metering services by incorporating M2M devices in the meters. A variant application of the smart meter DR capabilities can also be utilized to support a pre-payment arrangement where a consumer purchases a specified amount of the commodity (e.g., electricity, gas, and so on); the data related to the amount purchased is then downloaded to the metering device and stored on the (M2M); when the purchased volume has been consumed, the supply is halted [11].

Home Area Networks (HAN) are also being deployed in support of a Smart Home. Furthermore, vendors have started to design products that integrate built-in-communication systems which interact with the AMI-enabled meter and with the HAN. The combination of the AMI-enabled meter and the HAN allows consumers to be aware of their electricity usage and associated costs on a quasi-real-time. Codifying information about the cost of power and the consumer's preferences, appliances can schedule their operation such as deferring or adjusting the operating parameters to reduce peak energy consumption. Thus, this method of intelligent management of energy supply potentially reduces expenditures as well as the peak demand. Peak demand reduction helps save money by avoiding the cost of auxiliary power plants' construction that is put in place to handle peak loads.

To be effective and expedite consumer penetration, a HAN's networking technology (i) supports open standards, (ii) is cost-effective, and (iii) does not require major new infrastructure investments. AMI should utilize a number of communications standards and networking technologies for connecting the domicile device (the meter) to the management applications of the utility. Several industry and standards-organizations are developing physical and upper layer standards, including but not limited to:

- European Commission (EC) M/411 Smart Metering Mandate. The goal was development of standards for smart meters to facilitate interoperability and consumption awareness;
- EC M/490 Smart Grid Mandate (March 2011). The objective was to build standards for European SGs;
- IEEE P2030/SCC21. Its objective is to address SG interoperability;
- IEEE P1901.2: defines an OFDM-based standard for transmission over power lines;

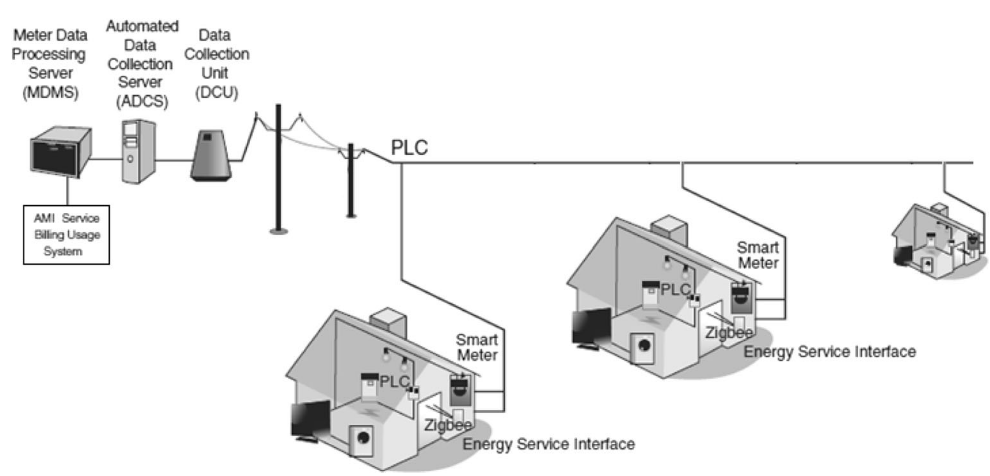

Fig. 3 Advanced metering infrastructure (wireline based)

- ETSI TS/TR 102: describes the M2M services and architecture, including smart metering [21];
- TIA: TR-50: the objective is to address smart device communications.

3 IoT-oriented wireless services

Connectivity of IoT/M2M devices can be achieved by wireline channels, such as PLC, however, a number of utility companies have started to use wireless technologies to support AMI/smart meter/SCADA functions. The wireless technologies discussed in the next subsections are among the major ones applicable to SG applications [22]; also see Fig. 4 for a positioning of these various technologies. For city-based devices transmission power consumption battery life is important; smart meter systems can utilize line power; remotely-deployed systems that employ satellite may need reliable power sources of various types, but solar cells may be an ideal solution for these installations.

3.1 Approaches

- Cellular (large footprint; but high endpoint cost, new cellular technologies coming, Low Power Wide Area [LPWA] competition);
- LPWA (cost-effective buildout, energy efficient, ideal for smart cities and mobility; but low bandwidth);
- Satellite (global; but higher endpoint cost than other solutions; strong regulatory oversight);
- Short range wireless/new technologies (high bandwidth, and use in consumer applications; but interference liabilities); and,
- Wireline (high bandwidth, also in conjunction with Wi-Fi, and used in consumer applications; limited mobility and dependent on Wi-Fi coverage/interference).

3.2 Licensed spectrum versus unlicensed spectrum

3.2.1 Licensed spectrum

- Wireless options: Long Term Evolution Cat M1 (LTE-M) Rel 13 (~10 km, licensed spectrum, 1 Mbps, battery ~10 years)[2];
- Narrowband NB-LTE Rel-13 (~15 km, licensed spectrum, 0.1 Mbps, battery ~10 years);
- Narrowband EC-GSM Rel-13 (~15 km, licensed spectrum, 0.01 Mbps, battery ~10 years);
- Next Generation, 5G cellular (~15 km, licensed spectrum, 0.01 Mbps, battery ~10 years, several years out in the 2020s.)

3GPP recently adopted a LPWAN system called Narrow Band IoT (NB-IoT) to define a new radio access for cellular IoT, based mostly on a non-backward-compatible variant of E-UTRAN (Evolved Universal Terrestrial Access Network). NB-IoT aims at improved indoor coverage, large number of low throughput devices, low latency sensitivity, low device cost, and low device power consumption. (Note: NB-IoT has replaced the previous NB-LTE and NB-CIoT proposals).

In summary, EC-GSM is a global solution for cellular-based IoT; it is supported on legacy GSM equipment and makes use of the existing infrastructure. LTE-M provides a number of transmission capabilities and can coexist with Mobile Broadband (MBB) traffic. NB-IoT is a scalable solution for low-end requirements having narrowband throughput requirements but broad coverage.) Fig. 5 provides a perspective on these available cellular technologies that have urban and/or regional applicability for SGs, while Fig. 6 depicts the recent evolution steps in advancing the technology to its current state.

3.2.2 Unlicensed spectrum

Unlicensed non-3GPP LPWA IoT wireless technologies (vendor proprietary), including [23]:

Platanus (<1 km; 500 kbps);

- OnRamp (4 km; up to 8 kbps);
- Weighless-N (up to 5 km; up to 100 kbps);
- Telensa (up to 8 km; low);
- NWave (10 km; up to 100 bps);
- Amber Wireless (up to 20 km; up to 500 kbps);
- LoRa (15–45 km suburban, 3–8 km urban; up to 50 kbps); and,
- SIGFOX (50 km suburban; 100 bps).

These wireless services and others support wireless sensor networks in general and smart city, SG, and crowdsensing applications, in particular.

3.3 Cellular services

Cellular networks may be a practical solution for IoT/M2M applications aimed at operating over a large area such as a nation, a region of the country, or even a city [25]. In general, even beyond SG applications, various M2M applications are expected to be a major contributor of traffic (and also revenue) for cellular networks in the near future.

Analysis shows that there are cost, reliability and deployment schedules, as well as performance, tradeoffs in choosing

[2] LTE-M is the industry term for the LTE-MTC (Machine-Type Communications) LPWA 3GPP Release 13 specification, specifically LTE CatM1, suitable for the IoT.

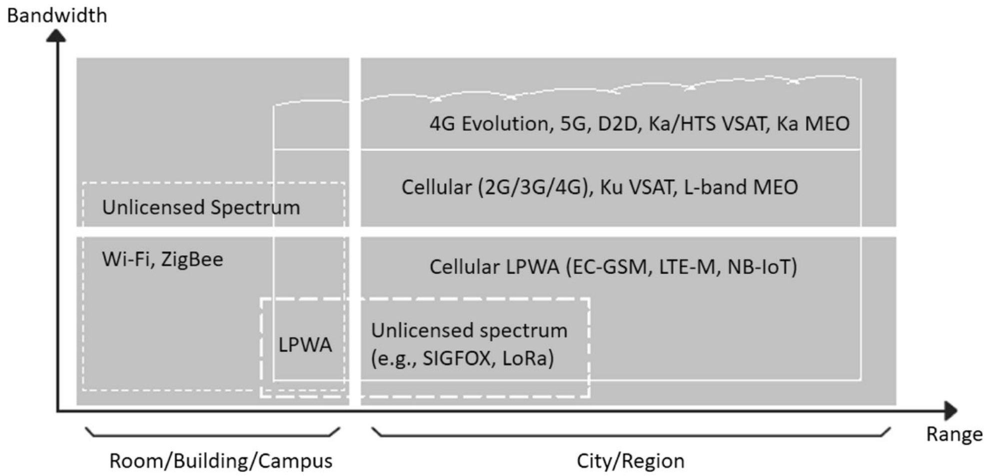

Fig. 4 Applicability of wireless technologies in the IoT environment

3G, 4G or 5G, and/or the M2M-specific cellular services for SG. It is well-known that IoT/M2M traffic has specific characteristics, including data priority, transaction size, the real-time streaming QoS requirements, and the higher delay tolerance of the AMI/SCADA data. In order to cost effectively employ cellular technologies, these characteristics have to be taken into account as design criteria [26]. Initially on the 3GPP front, efforts have focused on the ability to differentiate Machine Type Communications (MTC), and to enable operators to selectively support MTC devices in case of network congestion. Thus, a priority indicator was added to enable support of congestion control in both core and radio access networks [27]. Among them, reliability security and confidentiality are key considerations; endpoints need to provide and support virtual private network (VPN) constructs, embedded firewall, and other capabilities.

3.3.1 Device-to-device (D2D) communication

A promising approach for the IoT access in general, and for SG systems in particular, is by superposition of IoT SG traffic on cellular data networks such as LTE and 5G cellular systems. D2D communication is a promising method to improve spectrum efficiency of the cellular systems; this is achieved by enabling direct transmissions between end users in proximity to each other. By using proximity discovery and direct

❑ EC-GSM

- GSM is (still) the dominant mobile technology in many countries
- Most cellular M2M applications currently utilize GPRS/EDGE for connectivity
- GSM is likely to continue playing a key role in the IoT due to its global footprint, implementation time, and cost effectiveness
- Initiative undertaken in 3GPP Release 13 to improve GSM
- Resulting EC-GSM functionality enables coverage improvements of ~ 20dB compared to GPRS (at 900 MHz)

❑ LTE-M

- LTE is the contemporary mobile broadband technology and its deployment is expanding
- Focus has been on supporting mobile data (Gbps performance) with devices that make use of new spectrum
- LTE-M supports new power-saving functionality suitable for serving a variety of IoT applications over LTE-ready networks
  - Power Saving Mode and eDRX extend battery life for LTE-M to >10 years
- LTE-M traffic is multiplexed over a full LTE carrier
- New functionality enables reduced device cost and extended coverage

❑ NB-IOT

- NB-IoT technology is being standardized in 3GPP Release 13
- NB-IoT is specifically designed for ultra-low-end IoT applications
- NB-IoT is a self-contained carrier that can be deployed with a system bandwidth of only 200kHz
- It is enabled using new network software on an existing LTE network
- Rapid implementation is anticipated

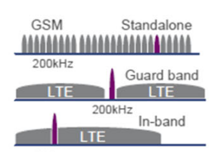

Fig. 5 Cellular solution for SG/M2M

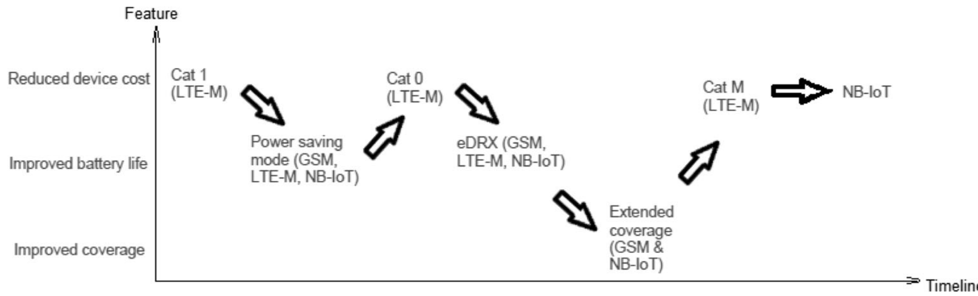

Fig. 6 Recent evolutions of 3GPP-based systems for cost-effective IoT support

communication between nearby users, D2D will enhance spatial reuse of spectrum resources and will at the same time facilitate the establishment of communication links with low latency [28–31]. This is the due to the widespread deployment of the network and plans for wider data coverage. However, the growth in the number of mobile devices and their demand for data has created scarcity of bandwidth on the available frequency spectrum. Furthermore, for SG and other data applications, relying solely on traditional cellular networking does not accommodate the ever-increasing number of users with an acceptable QoS for their transport. Therefore, in the last decade, providers and industrial telecommunication companies have developed new techniques and designs, such as cognitive radio, Femtocells, D2D communications, and the like, to satisfy data on cellular demand. D2D communication is a major distinction in LTE 5G vis-à-vis other cellular systems and therefore, it is discussed in some detail here.

D2D communication has recently attracted significant and substantial amount of attention from both industry and academia, mainly due to its unique advantages to offload cellular traffic, and improved system throughput, higher energy efficiency and robustness to infrastructure failures. These are critical attributes for all cellular applications and, in particular, for SG support.

In D2D communication, user devices (User Equipment [UE], such as IoT things) are enabled to communicate with each other using three different modes: reuse, dedicated, and cellular. In the reuse and dedicated modes, the UEs/IoTs directly connect to each other while in cellular mode the transmission between UEs/IoTs is through the evolved Node-B (eNB). In the reuse mode, the same frequency resource is reused by both D2D paired UEs/IoTs and other cellular devices in the network, which may cause interference at the receivers. However, in dedicated and cellular modes resources are dedicated to D2D and cellular devices separately, hence no interference is experienced at the UEs/IoTs. D2D UEs would select a single mode, or mixed modes to find the best way for their transmission.

Periodically, the UEs/IoTs report their measurements to the eNB, on time based, movement based, or distance based options. Relying on this measurement information a specific mode is selected and maintained throughout the session. Sometimes, based on the throughput maximization objective and due to mobility of UEs in the network, a selected mode might have to change in order to maintain the maximum throughput. The switching from one mode to another mode is handled by a vertical handover mechanism.

It has been shown that in traditional cellular networks, the distance based method which performs a location update, reporting the UE's location when its distance from the cell where it performed the last location update, exceeds a predefined threshold, results in the best performance for the handover mechanism compared to the time based and movement methods. Extensive research has studied the value and comparison of throughput and performance among the various modes. In the case of IoT SG since it may be the case that the devices are mostly static, the distance method might be more appropriate.

In traditional cellular networks, the distance is calculated from the border of a cell, which is defined by a circle representing the coverage area of the omni directional base station. However, it is shown that in D2D enabled networks, the coverage area that a specific mode is selected for is not always circular, therefore a new technique is needed to calculate the distance. This problem needs careful attention for the SGs deployed in broad areas and in locations far from eNB.

In later research, the set collection of regions denoted by the area around an eNB together with the border between them is defined as the "mode selection map" of the D2D cellular network. Recent research has produced handover algorithms based on the mode selection map and an approach to find the distance from the map and critical direction set for the UEs.

3.4 Satellite services

Satellite-based M2M provides connectivity over large areas. Since terrestrial networks may not service all locations on earth, satellite operators, such as Iridium, and Inmarsat offer global connectivity services that can extend M2M communication to almost 100% of the earth. Hence, delivery of relatively small quantities of data in almost all cases is supported by the satellite-based M2M. Some M2M services support simplex communication; other services support bidirectional communications; the latter is more flexible allowing data exchange. Table 1 defines some key satellite technologies usable in the M2M/SCADA/Grid applications [32, 33].

M2M satellite applications have been extended to Mobile Satellite Services (MSS) and to the L-band (1.3–1.7 GHz); these services support low data rate applications. Many of these applications are considered as being mainstream M2M applications (e.g., logistics, engine telemetry, environmental sensing), while other applications exist in the context of the IoT rubric, such as SGs, crowdsensing, smart cities, and so on. In SG systems SCADA information can be exchanged between end points on the grid and the operations systems from any points in the footprint of the satellite, including remote areas; this is particularly useful in geographic areas outside the U.S. and Europe [3, 4].

Traditionally, Ku-band Very Small Aperture Terminal (VSATs) have been employed for M2M/SCADA and other enterprise applications. In North America (as an example), the frequency of operation is 14.0–14.5 GHz for the uplink and 11.7–12.2 GHz for the down link (some variations exist for TV services operating at 12.2–12.7 GHz and 17.3–17.8 GHz). The VSAT system consists of a central hub that employs a relatively large multi-meter antenna with a gateway connection to the Internet or an enterprise or Utility network; the hub operates using a Time Division Multiplexing (TDM) outbound link and a Time Division Multiple Access (TDMA) inbound link. The DVB-S2X standard is typically utilized, defining the protocol procedures and parameters used on the channels. The remote terminals use sub-meter antennas. The large majority of deployed systems (approximately 96%) use proprietary technologies from companies such as iDirect, Gilat, Hughes, although the basic channel discipline is DVB-S2X (Digital Video Broadcasting – Satellite 2 Extensions); a small portion use standards-based systems through and through (specifically the DVB-RCS2 [DVB Return Channel by Satellite 2] protocol for the return channel); companies here include Advantech.

The recently adopted DVB-S2X standard has brought some major throughput extensions (allowing higher order modulation up to 256-PSK with tighter filter roll-off, which allows an increased usable bandwidth of the transponder.) VSAT systems used in a SG application would preferably consist of an Outdoor Unit (ODU) integrated with the antenna that would include both the Radio Frequency (RF) elements (Block Upconverter [BUC] and Low Noise Block Downconverter [LNB] as well as the baseband electronics (the modulator/demodulator) in a single enclosure; a typical enterprise system consists of an Indoor Unit (IDU) containing the baseband electronics and an ODU containing the RF elements. SCADA/M2M applications generally do not need very high throughput, for example 19.2 kbps might suffice, unless some video surveillance application along the SG is needed.

In recent years, one has seen the emergence of High Throughput Satellites (HTS) that operate at Ka-band. The advantage of Ka and HTS systems is the much higher total throughput available at the satellite (for example, 150 Gbps) as well as at the individual remote devices (for example, 50 Mbps). As noted, the SCADA/M2M SG applications may not need this kind of throughput, however, the related advantage

Table 1 Key satellite technologies usable for grid applications (from [3, 4] and various industry sources)

Concept	Definition
Geostationary Orbit (GEO)	The satellite orbits the equator. The satellite appears stationary with respect to an antenna on earth. Therefore, a tracking antenna is not required for the satellite.
Fixed-satellite service (FSS)	This is a satellite service between earth stations at fixed defined positions, when GEO satellites are utilized.
High Throughput Satellite (HTS)	When a large number of distributed satellite spot beams cover a service area, they provide contiguous service covering. HTS satellites offer covering a large service area contiguously, and therefore support high user throughput at a low cost per bit. HTS provide broadband data services typically using Ka-band frequencies. HTSs can be GEO or LEO systems. Spot beams cover only a portion of the earth, such as a nation or subcontinent. Shaped narrow beams point to different portions of the geographical area. This method supports higher satellite antenna gain, and therefore requires a small aperture antenna at the user device. Frequency reuse for different beams also increases the system capacity.
Ka-band	This band utilizes spectrum from 18 GHz to 30 GHz and, therefore, is the most susceptible to rain.
Ku-band	This band utilizes spectrum from 12 GHz to 14.5 GHz spectrum and is therefore more susceptible to rain fade than the C-band.
L-band	An Intermediate Frequency (IF, 950–1450 MHz) which is typically employed at earth stations for routing traffic over coaxial/waveguide. Regulatory agencies define a (slightly) different over-the-air L-band range. Typically, only a small portion (1.3–1.7 GHz) of L-band is used in wireless satellite communications, such as for M2M applications.
Low Earth Orbit (LEO)	Elliptical or (more often) circular orbits at 5000 km above earth or less. The duration of the orbit cycle is generally near 2 h. The time duration a specific LEO satellite is above the horizon is about 20 min.
Mobile Satellite Service (MSS)	A satellite service providing wireless communication to nearly any point on the globe, typically operating at the L-band.

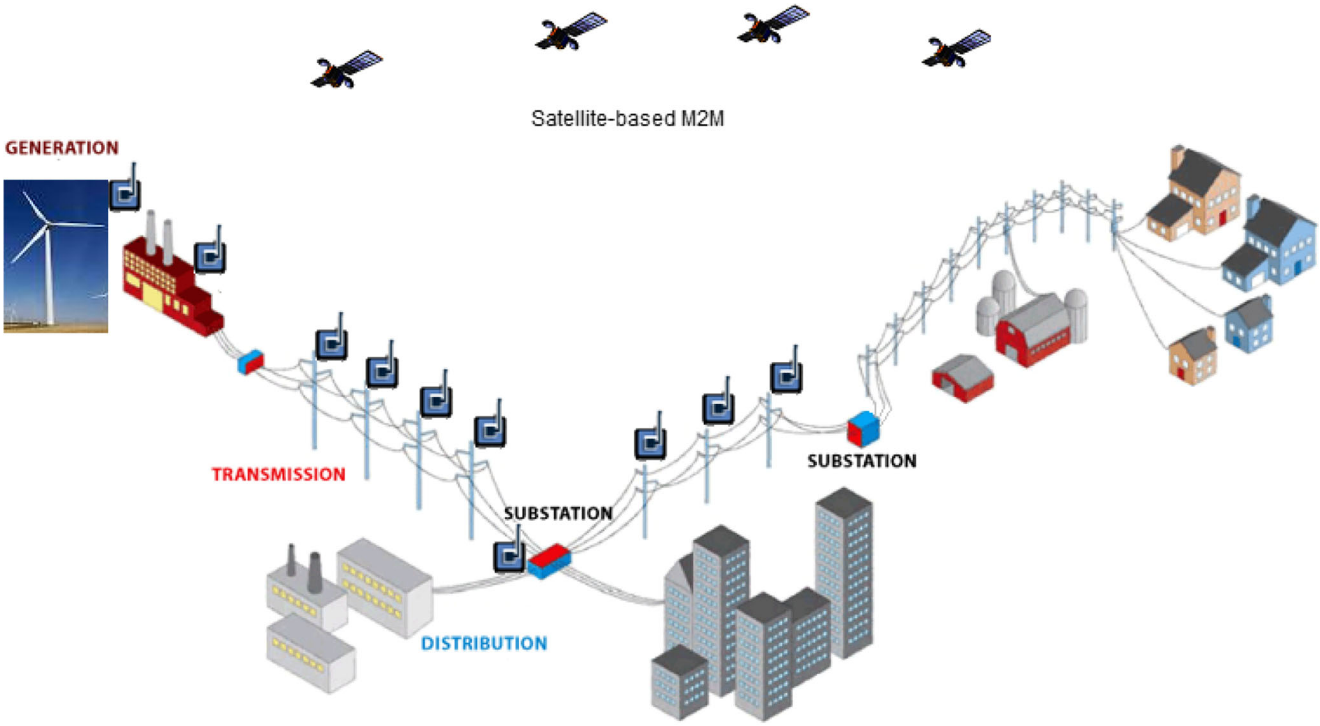

Fig. 7 Satellite-based SG

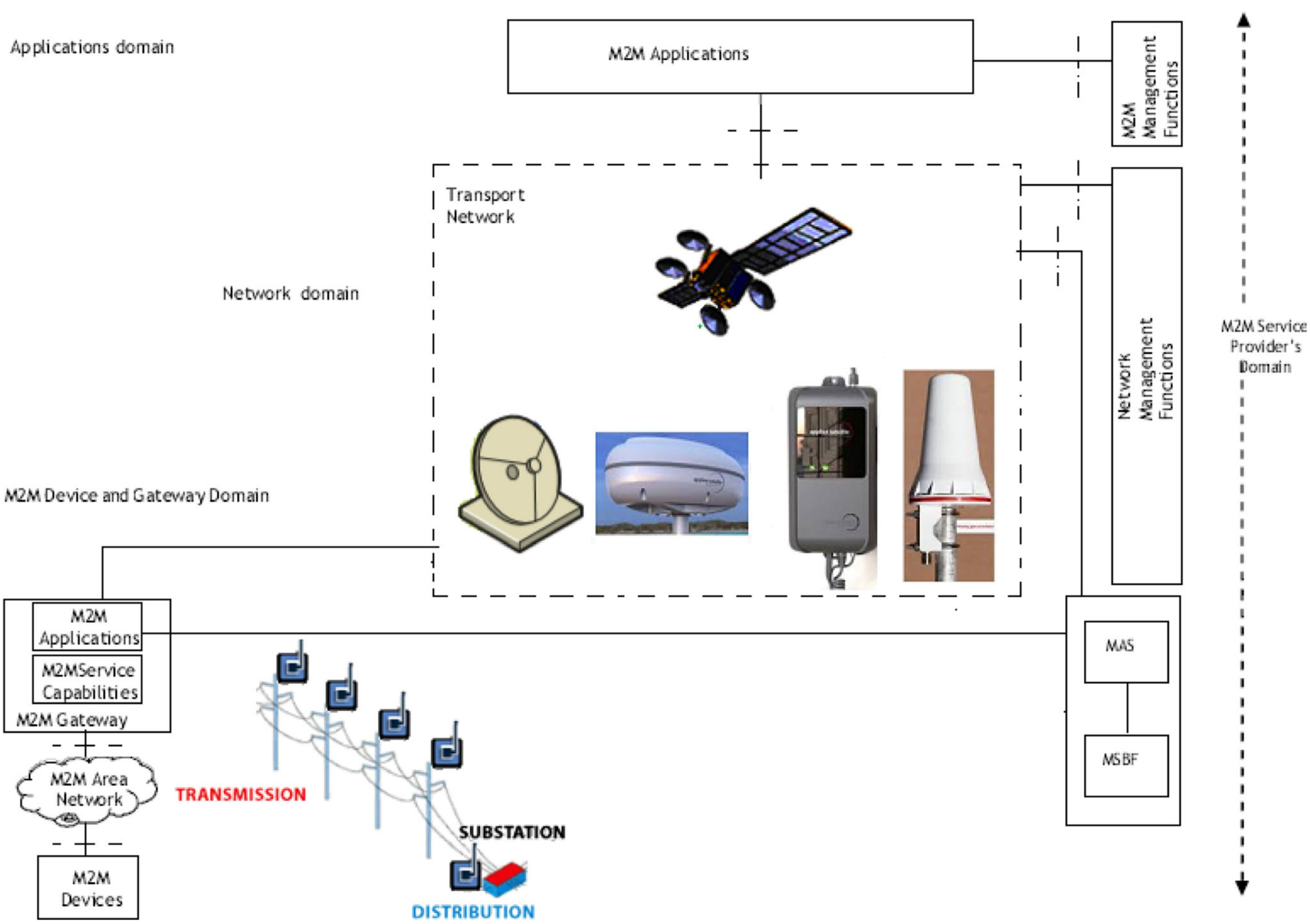

Fig. 8 M2M architecture applied to SGs

of Ka/HTS is to greatly decrease the transmission cost-per-bit. Ka band systems typically use frequencies in the range of 17.7–21.2 GHz for downlink and 27.5–31 GHz for the uplink. While the 19.7–20.2 GHz downlink and 29.5–30 GHz uplink is common to all regions (these are 500 MHz bands), Region 1 (Europe) allows a downlink band 17.3–17.7 GHz (400 MHz band) and Region 2 (North and South America) allows a downlink band of 18.2–19.3 GHz (a 1 GHz band). A band of 17.7–18.8 GHz downlink and 27.5–28.6 GHz (1.1 GHz band) is also allowed in some regions/administrations. There are other bands allowed for both 400 MHz and 500 MHz. The band 20.2–21.2 GHz downlink and 30–31 GHz uplink (1 GHz band) is used in some military applications. Some bands are being assessed by regulatory entities for future allocation, especially for Direct to Home (DTH) at Ka (e.g., 21.4–22.0 GHz). For example, Yahsat 1A (a joint venture with SES) and 1B support 25 × 33 MHz transponders (DTH is supported via Ku payloads, Ka supports secure military communications). Yahsat-1B has 25 × 110 MHz Ka transponders plus 21 × 54 MHz Ka transponders (a total of 46). In both of these cases, a 'non-standard' transponder bandwidth would need to be supported. Again, an integrated unit would be ideal for SG applications.

Another major area of development is the emergence of large constellations of Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites. Traditionally Iridium and Inmarsat have provided global services at the L-Band that can and have been used for M2M applications. However, the bandwidth has been limited and the cost relatively high. A new generation of LEO/MEO satellites are planned, which would greatly increase the throughput while also reducing latency. For example, OneWeb announced in 2015 the deployment plans for a future constellation of 700 low-altitude satellites. SpaceX also announced a plan to deploy 4425 LEO satellites.

Fig. 9 Commercial example of Ka/HTS VSAT technology applicable to SGs

(Used with explicit permission)

Table 2 Ability of specified wireless technology to meet various SG communications requirements

Communications-related Element	Requirement	Cellular	Unlicensed spectrum/LPWA	Short range wireless	Satellite	Wireline
Wireless Channels	Two-way channels	Y	Most of them	Y	2-way and 1-way solutions	Y
	Good coverage	Urban, suburban; issue in rural	Urban	In-building	Y	Urban, suburban; issue in rural or harsh environs
	Adequate throughput for a range of applications, including Variable Link Capacity	Y	Most of them	Y	Y	Y
	Adequate QoS, e.g., Packet Loss, Packet Errors	Y	Most of them	Y	Y	Y
	Interoperability	Y	Most of them	Y	Y	Y
	Scalability	In many instances	Limited; more for urban	Not particularly	Y	Y
	Scalable internetworking with overlay networks	In many instances	Limited; more for urban	Not particularly	Y	Y
	Low cost	Less so	More so	Y, but local	Less so	Usually less so
	Flexibility	In many instances	Limited; more for urban	Not particularly	Y	Y
	Reliability and self-healing capability, especially for backbone applications	Y	Y	NA	Y	Generally; issue in rural or harsh environs
	Intrinsic Security and privacy	To a degree	To a degree	To a degree	To a degree	To a degree
Remote devices (while using the shown communication link)	Ruggedness	Depends on design	Depends on design	NA	Depends on design	Depends on design
	Long lasting batteries (if not energized from the line)	Depends on design	Depends on design	NA	Generally, more power needed	Depends on design
	Ability to support multiple protocols (Multi-Radio Support and Spectrum Efficiency)	Depends on design	Depends on design	NA	Multi-band (e.g., Ku, Ka) more expensive	NA
	Self-Configuration and Self-Organization	Depends on design	Depends on design	NA	Depends on design	Generally, no
Gateways (while using the shown communication link)	Ability to support a plethora of physical links and protocol stacks	Depends on design	Depends on design	NA	Depends on design	Generally, yes
	Addressing, Routing, NAT, firewalling/security, authentication, interworking proxy	Depends on design	Depends on design	NA	Depends on design	Generally, yes
	Resource (channel) management	Depends on design	Depends on design	NA	Depends on design	Generally, yes
	Remote entity management	Depends on design	Depends on design	NA	Depends on design	Generally, yes
	History and data retention, transaction management	Depends on design	Depends on design	NA	Depends on design	Generally, yes

Table 2 (continued)

Communications-related Element	Requirement	Cellular	Unlicensed spectrum/LPWA	Short range wireless	Satellite	Wireline
	Compensation brokerage	Depends on design	Depends on design	NA	Depends on design	Generally, yes
Domicile/In-Home devices (while using the shown communication link)	Ability to support a large number of devices and appliances	Depends on design	Depends on design	Depends on design	(less common use of this link)	Yes
	Low power consumption	Depends on design	Depends on design	Depends on design	(less common use of this link)	Yes
	Ability to support a plethora of physical links (e.g., Ethernet, 802.15.4, Wi-Fi, Bluetooth, PLC, cellular)	Depends on design	Depends on design	Depends on design	(less common use of this link)	Yes

3.4.1 Antennas for M2M satellite communication

Small antennas are used in M2M applications, as pictorially shown in Figs. 7, 8 and 9 depicts an integrated ODU operating in a Ka HTS environment. Major M2M antenna technologies are as follows:

- Embedded Antennas: Most M2M devices use internal multi band antennas. These antennas are designed to match the radiating properties of the device itself. L-Band systems/LEO may utilize these antennas (although other types are also used).
- Stubby Antennas: these M2M products have antennas that are located external to the M2M device; they are optimized to the electromagnetic requirements of the product.
- IDU + ODU or preferably Integrated ODU VSAT submeter antennas.
- VSAT (Mini) Antennas: these M2M products use Ku and Ka tracking antennas (especially when broadband applications have to be supported); typically, these antennas are ≤1 m.

3.4.2 Comparison

It is well known in the satellite industry, there are pros and cons between GEO- and LEO-based solutions. First, the GEO satellites in services are more well established and are available from a large number of suppliers; LEO constellations are relatively newer and are available from a smaller set of providers. GEO generally provide more bandwidth, especially with the new-generation HTS; however, they also generally require higher power on the ground. LEO require less on-the-ground power and are available in 98% of the global surface; they are also ideal for mobile, aeronautical, and maritime applications (although this is less relevant for grid applications.) GEO require larger antennas (usually in the submeter range), while LEO services require smaller antennas.

3.5 Mapping of requirements

Earlier we listed some key requirements of the communications infrastructure required to support SGs. Table 2 provides a mapping between various SG communications elements and the wireless technologies under discussion.

3.6 Relative penetration

Market research observers claim that by 2020 numerically short-range technologies such as Bluetooth, Zigbee and Wi-Fi will be the dominant technologies for connecting the majority of IoT devices [24]. Cellular services will continue as the largest in terms of revenue (the 2020 worldwide application revenue is forecast at about $160 B). By revenue ~25% of the deployment will be on 2G/3G cellular, ~50% on LTE trending to 5G, ~15% on LPWA, and ~10% on wireline, short range, and satellite (the latter ~2%.)

4 Conclusion

With the ever-increasing demand to save energy, many technologies have evolved and are being experimented with for the realization of SGs. Most approaches naturally require access to and information gathering from millions of homes. Stations and control centers (e.g., SCADA) for power consumption monitoring and resource adjustment are the primary points of data aggregation, analysis, and decision making. Among the devices that are considered for data collection and information dissemination, are IoTs, among other regular monitoring devices at homes and in industrial buildings. The sheer volume of the number of these devices and otherwise exorbitant cost of connectivity using the traditional methods, calls for approaches for access and information gathering and dissemination that are beyond the traditional approaches. For this reason, all options which could support this formidable task should be called on. In this article, the authors have provided a brief overview of the application of SG in control of power systems and the options for their access and connectivity.

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