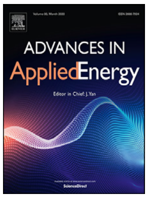
Advances in Applied Energy 1 (2021) 100003

Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen



Cyber-enabled grids: Shaping future energy systems

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ARTICLE INFO

Keywords:
Pervasive sensing
Contactless sensing
Cyber-enabled grid
Internet of things
Energy harvesting
Shielding
Energy grid

ABSTRACT

As the penetration of distributed energy resources based on renewable sources increases, several technical challenges are introduced into energy grids. These include real-time power balance, control of bi-directional energy flow, power quality, distributed optimization, state estimation and topology estimation in distribution grids, and multi-level electricity trading. To overcome these challenges and to create situational awareness in energy grids, pervasive sensing becomes essential. To overcome hurdles such as implementation and cost of such pervasive sensing, in addition to traditional contact-sensing methods, contactless sensors that can measure key variables in the grid needs to be leveraged. Contactless sensing enables measurement of process variables that may be hard to measure due to technological limitations of contact sensing, large measurement delays, or high costs. In addition to contactless sensing, pervasive sensing proves advantageous as it can leverage ongoing technological advances in Internet of Things (IoT), as they can lead to enhanced network connectivity between sensors as well as between the edge and the cloud. Finally, pervasive sensing proves even more attractive by integrating contactless sensing not only with wireless communication but also with shielding and energy harvesting. This paper reviews pervasive sensing techniques in power grids that encompass contactless sensing technologies, IoT connectivity, energy harvesting and shielding. In addition, we also explore how pervasive sensing in a Cyber-Enabled Grid (CEG) can contribute to the development roadmap of Autonomous Energy Grids (AEGs), a futuristic concept where the grid will be making automated operational decisions. The potential challenges and research opportunities in this pioneering research field such as data deluge, cybersecurity, and sensor fusion will be discussed. This review article, which addresses the role of pervasive sensing in CEGs, is a first of its kind. It will help engineers and scientists to understand its significant potential to shape future energy systems.

1. Introduction

There has been a concerted effort to develop future energy systems that accommodate greater penetration of renewables so as to move toward a reduced carbon footprint [1-5]. In order to deliver a clean and sustainable, safe and secure, affordable and equitable, reliable and resilient smart grid, the power grid requires a pervasive cyber-layer that senses, communicates, and acts, at the right place, at the right time, and in the right way. A power grid equipped with such a pervasive sensing and cyber-layer is essentially a Cyber-Enabled Grid (CEG), in which the grid is monitored (physical world) by connected sensors and the sensor data is telemetered (cyber world) for analytics and subsequent grid control, protection and microgrid operation (physical world). Realization of such a CEG is a very difficult task because it requires visibility over all the critical components of the entire grid.

Grid visibility plays an important role in power systems. Pervasive sensing is essential for grid visibility, which consists of sensors to measure consumption and generation, characterize the system operating states in both spatial and temporal domains, and detect the actual network topology, providing data for state estimation (e.g. voltages and angles at each bus) from SCADA (supervisory control and data acquisition) measurements, as well as for forecasting. State estimation is used for a number of purposes ranging from system monitoring to control of generation and economic operation to security assessment. Pervasive sensing is important not only during normal operation but also in the presence of outages, which are abnormal conditions, as accurate trigger-

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https://doi.org/10.1016/j.adapen.2020.100003
Received 22 October 2020; Received in revised form 26 November 2020; Accepted 26 November 2020

Nomenclature

AEG	Autonomous energy grid
BGO	Bi_3GeO_4
BSO	Bi_3SiO_4
CEG	Cyber-enabled grid
CT	Current transformer
DERs	Distributed energy resources
DG	Distributed generation
EH	Energy harvesting
IoT	Internet of Things
PCC	Point of common coupling
PMU	Phasor measurement unit
PT	Potential transformer
RF	Radio frequency
SCADA	Supervisory control and data acquisition
WAMS	Wide-area measurement system
WACS	Wide-area control system
WAPS	Wide-area protection system

ing of all protection equipment has to be ensured during such events. It is therefore clear that pervasive sensing, especially when scalable, is an important building block for a CEG.

Under normal conditions, monitoring and control capabilities, especially of the bulk energy components, are provided through SCADA as the central entity. When small disturbances occur, SCADA with schemes such as automatic generation control automatically restore power balance; should the post-disturbance operating condition be undesirable, the operator steps in, suitably changes the generation setpoints and network topology and restores the system back to a desirable normal condition. However, when disturbances are severe, SCADA is turned off, as they may trigger an incorrect action, until some semblance of normalcy is restored. This in turn implies that sensing is exceedingly important under abnormal conditions. As connectivity increases, pervasive sensing becomes vital, especially in a CEG, where the sensing can be followed by swift corrective action.

Under abnormal conditions, protective systems are in play, which form an important subset of controls. They isolate a faulted or short-circuited portion of the grid very quickly so that the equipment is not damaged. The proper operation of protective systems heavily relies on the measurement of key variables using sensors especially during transients. Of particular importance are two anomalies that are associated with transient phenomena, which are voltage collapse and frequency imbalance. The two important control goals that arise from these phenomena are 1) to maintain steady frequency during normal operation and restore frequency to its scheduled level during system contingencies when large imbalances between load and generation may be present; 2) to regulate voltages within safe limits at all buses after disturbances to prevent outages and blackouts. This in turn implies that sensing of voltages and frequencies is the first step in ensuring the stability of the overall grid.

The above underscores the importance of improving visibility and "having eyes on the field" – the more pervasive the sensing is, in terms of location as well as in type, the better the grid response. That is, pervasive sensing leads to smart, efficient, and autonomous action; it can respond as dictated by the system states and therefore make appropriate decisions. The questions that remain are whether a scalable sensing technique can be installed at low-cost without disruption to power systems, and if the technique is scalable.

The importance of pervasive sensing becomes even more vital in a CEG. As the penetration of distributed energy resources (DERs) increases, bi-directional flow may be introduced, causing traditional protective devices to become inadequate in detecting faults, especially with high levels of inverter-based devices. This pervasive sensing needs to be heterogeneous; in a CEG, both AC microgrids and DC microgrids may be present, the latter motivated by operational efficiency and reduced dependence on frequency regulation, losses, and power factor correction. Pervasive sensing enables big-data, which in turn allows the deployment of artificial intelligence and machine learning based methods.

The aim of this article is to review pervasive sensing techniques in power grids that encompass contactless sensing technologies, IoT connectivity, energy harvesting and shielding. In addition, we explore how CEGs can contribute to the development roadmap of futuristic autonomous energy grids (AEGs). A qualitative approach is adopted in this article with literature search on pervasive sensing and contactless sensing. Key research findings are summarized primarily from works from 1990 to 2020 but we also considered some seminal works, for example from the 1970s and 1980s, which strongly influenced later developments. This article begins with review of grid visibility (Section 1) and its imminent challenges (Section 2) to provide the context for the need for pervasive sensing. Section 3 offers a detailed discussion of working principles of various measurement techniques of current and voltage and the difference between contact and contactless sensing so that the readers can gain the scientific insight and understand the technological gaps that need contactless sensing to fill in order to realize pervasive sensing. Section 4 elaborates on contactless sensing, IoT connectivity, energy harvesting and shielding (Sections 4. 1 and 2) which together can form an IoT contactless sensing system and envision its application to pervasive sensing (cyber world) in the power grids (physical world) and providing data to operation and control centers and energy markets for analytics (cyber world) resulting in the decision making for grid operation (physical world), forming essentially a cyber-physical system. Such CEGs can overcome the challenges mentioned in Section 2. The contribution of CEGs to the AEG development roadmap is elaborated in Section 5 so that readers can gain further insight into the impacts of pervasive sensing. Research gaps and opportunities are then presented in Section 6.

2. Challenges in need of grid visibility

The integration of renewable energy and intelligent consumption and storage devices into the ever-expanding power grids due to rapid urbanization, particularly in Asia, is resulting in the issues of microgrids, bi-directional power flow, power quality and distributed control, which were unthinkable a hundred years ago when the power grid was born but are becoming imminent problems now. These unprecedented changes, expanded below, are underscoring the need for pervasive sensing to provide grid-wide visibility to overcome these challenges.

C1. Microgrids

Microgrids can operate in two modes: grid-connected mode and islanding mode. A microgrid imports or exports the electricity from/to the main grid depending on the generation and load as well as the contractual obligations of the power market [6]. In grid-connected mode, the goal is to control power flow between the microgrid and the main grid in order to participate with active and reactive power and satisfying the IEEE Standard 1547 [7]. In islanding mode, the target is to satisfy the load with the required level of power quality such as voltage and frequency stability and harmonic distortion. Islanding can be categorized as intentional or unintentional. Intentional islanding occurs when there is scheduled maintenance or degraded power quality of the main grid. Unintentional islanding occurs when there are faults or other unscheduled events [8]. Voltage source inverters are used to connect a microgrid to the main grid and they typically switch from a grid-following mode to a grid forming mode when run in an island condition. Voltage and current sensing are necessary for the control purpose of the process between these modes.

C2. Distributed Generation

Modern power grids are integrating distributed generation (DG) from renewables at the consumer side into power systems [9]. Inverter interfaced renewable resources and energy storage systems are becoming very common in microgrids as well [10]. With the increased penetration of DGs, bi-directional power flow is imminent, which will lead to problems such as high power losses and protection failure. This problem is particularly severe for low voltage distribution networks due to higher R/X ratio of the distribution lines and their radial topology [9]. Reverse power flow occurs when the voltage at the consumer side is higher than the substation voltage, which leads to overvoltage at the point of common coupling (PCC) of DGs and possibly also at some other neighboring busses [11]. In addition, line losses increase when energy is supplied through the lines with high R/X ratio. On the other hand, undervoltage may also occur at the PCC when the network loading is maximum but DG supply drops due to perhaps wind speed variations or cloudy weather. Microgrid energy management systems are needed to control the power flow to mitigate the negative impacts of microgrids, particularly on distribution networks. The voltages of PCCs need to be measured to monitor the situation of undervoltage/overvoltage and enable the control of power flow through the distribution lines with lower R/X ratio to reduce power losses.

C3. Distributed Control

The modernization of power grids is accompanied with the increasing number of small distributed and renewable energy resources, moving from thousands of distributed resources to millions will exceed the capabilities of available control systems. In addition, communication needs over the geographical span and difficulty of sharing data (due to lack of means or unwillingness) are becoming daunting as the power networks keep on expanding. As the power system becomes more complex, traditional centralized control schemes are becoming ineffective. The central controller also suffers reliability and security vulnerability as potentially a single point of failure. Therefore, ideas have been proposed to decouple the control target among different cell units to achieve noncentralized control which can be either decentralized or distributed. Decentralized control is not ideal because it assumes that the interaction between subsystems is not necessary which can result in disastrous system-wide issue. An example is the large-scale blackout in August 2003 in North America [12]. In that incident, there was no coordination among the subsystems. Each subsystem was trying to maintain its own stability, tripped and transferred the extra load to the other subsystems, leading to a cascading overloading consequence [8]. Hence the trend is moving towards distributed, hierarchical control of cells which can help to reduce the computational and communication burdens caused by increased number of DGs.

Distributed control techniques mandate interactions among smaller energy cells. These cells may be divided into a number of regions, where each region can contain DER units, loads and power lines [8]. In this way, a large problem is segmented into a series of smaller problems, making the solution more computationally viable. When each cell is operated as a microgrid, the control hierarchy consists of primary (local), secondary (microgrid) and tertiary controls (main grid) based on required time frame [8]. Primary control responds the fastest and is the first level of control. Secondary control acts as the energy management system managing power quality control, voltage profile control, reactive power sharing, and loss reduction. Tertiary control is at the main grid level and provides long-term policy [8]. However, real-time distributed control is difficult to implement because of lack of sensing devices and communications among sensing devices and controllers. Large number of sensors are needed to be deployed for the real-time monitoring of the operations of local generators, batteries and controllable workloads of appliances which is key to the stability and reliability of a microgrid. These sensor data are also needed for prediction of future power demand to optimize the operations of local generators [13] and determine energy price. Sensors will be required in each home to measure energy related data such as power, voltage and frequency.

C4. Power Quality

Power quality issues become more severe as the size of a microgrid is smaller and its stability is not as steady as the main grid because all stability issues must be resolved within the microgrid itself. Power quality issues caused by nonlinear loads were once confined to isolated devices and computer rooms, but now as the computing and electronic devices become more and more common, the issues can prevail throughout buildings and power networks [14]. The common power quality issues include voltage sags (or dips), voltage swells, harmonics, transients, and voltage and current imbalance. Knowledge of the network topology (e.g. from one-line diagram) is critical for investigating power quality problems [15]. Transient voltages exceeding electrical insulation ratings can lead to gradual insulation dielectric breakdown or possibly abrupt failure and damage electronic components. Unbalanced currents endanger motors with torque pulsation, increased vibration and mechanical stress, increased losses and overheating. Unbalanced currents are more difficult problem than open-circuit or closed-circuit faults because they typically require corrective system-level design changes. Harmonic currents can cause inductive heating of transformers, generators, other electromagnetic devices such as motors, relays, and coils, and metal parts. Voltage distortion can lead to unpredictable equipment operation and electronic equipment failure. A sensing technique that can monitor three-phase power quality is important for analyzing the overall power quality issues and investigating the effect to the individual loads [16].

C5. Topology Estimation

Grid-state determination has always been a daunting task because of the complexity of the transmission and distribution grids as well as the instrumentation cost [17]. For the transmission grid, its state can be estimated from a system model and physical parameter measurements. Phasor measurement units (PMUs) can significantly improve grid observability. A rough design guideline is 1/3 of the buses in a transmission system need to be equipped with PMUs for complete observability and the locations of these PMUs need to be optimized. This can serve as a starting point. Additional PMUs can be installed if needed. Topology determination is an intricate problem in modernizing power grids. Achieving observability in distribution grids is more challenging than in transmission grids because of complicated circuit topology (e.g. feeder branches, laterals and inter-ties, unbalanced circuits, poor documentation, large quantity of attached loads and devices, time-varying dynamic circuit topology). Data flows and voltage levels in the circuit may reverse. Besides, due to distributed generation, power flow reversals and loops can occur which adversely impact the system protection and Volt-Var regulation. As such, it is difficult to conduct accurate state estimation for interpreting grid data, events and control commands, and thus state measurement plays a more important role for distribution grids which needs sensors. The monitoring of state transitions of grid switches, reclosers, sectionalizers and inter-ties is traditionally problematic because of lack of sensing devices providing measurement of power state variables that enable inference of the switch state transitions (by detecting line voltage or current flow). Observability strategy requires advanced sensors that detect changes of power state variables for determining switch state transition.

C6. Price Determination

In the future electricity markets, microgrids will play a critical role in determining proper pricing tariffs for consumers. Energy must be delivered while satisfying technical and economic criteria. Besides, data about consumers' patterns are important for designing optimal pricing schemes to various consumers [18]. Microgrids constitute part of real-time energy arbitrage [19]. On one hand, microgrid operational cost can be minimized by purchasing electricity from the grid when the price in the market is lower than the energy generation cost in the microgrid. On the other hand, renewable energy can also be stored for future use at peak hours. The purpose of the price determination is to make the power market efficient in reducing energy cost through competition among all the market participants [20]. For that, the energy

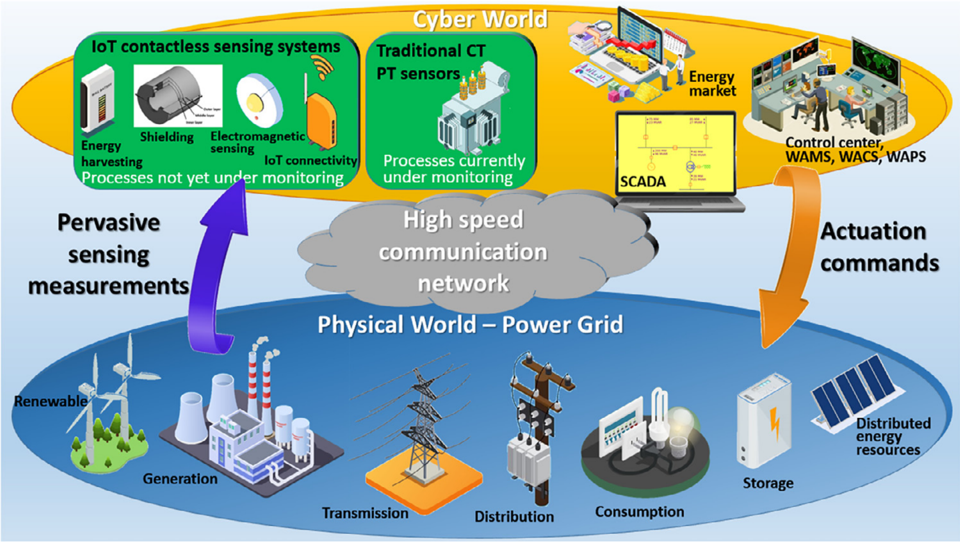

Fig. 1. A power grid equipped with pervasive sensing is a large cyber-physical system. The sensors and actuators interact with the physical world which is the power grid. IoT contactless sensing systems can complement the traditional contact sensors and help to monitor processes which are currently not measured by existing CTs and PTs to realize pervasive sensing. The pervasive sensing measurement data is transmitted via various communication means to the cyber world which are the control centers and energy market for analytics. WAMS, SCADA and other advanced grid applications are implemented in the cyber world. Subsequently, control, protection and microgrid operations will be executed in the physical world through actuation commands. Such a grid is a CEG.

consumption and generation of a microgrid need to be measured accurately in real time in order to provide data for the price determination algorithm.

C7. Battery Lifetime

In order to enhance the reliability and efficiency of a microgrid, an energy storage system is usually necessary to strengthen its self-regulation. Chemical batteries are typically used in microgrids to store energy. However, the lifespan of a chemical battery is limited and it may deteriorate severely due to overcharging, high charge/discharge rate, deep discharge, etc. Thus the overall system service life and performance are dependent on the battery. Sensors, regulators and limiters are needed to be integrated into the battery system to monitor and protect the battery from surge power demand, over charged/discharged, high charge/discharge current and over-voltage [21].

3. Increased visibility with pervasive sensing

The challenges in Section 2 can be overcome by increasing visibility with pervasive sensing (cyber world) where sensors are pervasively deployed to provide a vision of physical devices of the grids (physical world) by measurement. The most important variables to measure in a power system are current and voltage in both time and frequency domains. These sensor data can be inputted to PMUs and SCADA by various communication means for many monitoring purposes, such as power flow, fault detection, state estimation, power quality, etc., to achieve optimal system operation and control. By pervasive sensing, a wide-area measurement system (WAMS) (cyber world) composed of time-synchronized PMUs can monitor the power system. The data from WAMS can be utilized by the wide-area control system (WACS) to control the transient and oscillatory dynamics of system operation (physical world) and wide-area protection system (WAPS) for relay protection and remedial actions such as load shedding. Increasing the visibility over the whole grid requires a scalable pervasive sensing technique for measuring power state variables. A power grid with pervasive sensing is a large cyber-physical system, and thus a CEG. Fig. 1 illustrates the relation among power grid, pervasive sensing and cyber-physical system.

Although a state estimation algorithm can be used to obtain the system state, it cannot substitute the need of pervasive sensing. State estimation is used because some desired states currently cannot be directly measured. It can only provide estimation for processes from busbars and major nodes and its reporting rate is typically in the order of minutes because measurement data arrive at different time points and the traditional SCADA refreshes every few minutes due to the low acquisition rate of remote terminal units [22]. Although WAMS with PMUs can have a very high reporting rate in principle, the practical refresh rate of the existing SCADA-based state estimation is the constraint [23]. In order to reduce the reporting rate to regime of less than a second, state estimation would need to be conducted with only synchrophasor data [24], which is still challenging today due to insufficient PMU placement as explained later. For example, China has a relatively new power grid, yet PMUs can only mainly be found in major substations (all 500 kV and some new 220/110- kV substations) and generation plants [25]. In United States, PMUs can only be found in key locations of North American power grid, such as major transmission inter-connections, key generation plants, substations, and major load centers [26]. The temporal and spatial resolutions of the results from state estimation are not sufficient for the situational awareness of smart grids and microgrids which essentially require real-time data from the whole grid. Besides, estimation is not the same as the actual direct measurement by sensors. The estimation obtained by weighted least squares of the bus voltages at the major nodes of the network and pseudo measurements are not as accurate as the actual measured data to the real state parameters. State estimation can mainly be used for off-line applications which is inadequate for online monitoring of future energy grids. Therefore, state estimation cannot eliminate the need of a cyber-physical system with pervasive sensing which will measure voltage and current throughout the system (physical world) and telemeter the values to the control center and energy market (cyber world) for analytics. In the case a sensor breaks down and send in erroneous data, nowadays statistical technique or machine learning algorithm can easily detect malfunction sensors and remove their data from analytics.

3.1. Current measurement

In general, there are four physical principles that can be applied to measure electric current including Ohm's Law, Faraday's law of induction, magnetic field sensing, and the Faraday effect (magneto-optic phase shift). Shunt resistors making use of Ohm's law are commonly used to measure current due to their simple principle where the voltage drop across the shunt is proportional to the current flow. However, this method causes power loss, and it is invasive and requires making contact with the circuit which can be dangerous and expensive for high voltage cables. Current transformers (CTs) and Rogowski coils can measure electric current by Faraday's law of induction that states an electromotive force induced in a conductor is proportional to the rate of change of the magnetic flux that cuts across the conductor. As such, they are only applicable for AC current measurement which is unfavorable to

Table 1
Comparison of existing current measurement techniques.

	Current measurement							
	DC				AC			
	Physical principle	Examples	Contact / Contactless	Single / Multiple phase conductors	Physical principle	Examples	Contact / Contactless	Single / Multiple phase conductors
Ohm's law	Measure voltage across a fixed pure resistance	Shunt resistors	Contact and invasive	Single	Measure voltage across a fixed pure resistance	Shunt resistors	Contact and invasive	Single
Faraday's law of induction	(not applicable)				Measure stepped-down current on secondary circuit due to magnetic induction	Current transformers (CTs), Rogowski coils	Contact but noninvasive	Single
Magnetic field sensing	Measure magnetic field by Bio-Savart law	Magnetoresistive sensors, Hall effect sensors	Contactless (both physical and galvanic isolations) for overhead cables Contactless (galvanic isolations) for underground cables	Multiple. Individual current sources can be reconstructed from an array of measurement.	Magnetic field sensing by Bio-Savart law	Magnetoresistive sensors, Hall effect sensors	Contactless (both physical and galvanic isolations) for overhead cables Contactless (galvanic isolations) for underground cables	Multiple. Individual current sources can be reconstructed from an array of measurement.
	Measure magnetic field by Ampere's Circuital law	Hall effect current sensor in current clamp	Contactless (galvanic isolation)	Single	Measure magnetic field by Ampere's Circuital law	Hall effect current sensor in current clamp	Contactless (galvanic isolation)	Single
Faraday effect	Measure the change of polarization due to the magneto-optic effect	Fiber-optic sensors	Contactless (galvanic isolation)	Single	Measure the change of polarization due to the magneto-optic effect	Fiber-optic sensors	Contactless (galvanic isolation)	Single

modern smart grid because our power networks are adopting more and more DC power nowadays as discussed earlier. Besides, they have to clamp around each individual conductor and installation is difficult or impossible with multi-core, multi-phase cables. Current measurements by magnetic field sensing and Faraday effect possess the unique advantage that they do not need to have electrical contact with the primary circuit (galvanic isolation).

3.2. Voltage measurement

In general, there are four principles that can be applied to measure electric voltage including Ohm's law, Faraday's law of induction, electric field sensing and the Pockels effect (electro-optic phase shift). Voltmeters and their alike measure current across a resistance or impedance and make use of Ohm's law to determine the potential difference between two points. It requires making electrical contact with the high voltage cable, thus it is invasive and it is only suitable for relatively low voltage measurement. Potential transformers (PTs) are the instrument transformers that are most commonly used these days. They measure the stepped-down voltage on the secondary circuit due to mutual induction and then the voltage of the primary circuit can be determined. They are not invasive to the primary circuit; however, they have to make contact with the live high voltage cable. Besides, they cannot work with DC voltage. Electric field sensing and optical Pockels effect open up possibilities to contactless measurement [27] of both DC and AC voltages.

A summary of existing current and voltage measurement techniques is provided in Tables 1 and 2 respectively.

3.3. PMUs enabled by sensors

PMUs are critical for real-time monitoring, protection and control of power systems [28]. They provide synchronized phase-angle measurements that can indicate imminent instabilities so that timely remedial actions can be taken to avoid power system outages. PMU information can also improve the performance of relay during power swing, voltage stressed conditions and load encroachment. The synchronized phasor provided by PMUs enables fault location estimation and identification which significantly improves reliability and security. Synchronized phasor is applied in dynamic security assessment for wide-area monitoring, which can provide catastrophe predictors. PMU measurements are used to cross-check the power-system monitoring techniques such as state estimation and stability assessment.

PMUs are installed in various places over the topology of the power network to provide observability to achieve wide-area monitoring. The data of the PMUs are time-synchronized by using a sampling clock which is phase-locked to the one-pulse-per-second signal provided by the GPS to ensure data from multiple units over the complete network can be seamlessly integrated. It is worth noting that a PMU itself does not measure current or voltage. Traditionally, the PMUs are connected with CTs and PTs to obtain various data including voltage and current phasors, frequency, rate of change of frequency, under/over voltage, over current, and over/under power. Unfortunately, the performance and wide-scale use of PMUs are constrained by the inherent weaknesses in traditional instrument transformers. PMUs obtain current and volt-

Table 2
Comparison of existing voltage measurement techniques.

	Voltage measurement							
	DC				AC			
	Physical principle	Examples	Contact / Contactless	Single / Multiple phase conductors	Physical principle	Examples	Contact / Contactless	Single / Multiple phase conductors
Ohm's law	Measure current across a fixed pure resistance	Voltmeters, voltage dividers	Contact and invasive	Single	Measure current across a fixed impedance	Voltmeters, series capacitance voltmeters, series impedance voltmeters	Contact and invasive	Single
Faraday's law of induction	(not applicable)				Measure stepped-down voltage on secondary circuit due to magnetic induction	Potential transformers (PTs), capacitive voltage transformers	Contact but noninvasive	Single
Electric field sensing	Measure induced voltage due to electrostatic coupling (*only works with unshielded cables)	Induction bars	Contactless (both physical and galvanic isolations)	Multiple. Individual voltage sources can be determined by solving transformation matrix from an array of measurement.	Measure induced voltage due to capacitive coupling (*only works with unshielded cables)	Induction bars	Contactless (both physical and galvanic isolations)	Multiple. Individual current sources can be determined by solving transformation matrix from an array of measurement.
Pockels effect	Measure the change of polarization due to electro-optic effect	BGO crystal or BSO crystal with optical fiber	Contactless (galvanic isolation)	Single	Measure the change of polarization due to electro-optic effect	BGO crystal or BSO crystal with optical fiber	Contactless (galvanic isolation)	Single

age measurement signals from CTs and PTs respectively and thus they are vulnerable to the effects of saturation magnetization and nonlinear induction. Since CTs and PTs for high voltage systems require oil or sulfur hexafluoride (SF_6) gas for insulation and their deployments necessitate large footprint, these significantly raise the installation and maintenance costs which is unfavorable to scalability and pervasiveness. These issues become daunting as an increasing number of PMUs are being deployed.

3.4. Background of contactless sensing

The health condition of critical infrastructure needs to be closely and constantly monitored for the safety and quality of service. The development of contactless sensing for condition monitoring [29] enables the early detection of any events that may lead to increased likelihood of system failure, allowing pre-emptive remedial actions to be taken to avoid power outage. Contactless sensing sometimes provides the only means of obtaining the current health status of the power systems. Appropriate contactless sensing technologies need to be adopted to realize pervasive sensing.

The costs of installation and communication network can be higher than the cost of sensors themselves which greatly obstruct the development of pervasive sensing, resulting in the current situation that many relevant electrical parameters are not monitored and rendering many new smart grid applications impractical. This problem is particularly severe at the distribution level. There are two distinct types of sensing: contact and contactless. Contact sensing requires contact for measurement and its installation is difficult and often leads to system disruption. Thus, it is difficult to scale up contact sensing techniques for pervasive sensing. Conversely, contactless sensing do not require contact. Examples of contact systems include potentiometers and shunt resistors. Traditionally, contact sensing has had a price advantage. However, contact sensing has been recently challenged by contactless sensing because the cost of contactless sensor has been dropping drastically. Contactless means of sensing include optics, lasers, capacitive, inductive, ultrasonic and electromagnetic methods. Contactless sensing based on wireless electromagnetic and optical technologies has attracted a great deal of interest from both academia and industry recently. Contactless sensing is gaining popularity because of its unique benefits. The major benefits of a contactless sensing system are the ease of installation and reduced footprint. Besides, it generally offers long life and high reliability due to limited component wear and degradation as there is no contact with a work piece. The sensors can often be encapsulated or potted, protecting them from harsh environment. When selecting a system for condition monitoring, weighing cost versus benefit is needed to determine whether the sensing system will fit the application. Therefore there has been an increasing trend towards contactless sensing technologies. This will minimize cost, avoid wear and tear, and meet stringent reliability requirement. Furthermore, contactless sensing provides a possible route to retrofit to the existing grid at low cost, which is beneficial to the scalability of pervasive sensing. Contactless sensing will further promote the use of PMUs in power distribution systems and micro-grids. PMUs enabled by contactless sensing will support the monitoring of processes which are yet to be measured because traditional contacting sensing techniques such as CTs and PTs are currently limited in their deployment for reasons discussed earlier. For example, the electrical parameters of the transmission networks are currently only measured at the substations, and there may be just one substation over around 100 km of transmission lines in remote areas. The electrical parameters are assumed to be the same in-between the substations, which however may not be the case for abnormal circumstances. Contactless sensing, due to its easy installation, does not require regular maintenance and offers reduced footprint, is suitable for monitoring processes which are not currently measured to enhance situational awareness. Contactless sensing will complement the traditional sensing techniques to fulfill the coverage requirement of pervasive sensing. It will bring significant breakthrough in real-time monitoring, wide-area control, dynamic security assessment, system integrity protection, state estimation, forecasting and planning, greatly enhancing grid visibility and making the power grid sustainable and reliable.

4. Enabling pervasive sensing with contactless sensing and supporting technologies

Pervasive sensing is enabled by adding contactless sensing to the current suite of sensors prevalent in the power grid. In addition to contactless sensing, not only do we need network connectivity through an IoT system but also a few other supporting technologies to have a robust sensing system that is self-sustainable and minimizes noise. Connectivity among the sensors must be established by adopting the appropriate communication means to form the IoT to enable both edge and cloud computing to make smarter decisions for the power grids. Since the number of sensors to be deployed for pervasive sensing over the power grids to enable CEGs will be huge and of the order of millions, providing wired power supply to each sensor will be dauntingly expensive or not even possible in some remote areas. The sensors must be self-sufficient by harvesting energy. Since contactless sensing is not as strongly coupled to the signal source as contact sensing, it may be susceptible to background electromagnetic interference. When necessary, shielding can be designed to provide protection to the measurement and eliminate the background noise. These technologies are outlined in the sections that follow.

4.1. Contactless sensing

Low-cost, easy-to-mount contactless sensors including electromagnetic-field and optical sensors will enable contactless sensing of electric and magnetic fields to determine the states of the critical components of power systems. Continuous monitoring of voltage, current, electric field and magnetic field strength in generators, transformers, motors and other power equipment by contactless sensing can provide sensing data for diagnosis and prediction of incipient faults. The information of fault currents, harmonics, power quality and signatures of incipient failures can be extracted from the sensing data of the electrical parameters of power systems.

4.1.1. Current measurement based on magnetic field sensing

By using sensitive magnetic sensors such as tunneling magnetoresistive sensors or giant magnetoresistive sensors [30] to measure the magnetic field by Bio-Savart law, current can be measured non-invasively and contactlessly without clamping around the primary circuit (physical isolation) [31]. In addition, it offers the unprecedented opportunity to carry out current measurement simultaneously with multiple phase conductors, for example, multiple overhead transmission lines [32-34] and multi-phase multi-core underground cables [35, 36], rather than individually with each phase conductor. The current information of each phase conductor in these scenarios involving multiple conductors can be reconstructed from an array of magnetic field measurements through computational intelligent algorithms [37] or closed-form approach in some circumstances [38]. Since the metallic sheaths of underground power cables are not magnetic and do not shield against magnetic field, this current sensing technique based on magnetic field is applicable to both overhead transmission lines and underground distribution cables.

4.1.2. Voltage measurement based on electric field sensing

It is possible to measure voltages of overhead transmission lines contactlessly at a distance through electric field sensing by electrostatic coupling [39, 40] or capacitive coupling [41]. It enables the determination of the individual voltages from a group of overhead transmission lines by solving the transformation or coupling matrix relating the induced voltages to the original voltages of the transmission lines from an array of measurement of the induced voltages [42]. Contactless voltage sensing based on electric field sensing is not possible for armored or shielded cables because an electric field cannot penetrate through an earthed or grounded metal armor or shielding, which is typically the case for underground power cables. Alternative voltage measurement method was also proposed by using electric field sensors to directly measure the field generated by the voltage lines without any capacitive coupling but it requires the sensors to be placed in proximity of the voltage lines [43].

4.1.3. Introduction to optical sensors

Optical sensors are made of optical fibers and the detection is enabled by the phenomenon that external influences modulate the intensity, phase, wavelength of the light passing through optical fiber cables. There are two types of optical sensors: intrinsic and extrinsic sensors. For intrinsic sensors, the optical fiber itself conducts the measurement while for extrinsic sensors, a coating or a tiny transducer is placed at the fiber tip for the measurement. They can measure many power system parameters such as temperature, pressure, strain, and process chemistry. Based on the principle of electrostriction and Ampere's law, optical sensors can measure voltage signal with high fidelity without suffering saturation effect. Optical sensors can find applications in measuring current and voltage in power systems [44]. They can carry out measurement with high fidelity because they are not susceptible to magnetic saturation or ferro-resonances. They are compact and light, and can be integrated into electrical equipment, reducing footprints of substations. Research on optical current and voltage sensors could be found from 1970s [45-47]. After decades of efforts, optical sensors, particularly fiber-optic current sensors, have gained adequate maturity for actual application in power grids since 2000.

Compared to traditional transformers, optical sensors provide linearity over dynamic range, seismic performance, free of magnetic saturation, EMI immunity (nonelectric sensing), enhanced safety (contactless sensing), no spark hazard, low power consumption, compactness and easy installation and maintenance [48]. In addition, optical fibers offer high data capacity with high signal purity. The signal attenuation is minimal which is ideal for obtaining sensing data from remote areas. A single optical fiber can carry out measurement at multiple points along its path or measure multiple different parameters by multiplexing. Optical sensors can be an ideal candidate to provide signals for PMUs [49].

4.1.4. Optical current measurement

Fiber-optic current sensing is based on polarimetric sensors measuring the Faraday effect via the rotation of the polarization state of linearly polarized light in the magneto-optic transducer material [50-53]. Two orthogonal linearly polarized light waves are generated by the optoelectronics module and sent through a polarization preserving optical fiber to a coil of sensing fiber wound around the current-carrying conductor. The orthogonal polarization states are transformed by the fiber-optic quarter-wave retarder into left and right circularly polarized light waves. A Faraday rotation mirror is incorporated at the end of the coil to enhance the signal strength and suppress susceptibility to mechanical vibration. These two circularly polarized light waves accumulate a differential magneto-optic phase shift during their roundtrip through the coil due to the Faraday effect. The returning circularly polarized light waves are transformed back to orthogonal linear waves at the retarder, and the magneto-optic phase shift can then be detected to find out the current. Essentially, the closed-loop integral $\oint H \cdot ds$ of the magnetic field measured around the current-carrying conductor is equivalent to the current according to Ampere's law. Another optical current sensing method was demonstrated with fiber bragg gratings (FBG) attached to magnetostrictive materials despite its non-linearity and magnetic saturation effect [54, 55].

Table 3

Recent demonstrations and applications of contactless sensing in energy grids.

	Generation		Transmission/Distribution			Consumers	
(Both AC and DC systems)	Conventional	Renewable (energy harvesters, converters)	Transmission cables	Distribution cables	Substation (protection, control, metering)	Appliances (metering, power quality)	Circuit breaker panel
Electromagnetic-field current measurement	[69]	[70-72]	[27, 33, 34, 37, 73-78]	[35, 74, 79-85]	[83, 86-89]	[74, 90-93]	[91, 93, 94]
Electromagnetic-field voltage measurement			[27, 43, 74, 95-107]	[74, 82, 102, 108, 109]	[110, 111] (partial discharge of transformers), [43, 97, 99, 112]	[74, 90, 91, 109]	
Optical current measurement	[113-116]	[117]	[118-123]	[82, 119, 124, 125]	[113, 121, 122, 126-131]		
Optical voltage measurement	[113, 132]		[133-138]	[139-141]	[113, 126, 127, 129-131, 137, 140, 142]		

4.1.5. *Optical voltage measurement*

Optical voltage sensors are still catching up with the level of technological readiness as the fiber optic current sensors. Conventional glass fibers cannot be used to measure the path integral $\int E \cdot ds$ of the electric field E between the high voltage potentials of the cables and the ground. Typically bulk crystalline transducer materials such as Bi_3GeO_4 (BGO) or Bi_3SiO_4 (BSO) are used because they possess electro-optic effect (Pockels effect) [56-59]. Besides the adoption of piezo-electric transducers with optical interrogation [60-64] and electrically poled fibers [65] have received extensive investigation. The cubic axis of the BGO or BSO crystal is aligned with the optical path [50]. A potential difference applied along this direction introduces a differential electro-optic phase shift between the two orthogonally polarized light waves due to the Pockels effect. This phase shift corresponds to the path integral of the electric field over the crystal length. Therefore the optics signal can be used to reconstruct the voltage waveform. Based on this principle, several schemes can be applied to measure the high voltage. Power line voltage can be measured by a local electric field measurement near the energized conductor using the transducer BGO or BSO crystal [56]. A capacitive divider can be used so that an optical sensor only needs to measure a small fraction of the voltage [57, 58, 66]. Alternatively, a number of local field measurement can be used to approximate the path integral $V = \int E \cdot ds$ [60, 67]. Another scheme is to apply full line voltage to the transducer crystal where the sensor truly measures the voltage and the measurement is not susceptible to nearby field disturbance due to neighboring phases [68].

4.1.6. *Recent demonstrations and applications*

The realization and implementation of contactless sensing in energy grids are not far-fetched. Indeed, there are already conceptual designs, laboratory demonstrations, field tests or even commercial products for the contactless current and voltage sensing techniques. There are related works reported for each contactless sensing technique in some or all of the aspects of power grids (generation, transmission/distribution and consumers) as shown in Table 3 (This Table is not meant to be an exhaustive list. Many related works are being published). In the past decade, researchers and engineers have started to use these contactless sensing techniques to measure current and voltage in AC or DC power systems to monitor: the generators, energy harvesters or converters in generation; power cables, transformers, switchgears, busbars, etc., in transmission/distribution; appliances and circuit breaker panels in consumer side. The contactless sensing techniques discussed in this paper are practical, feasible, and scalable for power grids despite there are still many research gaps needed to be filled as will be discussed in Section 6. They can be deployed to carry out grid measurement and provide sensor data for the purposes of operation-state monitoring, metering, protection, automation and control, and energy management in generation, transmission/distribution and consumers, which is further illustrated and envisioned in Section 5. The deployment can be flexible where both current and voltage parameters are measured with contactless techniques, or either parameter is measured with contactless techniques while the other is measured with traditional contact sensing to solve the challenges mentioned in Section 2. In order to apply contactless sensing in pervasive sensing, some supporting technologies are needed to form Internet-of-Things (IoT) contactless sensing systems which can collect data from physical world for monitoring and transmit data to cyber space for analytics.

4.2. *Supporting technologies needed*

To apply contactless sensing in actual site environment and develop an IoT contactless sensing system, some supporting technologies are needed to provide connectivity, make the sensors self-sustainable and reduce noise. Connectivity among the sensors must be established by adopting the appropriate communication means to form the IoT to enable both edge and cloud computing to make smarter decisions for the power grids. Since the number of sensors to be deployed for pervasive sensing is large, providing wired power supply to each sensor will be dauntingly expensive or not even possible in some remote areas. The sensors must be self-sufficient by harvesting energy. When necessary, shielding needs to be designed to provide protection to the measurement and eliminate the background noise.

4.2.1. *IoT connectivity*

Contactless sensing needs connectivity to transfer sensing data and form IoT sensors. Various wireless communication technologies are available for IoT providing connectivity to the Internet for sensing devices. Data transmission requirements for sensor networks are very dynamic. They can change from small, intermittent payloads during normal situation to large amounts of continuous data during abnormal circumstances. A selection guideline is helpful for choosing the right connectivity technology to ensure seamless transmission.

Bluetooth is a short-range transmission technology well-positioned in portable electronic devices such as smartphones. The new Bluetooth Low-Energy (BLE or Bluetooth Smart) is optimized for low-power IoT applications. It does not require separate routers or networks. Bluetooth devices are generally cheaper than those for either WiFi or Zigbee. However, Bluetooth is designed for close-distance communication. An IoT hub can help to extend the Bluetooth range and connect to the Internet.

ZigBee is a short-range low-rate wireless data transmission. There is no single point failure because the ZigBee devices are linked and their communication paths between devices multiply. A ZigBee network is self-extending. It can cover more range by adding more nodes. It is a low-cost, low-power solution for sensor networks. Moreover, ZigBee is interoperable with standardized network and application layers. Sensors from different vendors can work together collaboratively. ZigBee devices do not need a router as WiFi does but they do require an IoT hub.

WiFi offers fast data transmission for processing large amounts of data, and it is the most common type of connectivity in LAN environments. A WiFi device can be monitored and controlled from afar because it is connected to the Internet via a router. However, it suffers the drawback of high power consumption. Considering the fact that the sensors may not be wired to a stable power source and sometimes they may need to run on button cells for years at a stretch or rely on energy harvesting, WiFi may only be suitable for sensors installed in substations or premises with power outlets.

Cellular technology rides on the mobile phone networks such as GSM, 3 G, 4 G, LTE and transfer large quantities of data over longer distances. This technology can be a good fit for sensor devices when it is near populated areas (i.e. cell towers) and provide a low-cost, low-bandwidth, and low-power connectivity. Perhaps the situation may change with the new cellular technologies such as NB-IoT (5 G) and LTE-M (4 G) which particularly cater for low-power connectivity and longer battery life. However, it may not be an appropriate choice when the sensors are located in remote areas and require a lot of data to be sent.

LoRa and LoRaWAN are becoming a popular solution for IoT connectivity. LoRa is a radio modulation technique at license-free and cost-free ISM (Industrial, Scientific, Medical) bands for establishing wireless LAN networks. LoRaWan is a Low Power Wide Area Network protocol based on LoRa to support long range, low-cost, mobile, energy-efficient, indoor penetration and end-to-end bi-directional communication for IoT applications. It focuses on long range applications such as in smart cities, smart buildings etc. It can connect devices up to 30 miles apart and their geolocations can be calculated based on time of flight analysis without the use of GPS. Its data rate is relatively slow. It may also be suitable for some indoor smart home applications which do not require high speed connection. LoRa IoT products must be tailor-made for each specific country/region because LoRaWAN uses different frequencies in different countries/regions such as North America, Europe and India.

Satellite communication technology has been prohibitively expensive in the past. The situation has now changed. The emergence of nanosatellite (1 kg to 10 kg) operating at low earth orbit (1200 miles) has opened up the possibility of using satellite communication for remote IoT applications at reasonable cost. The construction and launching of a nanosatellite is around $0.5 m, which is 100 times cheaper than a conventional satellite. Since these constellation of nanosatellites are in a much closer low Earth orbit as compared to the geostationary satellites (22,000 miles), the signal does not have to travel as far and thus power needed for connectivity is significantly lower. The nanosatellites hand off the signal to another satellite or a local ground-based gateway once it passes beyond direct view. Low-earth-orbit satellite communication provides an effective and feasible means for transferring sensor data in remote areas which would otherwise be impossible.

A summary of existing communication technologies is provided in Table A1. Their frequencies, transmission range, data rates and features are compared. The selection of the communication technology for a particular sensor depends on the technological features, the situation of actual site environment and the availability of the communication infrastructure and power supply. In general, Bluetooth, Zigbee and WiFi can be considered for providing connectivity to sensors for short-range indoor environments. Bluetooth and Zigbee are suitable for low data rate while WiFi can provide high data rate at the expense of high power consumption. For long-ranged outdoor environments, cellular, NB-IoT and LoRa can be used to provide connectivity in regions where cellular infrastructure is available. For remote areas, sensor connectivity is still feasible with low-earth-orbit satellite communication which is becoming more economically viable recently.

4.2.2. Energy harvesting

Energy is needed to provide the power that run the IoT contactless sensing systems. Since IoT sensors may be in remote locations and often use wireless communications, there is a need to provide power directly or to extend the life of batteries for remote and wireless sensing applications. IoT contactless sensing applications in power grids will require highly durable batteries or self-powered because of the difficulty to access power source or labor and it is a daunting task to frequently replace batteries for millions/trillions of sensors. Energy harvesting (EH) is the capture of small amounts of readily available energy in the environment and convert it into usable electrical energy. Energy harvesting systems require a source of energy such as heat, light, or vibration, to convert to usable electricity. There are several technologies such as piezoelectric or electromechanics to harness kinetic energy through vibrations [143-145], harvesting radio frequency (RF) energy [146, 147], thermoelectric energy [148], micro-wind turbine, and solar energy through small photovoltaics cells [149]. The electrical energy is conditioned for either direct use or accumulated and stored for later use. For the applications of small contactless sensors, 1 cm^3 is the standard volume for the power supply modules [144]. This volume restriction sets the limit of energy harvesting. The power consumption of the sensing, processing and communication modules need to operate within this limit. Autonomous EH powered sensors are critical for large-scale and unattended deployment of contactless sensing [149], and a reliable energy harvesting source is critical to the self-sustainable implementations of IoT contactless sensing systems for pervasive sensing of power grids.

Electrostatic kinetic energy harvesters make use of the change of capacitance due to vibration to harvest, in general, μW power [150]. Thermoelectric energy harvesters can provide a power of μW approximately [149, 151]. Thermoelectric generators are usually of large volume form factors to produce useful amounts of power. For a small-sized generator of 1.8 cm^3, power level is limited to 150 μW [150]. In order to generate sufficient power, a photovoltaic cell requires a large area as its conversion efficiency is typically less than 40%. Besides, its output is highly dependent on orientation and timing. Ambient RF power harvesting possesses the advantage that it is available anytime and everywhere, particularly in urban areas [146]. However, it has a relatively low energy density of 0.2 μW/cm^2 – 1 μW/cm^2 compared to other energy sources such as kinetic energy harvesting [152, 153]. A high gain antenna is required to harvest more power, which is a challenging task.

Out of these energy harvesting solutions and based on the standard volume of 1 cm^3, kinetic energy harvesters which capture mechanical energy usually in the form of vibration or random displacements [154] via piezoelectric or electromagnetic transducers possess the advantages of cleanliness, stability and compactness. Piezoelectric and electromagnetic technologies can be applied to harvest kinetic energy. Piezoelectric generators act as transducers transforming mechanical strain on the piezoelectric material to electric charges. There are human-powered and vibration-based piezoelectric generators, the latter is more relevant to the applications in power grids. Piezoelectric generators can harvest energy from the vibration of buildings or other supporting structures (e.g. transmission towers). Piezoelectric generators are relatively compact and light because a small crystalline structure is adequate for generating power. For vibration-based piezoelectric generators, they can generally generate μW [154-159] to mW [160, 161] power. Of particular relevance is the work done by Leland's group at the University of California at Berkeley [156]. The group harvested the piezoelectric energy from the vibration generated by the alternating magnetic field emanated from the power cord. The system could produce up to 345 μW. Electromagnetic generators employ Faraday's law of induction to induce charges in the conductor when there is relative motion between a conductor and a magnetic flux. Electromagnetic generators can harvest energy from vibration due to alternating magnetic field. There are three types of electromagnetic energy harvesting, namely, resonant, rotational and hybrid devices. Their generation capacity is in general in the order of μW [162-169] to mW [166, 167, 170-172].

In order to adopt an EH source, power conversion, energy management and energy storage techniques are required because of the significant power profile mismatch between the low-power, low-voltage nature of small form factor EH sources and the sensing, processing and communication modules. Step-up converters, maximum power point tracking, storage facilities, cold-start circuitry are necessary for connecting the EH source with the sensor. Since the outputs from energy harvesters are usually within the range of mW to μW, there are limitations on the range of functionalities and data transfer rates of the sensors [149]. Essentially, the sensors need to operate in a pulsed manner rather than continuously, which allows the energy harvesters to provide sufficient energy to the storage for the subsequent sense and transmission operation. For example, the TI eZ430-RF2500 temperature sensor consumes instantaneously up to 80 mW for one sense and transmission operation [173].

The issue of fluctuated energy resources can be handled in three ways. First, as discussed above, the energy harvesting unit is composed of harvesting source, power converter, energy management and energy storage. The excess energy harvested will be saved in the energy storage device for later use when there is not enough energy. This will mitigate the effect of fluctuation of energy resources. Second, as mentioned earlier, to minimize energy consumption, the system can operate in pulsed mode rather than continuous mode. For example, in every second, the system is in standby mode for 900 ms and only operate for 100 ms to sense and transmit data. Third, the interval of transmitting data can be adjusted according to the energy reserve to reduce energy consumption. When the energy reserve is running low, the system can transmit sensor data to the cyber space less frequently to preserve the energy. For example, the system can transmit once a minute instead of once a second.

Frequent charging/discharging may lead to degraded battery life and this problem can be solved by adopting the right type of energy storage devices. For systems involving energy harvesting and frequent charging/discharging, supercapacitors may be a better energy storage device than batteries because supercapacitors function by physical electrostatic process rather than chemical process and thus can tolerate exponentially more charging/discharging cycles. Although batteries offer larger energy densities, supercapacitors should be sufficient in this scenario because the energy harvested is expected to be modest, unlike solar panels or wind turbines.

The energy harvesting techniques are generally passive and do not create interference. Since the energy harvested is rather small approximately in the order of μW, it is unlikely to affect the sensing process. Moreover, the energy harvester can be placed at a distance from the sensors to further eliminate the unlikely interference. For example, RF energy harvester can be placed outside the shielding to harvest RF energy without disrupting the sensing process.

4.2.3. Shielding

Electric field can be shielded by the Faraday cage effect where free charge on an enclosure relocates itself to exactly cancel the fields within or external to the enclosure. The enclosures do not need to be perfect conductors as long as the charges can redistribute themselves fast enough to cancel the field. Metallic enclosures without substantial seams or apertures usually can provide sufficient electric field shielding over a wide range of frequencies. A partial shield or even a simple metal plate can alter the path of the electric field lines and prevent them from reaching the victim circuit, reducing the interfering potential differences. A guideline to designing practical electric field shielding is to determine a location that can intercept the stronger field lines and choose a suitably conductive material [174-176]. One should first visualize the field lines that may cause the undesired coupling, and then, position the shield in such a way that it blocks these fields from reaching the victim circuit. The conductivity of the shield material needs to be high enough for high-frequency electric fields to make sure the charges move fast enough to reorient themselves as the field varies to cancel the field.

Since there are no magnetic free charges, magnetic flux lines cannot be terminated by a shield, unlike electric fields. Magnetic-field shields function by redirecting magnetic flux lines to prevent undesired coupling [177-179]. This can be achieved by electric currents (eddy currents) induced in a conductive shield (for high-frequency magnetic fields) or by diverting the path of magnetic flux lines using highly permeable (μ_r>>1) materials (for low-frequency magnetic fields). Power systems typically run at 50 or 60 Hz which are rather low frequencies. Therefore, the magnetic shields have to function by the latter principle. The interfering time-varying magnetic field reaching the shield causes currents to flow (eddy currents) in the shield according to Faraday's law, which in turn generate their own magnetic flux that opposes the incident flux. However, a static magnetic field does not create eddy currents. Even if the field is slowly varying, the resistive losses in the shield would dissipate the eddy currents. Therefore, at kHz frequencies or lower, highly permeable materials are used to divert the magnetic fields [180, 181]. Magnetic flux lines tend to follow these materials because their reluctances are much lower than that of air. These materials provide a permeable path for rerouting the magnetic flux lines and protect the victim circuit. The magnetic shield saturates when the flux density is too strong. In this case, a two-stage or three-stage design can be used with the outer layer to dilute the burst of dense magnetic interference. The second and the third layers can then absorb the residual magnetic flux. Multi-layered shielding can protect from sudden and dense magnetic fields.

4.2.4. Cost and practicality

The cost of contactless sensing is lower than contact sensing in terms of installation costs, safety, maintenance and space. In general, contactless sensing cause less disruption to the power systems during its installation and they can be retrofitted to the existing systems. They do not explode during catastrophic failure because the measuring part is isolated from the primary circuit and also they do not have an open secondary circuit. There is not much maintenance needed to do for contactless sensing as compared to contact sensing because contactless sensing usually does not need sophisticated insulation. On the contrary, traditional contact sensing techniques such as CTs and PTs require insulating oil or gas which needs regular maintenance. Because of its small size and flexible form factor, contactless sensing results in substantial savings in space and reduce substation size and real estate costs. The costs of the sensors themselves are also rather low. For example, magnetic sensors such as magnetoresistive sensors can be cheaper than US$10 each and the price is still dropping. The optical voltage and current sensors may be more expensive than magnetoresistive sensors because they require light sources, fiber-optics, modulators and photodetectors but all these costs are dropping rapidly because of the remarkable progress made by the optical communication industry. The costs associated with shielding are reasonable as well. The shielding raw materials are economical. Conductive metallic plates such as copper plates (conductivity ~6×10^7 S/m) can be used for shielding against electric field. A 0.4 mm x 610 mm x 610 mm copper sheet costs less than US$60. Mu-metal (NiFeCuMo alloy) is a very soft magnetic material (relative permeability over 80,000) commonly used for magnetic shielding. A 0.1 mm x 610 mm x 1000 mm mu-metal sheet costs less than US$100. Shielding materials of these sizes are sufficient for building multiple electric and magnetic shieldings (the exact number depends on sensor sizes). Both capital cost and ongoing maintenance cost of contactless sensing are lower than conventional contact sensing. In addition, unlike the traditional contact sensing, the sizes, weights and costs of contactless sensing in general do not scale up with the voltage level.

The feasibility and accuracy of the contactless sensing techniques were already experimentally verified and studied. The accuracy of con-

Table 4

Comparison of traditional contact sensing and contactless sensing in practical aspects. Note that these are just rough estimates. The exact figures depend on the actual applications and circumstances.

	Traditional contact sensing (CTs, PTs)	Contactless sensing
Sampling frequency	A few kHz	From DC to over 1 MHz
Size and weight	145 kV: size > 10 ft^{3,} weight > 300 kg 550 kV: size > 30 ft^{3,} weight > 7000 kg Size and weight scale up with voltage level. [188]	Sensor, associated electronics and shielding: size < 3 ft^3, weight < 30 kg Generally, size and weight do not scale up with voltage level. [189]
Cost	Oil insulated 35 kV: >10^3 (US$) Oil insulated 500 kV: >10^4 (US$) Gas insulated 35 kV: >$10^4$ (US$) Gas insulated 500 kV: >10^4 (US$) Prices scale up with voltage level.	Sensors, associated electronics, and shielding: <10^3 (US$) Generally, prices do not scale up with voltage level.
Accuracy	Various accuracy classes depending on the burdens and application purposes according to IEC 61,869 Standard and IEEE C57.13 Standard (e.g. 1% error at 100% of rated current for accuracy class 1.0 of IEC 61,869–2, 3% error at 80–120% of rated voltage for accuracy class 3.0 of IEC 61,869–3) [190-193]	Based on optical sensing: < 0.2% [118, 184] Based on magnetic and electric field sensing: < 5.5% [182, 183, 185, 186]
Reliability	Regular maintenance required. Ferro-resonance can cause transient overvoltage. Partial discharge can cause insulation breakdown.	No particular maintenance or recalibration for sensors or shielding is necessary during a lifetime in the field. Magnetic and electric sensors are robust to dust and humidity. Optical sensing has high immunity to electromagnetic interference.

tactless current measurement based on optical sensing and magnetic field sensing were demonstrated to be better than 0.1% [118] and 5.5% [182, 183] respectively. The accuracy of contactless voltage measurement based on optical sensing and electric field sensing were demonstrated to be better than 0.2% [184] and 3% [185, 186] respectively. These experiments were carried out on-site in substations, under overhead transmission lines, or using various appliances.

In general, contactless sensing has larger frequency bandwidth than traditional contact sensing. The exact sampling frequency depends on the data acquisition devices used, and its upper limit is determined by the bandwidth of the sensors. For example, magnetoresistive sensors that can be used for current measurement based on magnetic field sensing have a bandwidth from DC to over 1 MHz. Optical fiber sensors for measuring voltage and current based on Faraday effect and Pockels effect have a bandwidth from DC to over 10 MHz. Therefore, the sampling frequency of contactless frequency can reach over MHz, which is much higher than those of the traditional sensing techniques. A sampling frequency of over 1 MHz was demonstrated in [187].

Contactless measurements based on magnetic field sensors or electric field sensors are robust to dust and moisture in harsh environment. Contactless measurements based on optical sensing are immune to electromagnetic interference. No particular maintenance or recalibration is necessary during a lifetime in the field. Self-diagnostic functions can continuously monitor the operation of the sensors.

A comparison on the practical aspects between traditional contact sensing and contactless sensing is shown in Table. 4. Contactless sensing possesses the unique advantage that it can function from DC to over Mega Hz whereas the traditional contact sensing techniques can only work at low frequency AC. This is becoming particularly important as HVDC is gaining popularity. The size, weight and cost of traditional contact sensing scale up with voltage level. The difference in the cost of traditional contact sensing can vary by an order of magnitude from, for example, 35 kV to 500 kV. On the contrary, the size, weight and cost of contactless sensing in general do not scale up with voltage level because of its signal transducing mechanism and non-contact measurement. The accuracy of contactless sensing is catching up and some standards such IEEE or IEC standards will probably need to be established to facilitate its pervasive applications. The reliability of contactless sensing will strengthen the assurance of continuity and quality of the energy systems.

5. Impacts of pervasive sensing on future energy systems

5.1. *Pervasive sensing in CEGs*

Based on the sensing capabilities (as discussed in Section 4.1 and evidenced in Table 3), features of communication technologies (as discussed in Section 4.2 and compared in Table 4), on-site communication requirements and availability of infrastructure and power supply, pervasive sensing enabled by scalable contactless sensing techniques will deploy IoT contactless sensing systems throughout an energy grid to form the cyber layer as envisioned in Fig. 1. From the current and voltage measurements by IoT contactless sensing systems which complement the traditional contact sensing techniques, many electrical parameters about the power systems can be derived such as operating condition, power, load, energy consumption/generation, power quality, state estimation, fault analysis, anomalies, etc. They can be of great use to develop CEGs to overcome the challenges (C1-C7) mentioned in Section 2. Due to easy installation of contactless sensors, pervasive sensing can be implemented throughout the grid from generation, transmission, distribution to consumer side as illustrated in Fig. 2. Fig. 2 shows an overview of a main grid connected with microgrids. The operating states of the generation plants (conventional and renewable), transmission and distribution networks are monitored in real time (C3, C5). In urban areas, cellular communication networks composed of multiple base stations can be utilized to transmit sensor data. In some remote areas, satellite or LoRa may be used to transmit sensor data. The sensor data from operation-state monitoring, automation control and protection are sent to the SCADA system to facilitate remote monitoring, automate the entire network, maintain stability of desired voltages, currents and power factors, generate alarms, and determine network topology (C3, C5). The energy generation and consumption data from metering in industrial, commercial and residential regions (prototype demonstrated in [91]) are sent to the utility for billing purposes. The operation-state and automation control data from the sensors at the distribution station and PCC (C2) are sent to the distribution management for coordinating the

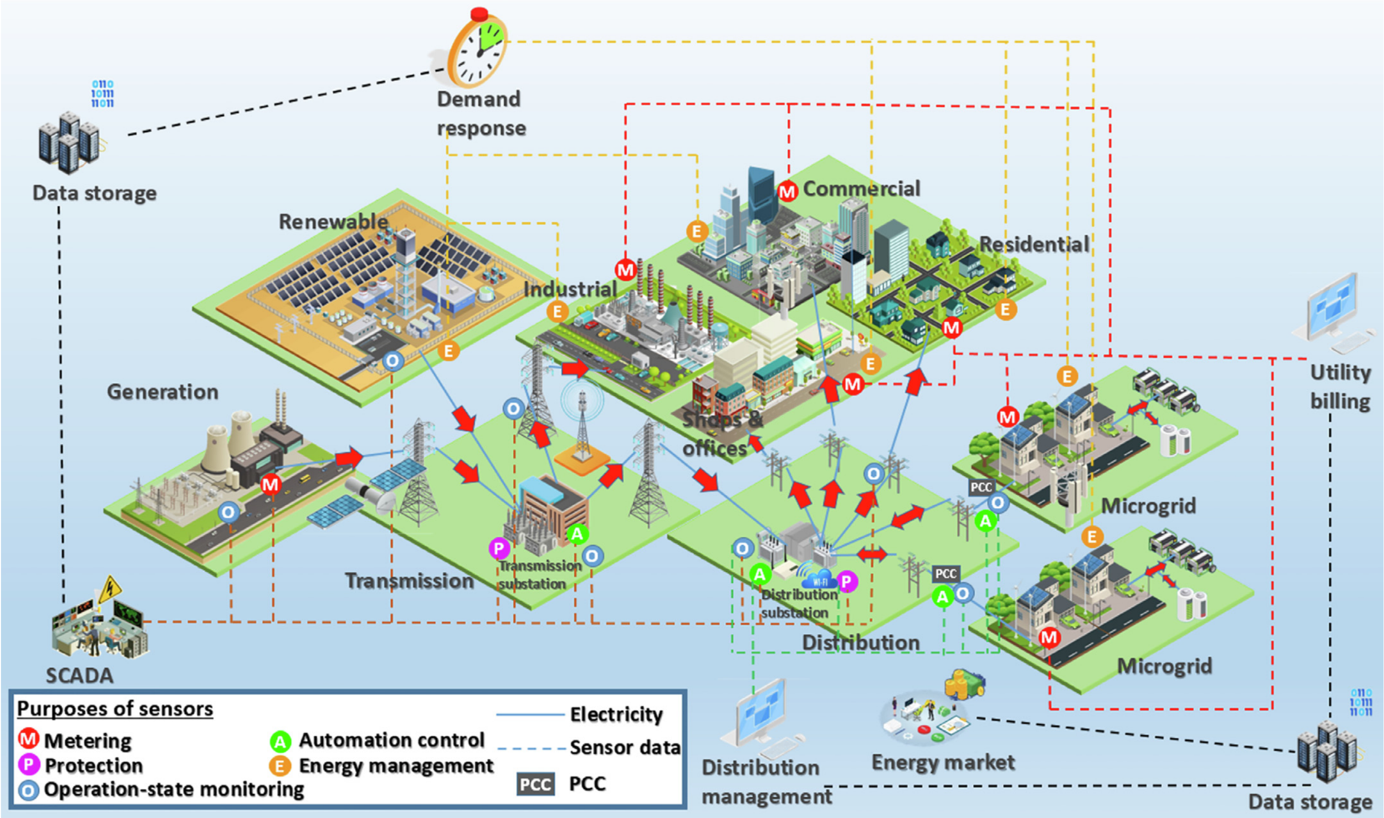

Fig. 2. Pervasive sensing in a power grid. Contactless sensing can complement traditional contact sensing to fulfill the requirement of pervasive sensing and form the cyber layer to enhance grid visibility. The IoT contactless sensing systems will be deployed over the whole grid to monitor various processes (physical world). The sensor data will be transmitted by various communication means to SCADA, WAMS, distribution management and energy market (cyber world) for analytics and subsequent grid control and protection and microgrid operation (physical world). The power grid equipped with pervasive sensing is a large cyber-physical system and it is a CEG.

interconnection (C5) and bi-directional power flow between the main grid and microgrids (C1, C3). The overvoltage or undervoltage at PCCs can be monitored (prototype demonstrated in [109]) and rectified when necessary (C2). The energy-management meter data from the consumer side are used to predict their energy demand profile (C3). Data from the renewable energy sources are also needed to track the highly variable production of renewable energy (C1). These data are sent to demand response for balancing supply and demand (C3). Data storage is needed to collect and store sensor data from the dispatched sources and deliver data to analytics tools. SCADA, WAMS, distribution management and energy market will have access to this secure data storage. The energy market is a platform for direct energy trading between peers as well as between microgrids and the main grid (C6). The meter data and sensor data such as power quality (C4) are input into a matching algorithm which makes use of game theory to match the market participants optimally (C6). Fig. 3 shows the deployment of sensors on transmission lines (commercial products available from [194]), distribution lines (prototype demonstrated in [195]), underground cables (prototype demonstrated in [183]), transformers (commercial products available from [196]), circuit breakers (prototype demonstrated in [197]), meters (commercial products available from [198]), protective relays (IEEE Standards established [199]), etc., in a substation. The communication technologies are chosen based on the comparison in Table A1. The sensors inside the substation can connect through ZigBee with the IoT hubs which have connectivity to the outside through the substation. Substations can transmit these collected sensor data by cellular network, satellite communication or Ethernet connection depending on the availability of these communication infrastructures on site. The sensors monitoring the overhead distribution lines are typically in urban areas with telecommunication infrastructure and so they can usually transmit data by cellular technology. The sensors and transceivers for underground distribution cables can be installed through manholes, and the sensor data can be transmitted by LoRa. The optical sensors on underground distribution lines can transmit data themselves because they are made of optical fiber and are ideal for data transmission as described in Section 4. For sensors monitoring transmission networks in remote areas without LoRa, they may transmit data by satellite communication. The optical sensors on transmission lines can transmit data along their optical fibers. Fig. 4 shows a smart home with distributed renewable energy sources and a EV charging station forming a microgrid by itself. There are IoT hubs for collecting data from sensors in each room. Outdoor sensors are connected by LoRa. Sensors measuring data related to metering and energy management are connected by ZigBee or LoRa. Sensors that are within close range from each other are connected by Bluetooth. The operating states of home appliances and utilities are monitored (C1) (prototype demonstrated in [200] which can operate on standard power cables with two current-carrying wires). Sensors are deployed at the renewable energy sources and electric-vehicle charging station for monitoring their operation and protection (C1, C3). The energy consumption, generation, storage as well as power quality information (C4) are collected by the energy management system of the smart home for automation and control. The battery lifetime situation is constantly under monitoring (C7) (prototype demonstrated for rechargeable Li-ion batteries [201] and lead-acid batteries [202]). All these data from the smart home can be transmitted to the microgrid distributed controller by cellular network or Ethernet connection, which can then make a decision as to select grid-connected mode or islanded mode (C3, C5). These data from all the microgrids (prototype for microgrids demonstrated in [203]) are

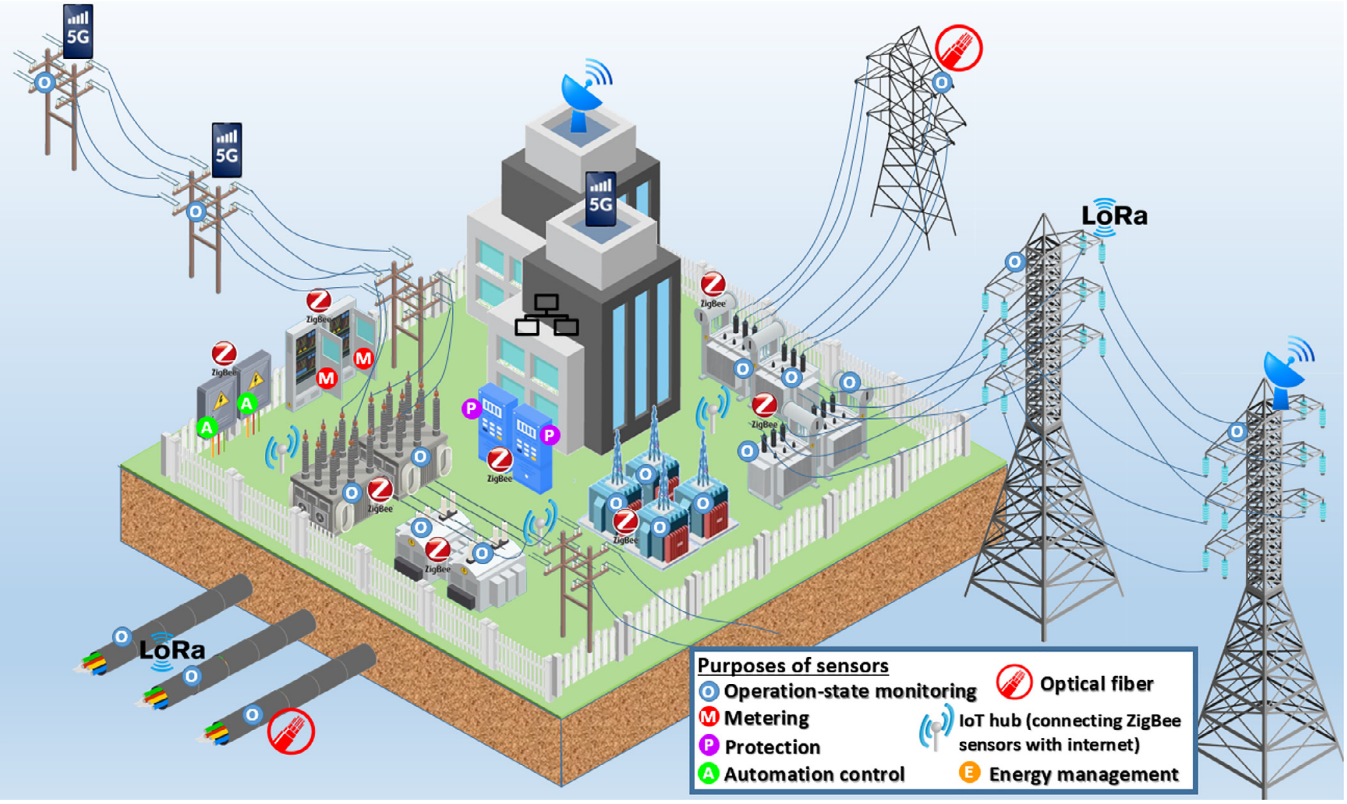

Fig. 3. Pervasive sensing in a substation. IoT contactless sensing systems can monitor processes that are not currently measured by traditional CT and PT instruments in transmission and distribution systems to enhance grid visibility.

shared with the energy market for price determination and trading (C6). Due to its non-invasiveness, the installation of IoT contactless sensing systems is much easier and less disruptive to power grids and thus contactless sensing is promising in terms of scalability. The deployment of IoT contactless sensing systems over power grids as depicted in Figs. 2, 3 and 4 will facilitate the development of CEGs as the cyber layer to overcome the challenges mentioned in Section 2. In addition, CEGs can form the foundation for the futuristic AEGs as elaborated in the next section.

5.2. *Pervasive sensing in AEGs*

5.2.1. *AEGs and a glimpse into the future grid*

One of the main challenges with the future grid will be the pervasiveness of DERs, variable renewable resource, and controllable loads. New sensing and control technologies must be developed to enable the power grids to meet the challenge of the ever-increasing numbers of variable generation (wind and solar), DERs (solar, fuel cells, microturbines, gensets), distributed energy storage (batteries, ice storage), electric vehicles, light emitting diode lighting and intelligent appliances. These technologies are causing bi-directional power flows and voltage fluctuations that impact optimal control and reliable operation. The National Renewable Energy Laboratory of the United States has been researching AEGs [204] because the future energy grid will be too distributed and complex to control with existing technologies. It is envisioned that a self-operating power system composed of network of intelligent devices and distributed controls that can work together to efficiently match bi-directional energy flows will exist, in contrast to the current system where centralized control is used and one-way electricity flow is operated from central generators to consumers. The proposed AEGs will need to be scalable, reconfigurable and based on self-organizing cellular building blocks in which each cell can self-optimize when isolated from a larger grid as well as contribute in the optimal operation of a larger grid when interconnected.

5.2.2. *Structure and principle of AEGs*

AEGs operate using a cellular structure similar to microgrids except AEG cells are more intelligent and do not necessarily need to provide for islanded operations. Each cell can continually optimize its operating conditions while adjusting to constantly changing customer demand, energy availability and pricing using distributed control within each cell. These scalable cells communicate and coordinate with each other at the local and regional levels to form a hierarchical system that will cover the entire grid (Fig. 5), thereby creating a distributed, hierarchical control with minimal communication needs between levels of the hierarchy. They can self-organize as well as optimize themselves at the grid edge. In the case of grid disturbances, they can isolate problems and recover by reconfiguring the grid to achieve resilience. They can also self-schedule to maximize usage of distributed renewable energy sources such as wind and solar energy while maintaining reliability during both normal and emergency situations. The AEG may initially automate with human in the loop, although it aims to operate without human intervention eventually. Control will be conducted in a distributed manner and at the local level, which will enable faster response to abnormal events. When islanded, the cells will self-optimize. For example, an AEG will decide the best time to charge an electric vehicle at home by looking at how charging impacts home energy use and power quality and how much stored energy and renewable energy is available. When interconnected, the cells will help the grid to enhance reliability and efficiency and achieve optimal operation. For example, an AEG will provide home-based distributed energy to the main grid to enable services such as peak shaving and frequency regulation.

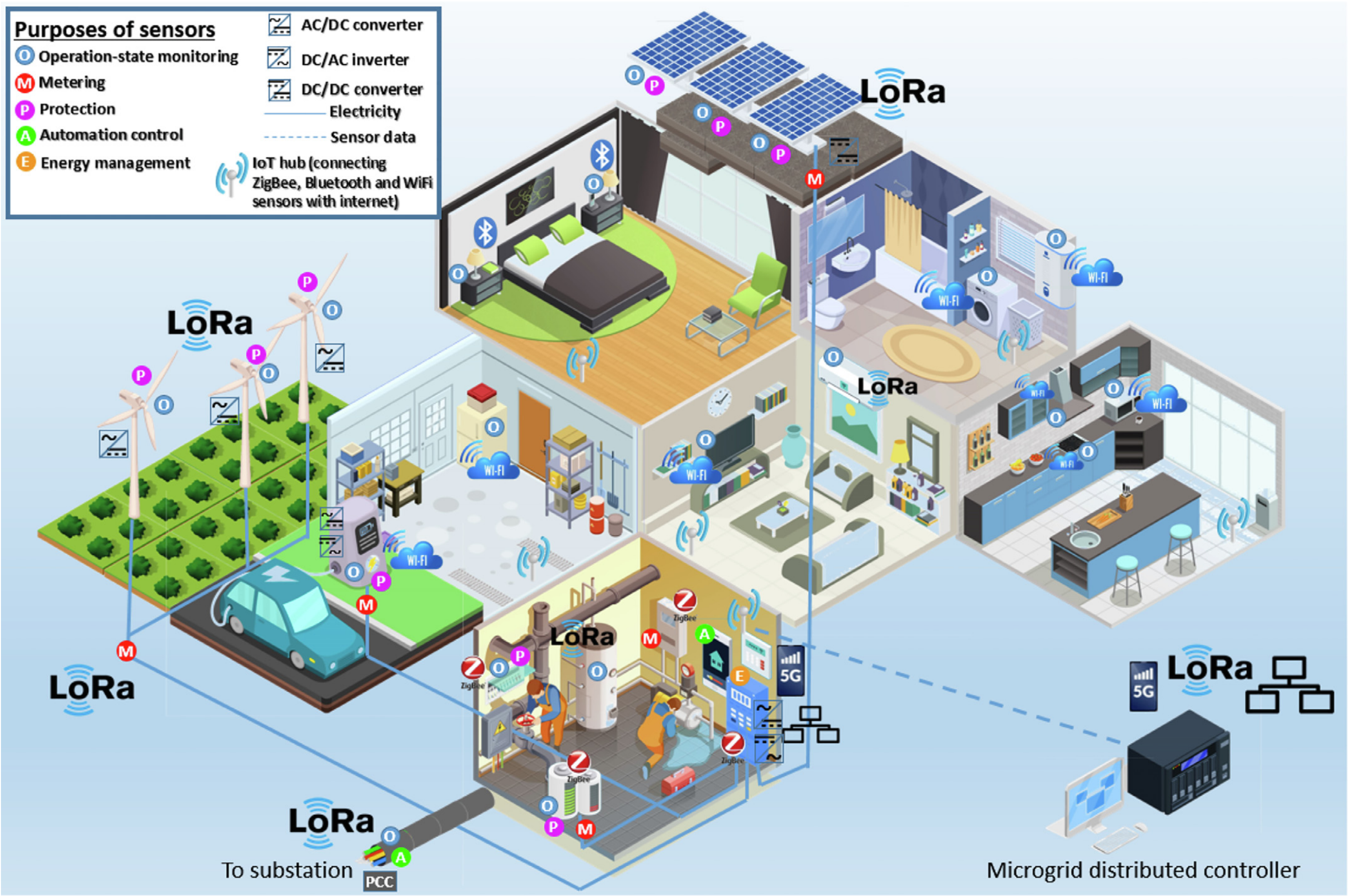

Fig. 4. Pervasive sensing in a smart home. A smart home with renewable resources is a microgrid and IoT contactless sensing systems can be deployed to provide useful data for microgrid management and important operation-state information including power quality data to other microgrids and the main grid.

5.2.3. Development roadmap by phases

Pervasive sensing with IoT contactless sensing systems as the cyber layer will transform power grids into CEGs which will facilitate the development of AEGs in four phases. It will begin at the local level and then expand to the higher grids. The first two phases will probably be partially achieved in CEGs while the last two phases will extend beyond CEGs and will take more time and research effort.

5.2.3.1. 1st phase – IoT contactless sensing systems enabling pervasive sensing (device level). At present, sensor data is not always available where it is needed. The AEG control and optimization algorithms will highly depend on the grid topology and ability to communicate with devices. Sensors are needed for grid monitoring to provide an accurate model of the cellular building blocks and their interaction with the rest of the systems and state information of the main grid in real time at various timeframes: slow timescale (e.g., every 5–15 min), faster timescale (e.g., every second or tens of seconds), fast timescale (e.g., every 50–100 msec). AEG cells must have sensors for measuring their own frequency and voltage signals because they must operate autonomously when they are in isolated mode without access to the frequency and voltage signals from the larger grid. This sensor infrastructure can be provided by CEGs with pervasive sensing as illustrated in the previous section. Frequency measurement is critical for AEGs because low-inertia power systems composed of DERs based on renewable sources interfaced by power electronics are more susceptible to frequency deviations and suffer more severe disturbances than traditional synchronous-generator-based systems. Besides, at the moment, the power demands of distribution grids are often unmonitored and highly uncertain with significant errors. Therefore, sensors for monitoring system frequency and sensors deployed at distribution buses are required for the implementation of AEGs. Cost of installation is a significant part of the equation in deploying sensors for pervasive sensing. Contactless sensing will significantly reduce the installation costs of sensors and complement to the existing traditional contact sensing facilities. IoT contactless sensing systems will greatly facilitate the implementation of pervasive sensing in CEGs by scaling up its deployment over the grid. Since numerous sensors and associated hardware will be utilized in large scale to implement pervasive sensing, a number of years will still be needed to complete the infrastructure. This phase may be materialized in approximately 2025 – 2030.

5.2.3.2. 2nd phase – pervasive sensing enabling control and optimization (cell level). Numerous DERs are connected to the power grid and the number is still increasing. Due to the large number of devices, central control will not be possible but instead the optimization of control must be distributed which requires sensors at the local levels. Moreover, an AEG will need to sense and handle additional devices added to it while the grid is operating. More sensors will be needed to provide real time measurements for isolating faults and protecting systems as greater numbers of DERs are being integrated. With pervasive sensing in place providing measurement data of each device, new types of protection scheme and control of power flow can be developed to enable bi-directional flow of power in AEGs. The parameters of the optimization problem vary continuously over time because power flow is continuous, and it is critical to continually pursue the best operating conditions in real time. Further, real-time optimization must be developed for individ-

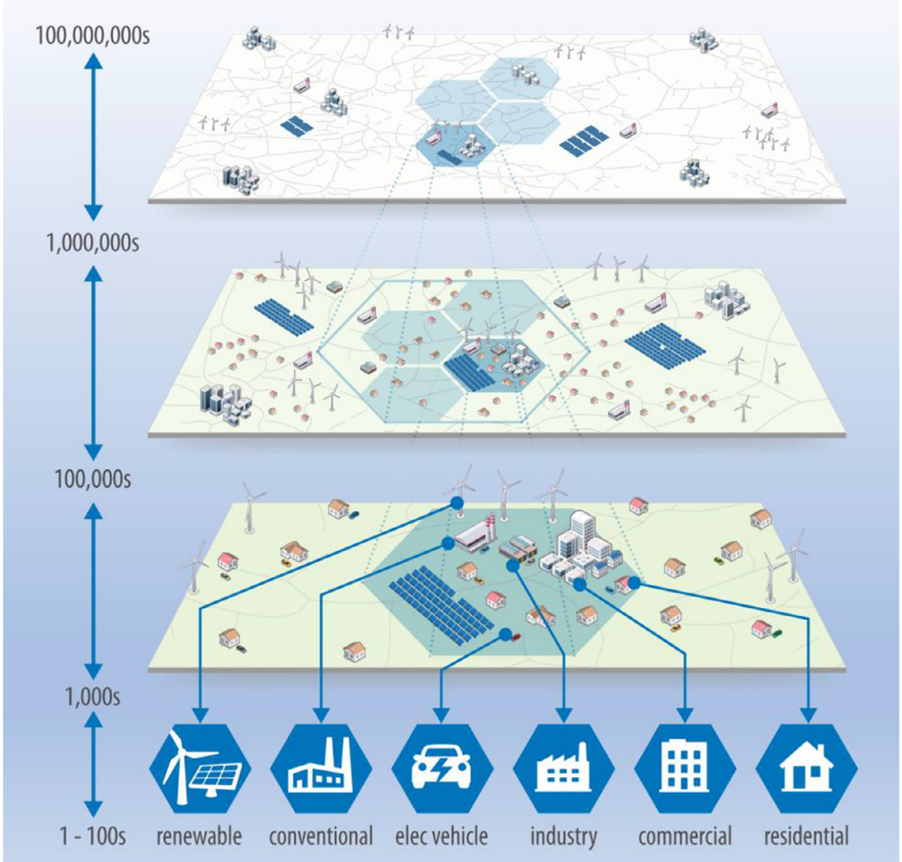

Fig. 5. AEGs are made up of cells that contain various distributed energy resources configured in a hierarchical system to enable control of 100 s of millions of devices. The numbers on the lefthand side of the diagram are the relative numbers of controllable devices at each level of the hierarchy.

ual cell in AEGs. It is expected that a very large number of sensors will be needed in each cell. Pervasive sensing established in the 1st phase will be required to provide data in real-time in order to enable the control and optimization at cell levels in the 2nd phase. The CEGs will need upgrading of the communication technologies connecting the sensors so that real-time data collection can be realized to fulfill this development phase of AEGs. Edge computing and learning will be necessary to facilitate the optimization task at the cell level. Depending on the progress of the control and optimization algorithms, this phase may be materialized in the early 2030s, and should be worked on in parallel with the 1st phase.

5.2.3.3. 3rd phase – wide-area monitoring based on pervasive sensing and communication infrastructure (system level). In AEGs, optimization problems must be solved in a distributed manner. Real-time cell-to-cell communications and intracellular message passing are needed during optimization, and multiple communication rounds are necessary to converge to solutions. Thus a communication infrastructure that is secured from cyberthreats should be established to connect with the sensors. A large-scale real-time measurement system enabled by CEGs with pervasive sensing covering every cell is necessary to monitor the AEGs continuously and seamlessly. With the establishment of the intra- and inter-cellular communication infrastructure, wide-area monitoring throughout the power systems will become feasible and sensor data can provide important parameters for optimization and control of cells. Sensor data provide important parameters in the control and optimization algorithms of AEGs. Solving optimization problems such as relaxations/linearizations of optimal power flow requires pervasive sensing to collect measurements of the noncontrollable loads at all locations in real time. Particularly, noncontrollable loads vary quickly for AEGs. A wide-area measurement system with intra- and inter-cellular communication infrastructure at all locations over the whole AEGs will be the target in the 3rd phase, which requires a much more advanced version of CEGs that we envisioned in Section 5.1. Since the CEG development pace of each cell may be different, it will probably take some time for the system-wide cells to reach a similar level. This phase may be realized in the late 2030s.

5.2.3.4. 4th phase – energy exchange through a game theoretic approach. Finally, the complex problem of energy exchange among cells and higher grids can be solved by the game theoretic approach [205] to provide services to the individual consumers and utilities at cell levels and grid levels. The energy exchange among the AEGs is essentially a collection of inter-dependent optimization problems which can be modeled as a game. This game can be viewed as a balancing problem of computing a generalized Nash equilibrium such that no node can improve its revenue by unilaterally changing its power schedule to another feasible one. The formalisation of all the optimization problems will depend on the sensor data collected by the wide-area measurement system and communication infrastructure throughout the AEGs established in the 3rd phase. Besides sensors, the solving of these optimization problems will require advanced algorithms which need to be highly efficient and implemented at the edge. The physical process of energy exchange will rely on advanced autonomous techniques and complicated hardware infrastructure which still need more research and development. Therefore, the materialization of this phase will probably take place after 2040.

Research and development of grid technologies determines the future of electric and energy infrastructure. Technological expertise in intelligent power grid systems such as grid automation, communication system and advanced metering is crucial to the materialization of AEGs. In the Asia-Pacific region, Japan and South Korea have been investing significantly in smart grid research and will probably be in a more advanced stage in AEG development. On the other hand, microgrids can be the cell blocks of AEGs and their development requires an energy market with freedom for energy exchange or trading. Moreover, utilities tend to have more incentive to develop and adopt new technologies when there is competition. Within the United States, technologically innovative states with deregulated electricity markets such as Texas, California and Massachusetts may take the lead in realizing AEGs and other states with high levels of DERs such as Hawaii are making significant progress in this area.

6. Outlook of research gap and opportunities

Looking into the future, CEGs enabled by pervasive sensing with IoT contactless sensing systems will open a new research area that offers a lot of research opportunities to fill the technology gap in order to realize these new concepts in energy engineering and sensing. These opportunities below may provide some interesting research ideas for the research community.

6.1. Big sensor data

Because of increased numbers and types of sensors, massive amounts of new data [206] are being collected on energy grid conditions, leading to the issue of data deluge. For example, a magnetic sensor on a circuit breaker panel monitoring the power consumption of an appliance may provide 10 kB data per second. This is equivalent to 6 GB per week or 24 GB per month. A home with 20 magnetic sensors can accumulate approximately 0.5 TB of data per month. Pervasive sensing where numerous sensors will be deployed will transform traditional discrete, point measurements by individual sensors to vectors of measurements by sensor arrays. Information arrays are formed by combining these vector fields with others. Parameter waves can then be constructed and analyzed. Contactless sensing provides a cost effective scalable solution to pervasive sensing which allows high-resolution sensing with aggregated measurements using correlation-based collaborative sensing over power networks. It can be foreseen that sensors will generate very large quantities of loosely held information packets in an unstructured format that need to be processed and acted upon. This big sensor data problem will require efficient methods or technologies to analyze and process. Artificial intelligence and its sub-branches including machine learning [207], deep learning, neural networks, etc., work as an intelligent layer to the big data and can carry out complicated and lengthy analytical tasks much faster than humans can to produce insightful results. Perhaps, sensor data need to be processed at the edge first before sending over to the cloud to avoid data deluge. Distributed file systems and NoSQL databases are also new database approaches to overcome the limitations of traditional databases in the case of massive data, which may provide a mechanism to meet the big sensor data requirements in power grids [208]. Researchers may also consider using batch processing tools such as Hadoop [209], real time processing tools such as Storm [210], and hybrid processing tools such as Spark [211], which are currently commonly used by data scientists, to analyze the massive sensor data of power grids.

6.2. Cybersecurity and sensor blockchain

Cyber-attacks on power grids is a national security issue and cyber-physical security threats can occur to sensors as well. As demonstrated in [212], IoT can be exploited in an adversarial way to launch large-scale coordinated attacks on the power grid. The contactless sensors deployed over CEGs to perform pervasive sensing essentially are IoT devices, and as a result can potentially be compromised by an adversary to disrupt the grid operation. The interdependence between the vulnerability of sensors to cyber-attacks and power grids requires our serious attention to secure power systems. Grid cybersecurity can be innovatively solved by the newly emerged blockchain technology that can enable distributed energy markets and the proliferation of DERs [213]. Blockchain may provide a mechanism for authenticating the decision-making process in hierarchical sensor networks to prevent any intrusion, threat or attacks to power networks. The blockchain will document the time-series ledger of transactions. All information exchanged transmitted in the networked sensors can be retained by blockchain in case of disrupted connectivity. This can be implemented in a microcontroller within a sensor node. The power grids will need their own blockchain protocols.

6.3. Multi-sensor data fusion

In addition to the current and voltage sensors we have discussed in this paper, future energy systems require other kinds of sensors to monitor the environment or control the intelligent devices [214]. Heterogeneous sensors besides sensors measuring electrical parameters will be deployed on generators, substations, transmission and distribution systems, and end users. In a substation, oxygen sensors, temperature sensors, hygrometers, SF_6 sensors, etc., are also needed to safeguard supply availability, reliability, safety and risk management in power grids. Sensor data of different physical types including gas concentration, temperature, humidity, and toxicity will be collected. In a power transmission tower, video camera, tower tilt sensors, infrared sensors, accelerometer vibration sensors, wind direction sensors, etc., will be installed to monitor the transmission assets. Sensor data of different format such as video, images, directions and numerical will be integrated together. Multi-sensor data fusion will require the processing, analysis and storage of data of different physical types and formats to derive smarter decision, which is a problem to be solved for accomplishing sensor fusion in future energy systems.

6.4. System miniaturization and power optimization

A self-sustainable perpetual IoT contactless sensing system must include sensing transducers, an embedded system for data processing, communication devices for end-to-end communication, and an energy harvester for scavenging ambient energy. As discussed in the previous section, the energy harvesting unit is a complicated system made of harvesting source, power converter, energy management, and energy storage. During product development, system miniaturization is needed in order to create an IoT contactless sensing system with small form factor for easy installation. On the other hand, even though the sensors themselves may consume very little power, the embedded computing modules and communication modules can be hungry for power and create a burden for power supply. As discussed earlier on, on one hand, we want the energy harvesters to produce as much power to the storage as possible for the subsequent sensing and transmission operations; on the other hand, the output power achievable for energy harvesting devices generally reduces rapidly as the device is scaled down [215]. Therefore, system miniaturization and power optimization are intertwined problems for IoT contactless sensing system design which still need to be solved collaboratively and innovatively. Insights into system miniaturization and power optimization may be sought from the open-source hardware and software designs of smart grid solutions, for example, power meters and multi-objective design optimization, published in some journals [216-218] and websites [219, 220].

6.5. Sensor information update policy

An energy harvesting sensor monitors physical parameters of a power grid and sends measurement updates to a destination. Updates must be sent such that the long term average age of information is minimized [221]. The age of information is defined as the time elapsed since the latest update has reached the destination. In general sensor situations, the optimal information update policy is the one that minimizes the age of information under the constraint of power supply. The sensor should submit an update only if the instantaneous age of information is above a certain threshold that depends on the energy in its battery/supercapacitor. However, this kind of energy-dependent threshold policy may not be suitable for the complicated circumstances in power grids where the time frame for information updating can vastly vary. When the grid is operating under normal conditions, the frequency of updating can be low (i.e., the threshold of information updating will be high), for example, every minute or tens of minutes, because the variation from the previous update is minimal. However, when the grid is under transient or fault conditions, the frequency of updating must be much higher (i.e., the threshold of information updating will be much lower) because the grid condition can vary very rapidly right before the occurrence of a problem and during the problem. Particularly for sensors measuring electrical parameters, the time frame for information updating may need to be reduced from minutes, down to seconds or even milliseconds or microseconds in order to provide data with sufficient temporal resolution for system analysis and fault detection. Therefore, a threshold policy specific to power grids must be developed in order to realize CEGs.

6.6. *Solving inverse problems*

Contactless sensing is essentially a process of determining the causes from the effects. The sources, which cannot be observed directly, are reconstructed from the measurements. In order to solve such inverse problems, there must be sufficient sensor data with spatial information of the sensors known. For example, for the current and voltage measurements of overhead transmission lines using magnetic and electric sensors, the relative positions of the sensors need to be well-defined in order to reconstruct the current and voltage sources and the accuracy of the source reconstruction is dependent on the number of sensors. Moreover, the solution should also be robust to the measurement noise. When the electric circuit is simple, the inverse problems may have an analytical solution which can be solved straight-forwardly. When the circuit involves multiple sources such as a multi-phase multi-core cable or a double-circuit overhead transmission line, it is very difficult to derive the analytical solution to find the sources. Stochastic optimization techniques such as genetic algorithms [222] and artificial immune systems [223] are needed to solve the inverse problems and reconstruct the sources. However, this kind of algorithm typically involves a search process that requires intensive computation resources and can be time consuming. This issue is particularly problematic for an embedded system which is needed for system miniaturization as discussed above. Research efforts on other machine learning systems may help to solve the inverse problems accurately and efficiently in terms of time and hardware resources. Signal processing techniques such as wavelet analysis or wavelet de-noising [79, 96] have been used to remove noise in data analysis in power systems and they may significantly improve the performance of source reconstruction. The innovative use of signal processing toolboxes will have a lot to offer in solving the inverse problems of contactless sensing.

Conclusions

In this paper, the challenges of power grids in need of grid visibility have been overviewed and their relation with pervasive sensing has been discussed. Contactless sensing which can help to overcome the major obstacle (installation cost) towards pervasive sensing has been introduced and reviewed. Pervasive sensing with IoT contactless sensing systems will complement the traditional contact measurement techniques and largely facilitate pervasive sensing and measurements in power grids due to their scalability resulting from non-invasiveness. The implementation of contactless sensing of current and voltage based on optical and electromagnetic-field sensors has been introduced, and the supporting technologies needed to construct IoT contactless sensing systems have been explained with guidance. Their working principles, IoT connectivity, energy sources, and shielding have been discussed and their feasibility and practicality have been assessed. We have elaborated on how pervasive sensing, particularly with IoT contactless sensing systems, will act as the cyber layer and transform the power grid into a cyber physical system where processes (physical world) will be measured by sensors, the sensor data will be transmitted by IoT communication technologies to SCADA, WAM, distribution management and energy markets (cyber world), resulting in decision making for grid operation (physical world). Such CEGs are promising for achieving the goals of future energy systems. An outlook for the potential contribution of CEGs to futuristic AEGs has been envisioned with a phase-by-phase development roadmap. Interesting research opportunities have been revealed for researchers to explore. It can be foreseen that the CEGs enabled by pervasive sensing will have a role to play in shaping our future energy systems. It should be noted that this paper does not aim to be comprehensive in its scope or viewpoints on contactless sensing for power grids, and our exposition and analysis may be colored by our own research experiences.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to acknowledge the support by the Seed Funding Program for Basic Research, the Seed Funding Program for Applied Research, and the Small Project Funding Program from The University of Hong Kong, the ITF Tier 3 Funding under Grant ITS/203/14, Grant ITS/104/13, and Grant ITS/214/14, by RGC-GRF under Grant HKU 17204617, and by the University Grants Committee of Hong Kong under Contract AoE/P-04/08. HVP would like to acknowledge the support from the U.S. National Science Foundation (NSF) under Grants DMS-1736417 and ECCS-1824710. AMA would like to acknowledge the support from the US NSF under the CPS grant 1932406. GZ's work was supported in part by the U.S. Department of Energy (DOE) EERE under the SETO ASSIST Initiative award number DE-EE0008769. This work was supported in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. DOE under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

Appendix

Table A1

Table A1
Existing communication technologies for sensor connectivity.

	Bluetooth	Zigbee	WiFi	Cellular	LoRa	Satellite
Standard	Bluetooth 4.2	ZigBee 3.0 based on IEEE802.15.4	IEEE 802.11	GSM/GPRS/EDGE (2 G), UMTS/HSPA/CDMA (3 G), LTE (4 G), 5G	LoRaWAN	
Frequencies	2.4 - 2.485 GHz (short-wavelength UHF radio waves)	868 MHz (Europe), 915 MHz (USA), 2.4 GHz (others)	2.4 GHz and 5 GHz bands	900/1800/1900/2100 MHz, 1–6 GHz and millimeter wave (5 G)	868 MHz (Europe), 923 MHz (Asia), 915 MHz (USA)	Super-high frequency 1–40 GHz
Range	50–150 m (Smart/BLE)	10–100 m	Approximately 50 m	35 km (GSM); 200 km (HSPA), 100 s m (5 G)	40 km (rural), 3 km (urban)	Continuous global coverage
Data rates	1 Mbps (Smart/BLE)	20 - 250 kbps	150–200 Mbps, 600 Mbps maximum	35–170kps (GPRS), 120–384kbps (EDGE), 384Kbps-2 Mbps (UMTS), 600kbps-10 Mbps (HSPA), 3–10 Mbps (LTE), 100 Mbps – 20 Gbps (5 G)	0.3 kbps to 50 kbps	128 kbps - 1 Mbps
Features	Very low range	Low power, low speed; smart metering, energy consumption monitoring, energy management	Indoor, high speed, high power	Outdoor, high speed	Outdoor, long range, low power	Remote area

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