Advances in Magnetics

Overview of Spintronic Sensors With Internet of Things for Smart Living

Xuyang Liu[1], K. H. Lam[1], Ke Zhu[1], Chao Zheng[1], Xu Li[1], Yimeng Du[1], Chunhua Liu[2], and Philip W. T. Pong[1]

[1]Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong
[2]School of Energy and Environment, City University of Hong Kong, Hong Kong

Smart living is a trending and connected lifestyle that envisions efficient and sustainable energy utilization, stable and reliable power supply, intelligent and coordinated transportation and mobility, and personalized and cost-effective healthcare. Its realization needs the Internet of Things (IoT). IoT is a compelling platform connecting trillions of sensors and collecting data for connectivity and analytics. It is more advanced than traditional monitoring systems where limited sensors and wired communication can merely collect fragmented data in the application domains. Spintronic sensors with the superb measuring ability and multiple unique advantages can be one of the critical sensing devices supporting the IoT and enabling smart living. In this paper, we review successful applications of individual spintronic sensors in electrical current sensing, transmission and distribution lines monitoring, vehicle detection, and biodetection that can help to fulfill the promises of smart living in energy management, power delivery, transport, and healthcare. The wireless spintronic sensor networks (WSSNs) working at the massive interconnected network level are proposed and illustrated to provide pervasive monitoring systems, which facilitate the intelligent surveillance and management over building, power grid, transport, and healthcare. The database of collected information will be of great use to policy making in public services and city planning. This paper provides insights for realizing smart living through the integration of IoT with spintronic sensor technology.

***Index Terms*—Internet of Things (IoT), smart living, spintronic sensors, wireless spintronic sensor network (WSSN).**

NOMENCALTURE

AMR	Anisotropic magnetoresistive.
CT	Current transformer.
EMS	Energy management system.
FAN	Field area network.
FM	Ferromagnetic.
GMR	Giant magnetoresistive.
GPS	Global positioning system.
HAN	Home area network.
IC	Integrate circuit.
ICT	Information and communication technology.
IoT	Internet of Things.
ITS	Intelligent transport system.
MNP	Magnetic nanoparticle.
MR	Magnetoresistive.
MTJ	Magnetic tunnel junction.
NILM	Non-intrusive load monitoring.
NM	Nonmagnetic.
PDC	Phase data concentrators.
PMU	Phasor measurement unit.
POC	Point of care.
SCADA	Supervisory control and data acquisition.
SQUID	Superconducting quantum interference device.
SNR	Signal-to-noise ratio.
SV	Spintronic valve.
TMC	Traffic management center.
TMR	Tunneling magnetoresistive.
WAM	Wide-area monitoring.
WAN	Wide area network.
WSN	Wireless sensor network.
WSSN	Wireless spintronic sensor network.

Manuscript received March 31, 2019; accepted June 19, 2019. Date of publication August 6, 2019; date of current version October 17, 2019. Corresponding author: P. W. T. Pong (e-mail: ppong@eee.hku.hk).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMAG.2019.2927457

I. INTRODUCTION

THE rapidly growing population, increasing demands on the quality of life, and rising pressure on environmental conservation have been initiating the social reform for a more intelligent lifestyle. Smart living has been introduced as a trending style of living that will bring about more efficient energy consumption, better healthcare, and elevated standard of living through integrating advanced information and communication technology (ICT), smart sensing technology, ubiquitous computing, big data analytics, and intelligent decision-making. Smart living will be primarily accomplished by the concept of the smart city [1]. The final goal of the smart city is to enhance the utilization efficiency of various public resources, promoting the quality of services offered to the citizens while reducing the operational cost of public infrastructure and administrations [2]. Smart building, smart grid, smart transport, and smart healthcare are the key application domains to support smart city vision [3]. Researches focusing on these areas have obtained considerable progress in the past decade;

nonetheless, there still exist roadblock challenges in these regimes due to the novelty and complexity of smart living, such as improving energy efficiency of buildings without reducing the comfort level [4], integrating renewables and self-healing for power systems [5], highly efficient management of traffic congestion [6], and provision of quality healthcare for growing populations at reduced overall costs [7]. Such challenges need to be tackled by new monitoring systems rather than the traditional ones that function with limited sensors and wired communications.

The Internet of Things (IoT) is a compelling paradigm to support smart living by means of connecting a great quantity of digitally augmented physical objects to the Internet. These objects, especially sensors are being connected everywhere and at all time collecting the information of interest. The wireless sensor network (WSN)-based IoT platform is popular in modern monitoring systems. It is predicted that the number of sensors in diverse applications will exceed one trillion by 2022 and over 100 trillion by 2030 [8]. According to the application note released by Libelium [9], magnetic sensors occupy a relatively high proportion (i.e., around 10%) in the smart sensor applications for IoT industries, as illustrated in Fig. 1. In addition, it is forecasted that the magnetic sensor markets will grow by 7% per year from 2016, to reach almost U.S. $2.5 billion in 2022 [10].

Over the last few decades, spintronic sensors working as linear magnetic field transducers have gained considerable attention. The typical features, such as high sensitivity (up to 300 mV/V/Oe [11]), compactness (generally mm level), low power consumption (lower than 0.1 mW [12], [13]), wide frequency bandwidth (above 1 MHz [14]), excellent thermal stability (typically $-40 \sim +125$ °C) and CMOS compatibility, make spintronic sensors being used in a growing number of emerging applications other than data recording. The ability to detect the ultra-weak magnetic field (~pT level) at room temperature provides great potentials to magnetoresistive biochips for biodetection. Spintronic sensors also find their wide applications in noncontact current measurement, power system monitoring, and vehicle detection, etc., as sensor nodes. Wireless connectivity enables the sensor data from the spatially distributed sensor nodes to be transported wirelessly through the network, forming a WSN. Due to the power consumption, size, cost, and scalability constraints of WSN for sensor nodes, all the abovementioned features of spintronic sensors make them more suitable for IoT applications involving magnetic sensing than other sensing technologies such as hall sensors, fluxgate sensors, and superconducting quantum interference devices (SQUIDs). Such wireless spintronic sensor networks (WSSN) are proposed and envisioned to seamlessly integrate spintronic sensors into the IoT to fulfill the promise of energy, power supply, transport, and healthcare in smart living.

While the previous papers [15], [17] on spintronic sensors focus on the development of their structures and industrial applications, there still lacks an overview and outlook on the potential roles that spintronic sensors may play in the realization of smart living. The objective of this paper is to bridge the gap between scientific research on spintronic sensors and the realization of the IoT-based smart living. This paper is organized as follows. Section II presents the working principle of spintronic sensors. Section III summarizes the sensing capabilities of spintronic sensors for electrical current sensing, transmission and distribution lines monitoring, vehicle detection, and biodetection. In Section IV, the construction of a sensor node based on spintronic sensors and the WSSN structure combining IoT and spintronic sensor nodes are proposed and discussed. More importantly, the WSSN-enabled IoT applications to support smart building, smart grid, smart transport, and smart healthcare are summarized and envisioned in Section V. Finally, Section VI provides the future outlook and concluding remarks.

II. Principle of Spintronic Sensors

To achieve smart living, various types of data are required to be detected and collected to the Internet. Spintronic sensors can provide measurement data of the magnetic field from which magnetic-field-related parameters of some real-world objects can be derived. Typically, the resistance of spintronic sensors depends on both the magnitude and direction of the external magnetic field, known as the magnetoresistance (MR) effect. Based on distinct underlying mechanisms as illustrated in Fig. 1, spintronic sensors are normally categorized into anisotropic MR (AMR), giant MR (GMR), and tunneling MR (TMR) sensors.

A. AMR Sensor

The AMR effect in ferromagnetic (FM) metals and alloys stems from the anisotropic scattering of conduction electrons induced by spin–orbit interaction. The spin–orbit interaction leads to a mixing of spin-up and spin-down electron states in the FM materials. This mixing of electron states is dependent on the magnetization direction of the material. This behavior gives rise to a magnetization-direction-dependent s-d scattering rate, which influences the resistance of the AMR system, as shown in Fig. 2(a). Since the magnetization direction of the AMR material can be changed by the magnitude and direction of an external magnetic field, a relation between the resistance of AMR sensors and the external magnetic field can be established. Based on this principle, the information of the magnetic field (e.g., direction, magnitude) can be obtained by using AMR sensors. Furthermore, the directional sensing ability of the AMR sensor can be utilized to determine the rotational conditions (e.g., angle and rotational speed) of a magnetic object. However, AMR sensors are generally limited by their relatively low MR ratios (typically around 1%) and they also suffer from large cross-field error [18] and over-field disorientation [19]. Thus, nowadays GMR and TMR sensors are gaining popularity over AMR sensors. Despite all the mentioned disadvantages, AMR sensors are still much more precise comparing to GMR and TMR sensors as they have lower linearity error, lower hysteresis, and higher temperature stability.

B. GMR Sensor

The GMR effect in FM/nonmagnetic (NM) thin-film stacks was discovered in 1988 [20], [21]. Unlike the AMR sensors where the electron spins are randomly oriented, the FM

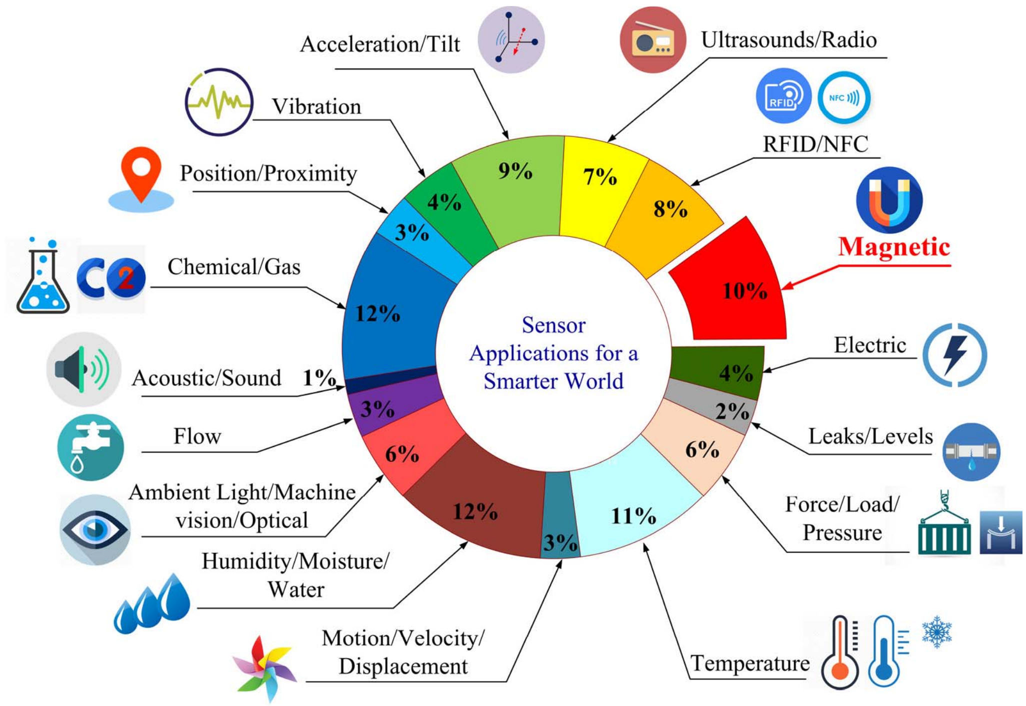

Fig. 1. Common sensor categories including magnetic sensors in IoT applications. Magnetic sensors are among the top four sensors in IoT.

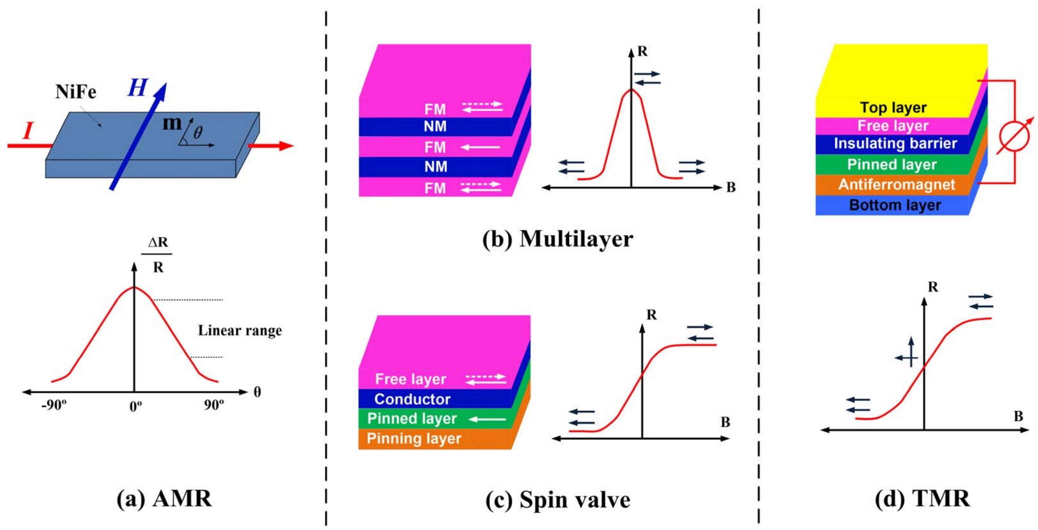

Fig. 2. Basic structures and working principles of spintronic sensors. (a) AMR sensor. (b) GMR multilayer. (c) GMR spin value. (d) TMR sensor.

layer in GMR sensors serves as a spin filter to polarize the spin of electrons. Hence, stronger spin-dependent scattering is expected when the spin current flows through the NM spacer to the interface of another FM layer. The resistance of GMR sensors is dependent on the relative orientation of the magnetizations of the neighboring FM layers. The GMR ratio is defined by

$$\mathrm{GMR} = \frac{R_{\mathrm{AP}} - R_P}{R_P} \tag{1}$$

where R_{AP} and R_P represent the resistance at antiparallel and parallel state, respectively. High GMR ratio is preferred for high sensitivity. Besides, the linear response of the GMR sensor defines the detectable field range while the coercivity determines the extent of the hysteresis effect in the magnetization transfer curve.

The magnetic multilayers and spin valves (SVs) are used in commercial GMR sensors. The magnetic multilayers are composed of repetitions of FM/NM layer pairs, as shown in Fig. 2(b). Under the zero magnetic field, the multilayers exhibit high resistance since the FM layers are oriented in the opposite direction through interlayer exchange coupling. When the magnetizations of the FM layers are gradually aligned to the parallel configuration by an external magnetic field, the resistance of this MR sensor decreases from the maximum resistance to the minimum value. A large magnetic field is required to overcome the strong exchange coupling amongst the FM layers, resulting in a saturation magnetic field up to hundreds of mT [22]. However, the extended linear detectable field range is accompanied with a drawback of relatively low sensitivity. The development of SVs can provide higher sensitivity through introducing a soft FM layer in the FM/NM/FM trilayer structure [see Fig. 2(c)] [23]. The soft FM layer can be freely rotated by the external magnetic field as the interlayer exchange coupling is reduced by the relatively thicker NM spacer. The hard FM layer is pinned by an anti-FM layer through direct exchange coupling to maintain its magnetization direction when the reverse magnetic field is applied.

The recent efforts on the development of spintronic sensors have been devoted to increasing the GMR ratio and reducing the coercivity. Through engaging FM materials with high spin polarization ratio (such as Heusler alloy [24], [25]), GMR ratio of 74.8% was achieved [26], which is much higher than that in conventional SVs (5%–10%) [22]. The insertion of nano-oxide-layer as the NM spacer led to a remarkable increase in GMR ratio due to the enhanced spin-dependent scattering at the metal–oxide interfaces [27], [28]. On the other hand, the coercivity can be reduced through engaging soft FM materials (such as supermalloy or Conetic alloy [29]) or synthetic FM structure [30] as free layers.

The compatibility of GMR sensors with a standard CMOS process [31], [32] and other integration technologies [33], [34] makes them attractive especially for the measurement of weak magnetic fields using miniaturized devices, such as for low-current measurement in the integrated-circuit (IC) level or biological measurement applications. On the other hand, unipolar field operation limits the application of GMR sensors made of multilayered structure (e.g., NVE AA-series magnetic field sensors [35]) in detecting the polarity of the magnetic field. Spin-valve GMR sensors are the promising candidates for bipolar operation. In addition, GMR material commonly exhibits a significant dependence on temperature, which requires thermal compensation to reduce the effect of field-sensitivity drift [36]–[38].

C. TMR Sensor

Compared to SVs, a typical TMR sensor [39], [40] has a similar basic structure but with the metallic spacer replaced by a thin (0.5–2 nm) insulating barrier, as shown in Fig. 2(d). As a result, instead of the spin-dependent scattering effect, the spin-dependent tunneling effect [41] is involved in TMR sensors, which are therefore called magnetic tunnel junctions (MTJs). The spin-dependent tunneling effect in MTJs can be coherent [39], [40] or incoherent [42], [43], depending on the type of the tunnel barrier. The incoherent tunneling is typically exhibited in the AlO_x-based MTJs. Their TMR ratio is phenomenologically described by Julliere's model [42], [44]

$$\mathrm{TMR} = \frac{2P_1P_2}{1 - P_1P_2} \tag{2}$$

where P_1 and P_2 are the spin polarizations of two FM layers, respectively. In the AlO_x-based MTJs, the highest observed TMR ratio at room temperature is 70.4% [45], which corresponds to spin polarization of 0.51 for the CoFeB FM layer based on Julliere's model. Considering the thermally driven spin fluctuation at room temperature, such a spin polarization is close to the spin polarization (usually 0–0.6) of the 3d Co- or Fe-based FM alloys measured in FM/AlO_x/superconductor junctions at an ultra-low temperature (<4.2 K). One of the breakthroughs with respect to the TMR effect is the use of oriented single-crystal MgO barrier, achieving the spin-dependent coherent tunnel in MTJs. In such MgO-based MTJs, the totally symmetric $\Delta 1$ Bloch states (spd hybridized states) in the FM layer can effectively couple with the evanescent $\Delta 1$ states in the MgO barrier and decay much slower than the $\Delta 2$ states (d states) and $\Delta 5$ states (pd hybridized states) [46]. Therefore, only highly polarized $\Delta 1$ states travel across the MgO barrier, which leads to extremely high spin polarization of the tunneling current and thus a large TMR ratio. By optimizing the fabrication process, the TMR ratio of the MgO-based MTJ can even reach 604% at room temperature [47]. In addition, other new magnetic materials are under research to enhance the performance of TMR sensors, such as Heusler alloys, ferrites, rutiles, perovskites, and dilute magnetic semiconductors.

For sensor applications, not only the sensitivity is required to be improved but also the noise level should be suppressed in order to boost up the signal-to-noise ratio (SNR). The MR ratio of TMR sensors is 1–2 orders of magnitude higher than that of GMR sensors [48], but the noise level of TMR sensors is much higher than that of GMR sensors. Therefore, the main roadblock to achieving ultra-high SNR of TMR sensors is their relatively high noise level compared to GMR sensors. Intrinsic noises in TMR sensors include thermal noise, shot noise, electronic 1/f noise, magnetic 1/f noise, and random telegraph noise [49]. In the sensing region of a TMR sensor, the dominating noise source is normally the magnetic 1/f noise, which is essentially attributed to the thermally driven magnetization fluctuation of the free FM layer. Such magnetization fluctuation can be experimentally suppressed by applying a hard-axis magnetic field, annealing in a high magnetic field, or utilizing the voltage-induced anisotropy modulation, reducing the magnetic 1/f noise of TMR sensors.

III. Sensing Capabilities of Spintronic Sensors

Researchers have developed extensive sensing capabilities of spintronic sensors. Section III-A–III-D primarily summarizes several typical capabilities of spintronic sensors, which are useful for IoT applications, i.e., electrical current sensing, transmission and distribution lines monitoring, vehicle detection, and biodetection.

A. Electrical Current Measurement

As they can measure currents non-invasively without contact by sensing the emanated magnetic fields, spintronic sensors are gaining increasing popularity beyond other sensing technologies such as current transformers (CTs), shunt resistors, Rogowski coils, fluxgate sensors, and Hall sensors. From [50]–[54], electrical current measurements based on GMR and TMR sensors are the more appropriate sensing technologies than AMR sensors due to their high sensitivity, good linearity, and low hysteresis effect.

Though CTs have been applied in power systems for a long time, they can only measure alternating currents with limited frequency bandwidth, and they are bulky in size. Shunt resistors interrupt the original circuit, and the intrinsic inductance limits its measuring sensitivity and bandwidth. Rogowski coils have poor accuracy when sensing small and low-frequency currents, which restricts their broader application. Although fluxgate sensors can significantly improve the measuring accuracy, they are now mainly employed in the calibration systems, diagnosis, and laboratory equipment because of the large size, high cost, and high power consumption. Integrated fluxgate sensors with cores made by sputtering or electrodeposition are developed to overcome the large size of common fluxgate sensors (i.e., diameter in unit of cm) [55]. Even though integrated fluxgate sensors offer high sensitivity and lower thermal drift, they suffer from the limited frequency bandwidth (e.g., the bandwidth of 47 kHz for DRV425 fluxgate sensor [56]) due to the close-loop feedback control and the relatively small field measurement range (i.e., typically less than ±5 mT). The low sensitivity (only up to mT range) of Hall sensors leads to the necessity of using a magnetic core to clamp around the current conductor for signal concentration which presents a difficulty to practical deployment, particularly when the conductor is not isolated and thus cannot be clamped. In contrast, spintronic sensors show great potentials in electrical current sensing due to their high sensitivity, compact size, low cost, ac and dc detection ability, broad frequency bandwidth, easy installation, and low power consumption.

The compactness and non-contact current detection make spintronic current sensors ideal for the IC design. Nowadays, current sensors are ubiquitous and essential in the IC design. For example, current sensors are placed on every power pin to ensure the homogeneous power distribution [69], or at the power connections of different blocks to indicate the levels of an activity performed by the blocks for rescheduling the workload [70]. Due to the compactness of spintronic sensors, current sensing modules in ICs can be further miniaturized. Moreover, spintronic sensors can carry out non-contact current measurement without interrupting the original circuit path, and thus they do not degrade the original circuit performance or introduce power losses.

The dc detecting ability enables the spintronic sensors to measure dc current while the broad frequency bandwidth for ac detection is conducive to transient current monitoring. DC residential appliances such as televisions, computers, and LED light fixtures are very common in the twenty-first century. It is envisioned to integrate dc buses into building electrical systems for connecting and accommodating the dc loads. Renewable resources (e.g., solar energy) and energy storage elements (e.g., batteries) are also inherently dc systems. Therefore, the dc detectability of the sensor is critical. Various kinds of transient ac currents (e.g., lightning currents, switch impulse currents, and leakage currents) can occur to a building, and they are usually of large amplitudes and wide frequency bandwidth (e.g., lightning current can be as high as several kiloampere and several megahertz frequencies). The broad frequency response of spintronic sensors makes them suitable for the tasks of measuring such ac currents.

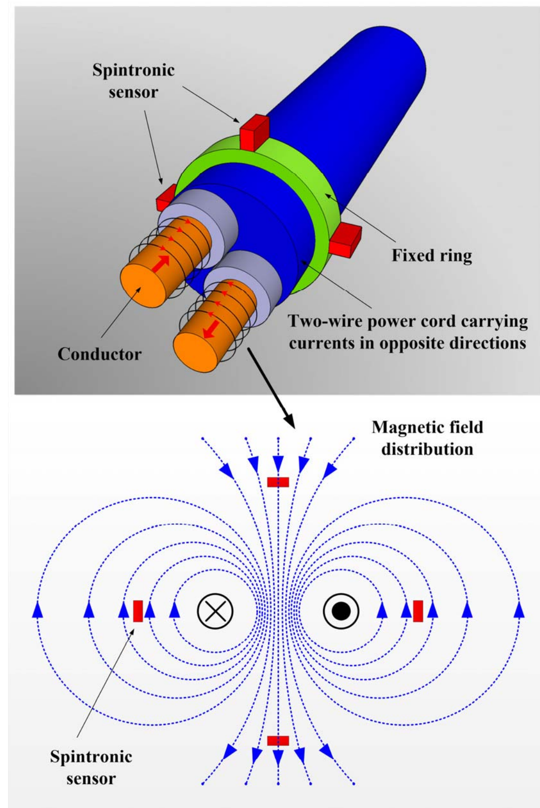

Fig. 3. Spintronic sensors for current sensing in a two-conductor power cable. The two conductors carry currents in opposite direction. The emanated magnetic field distribution is shown [57].

Low-cost and low power consumption of spintronic sensors is favorable for large-scale application and deployment. Currently, the current sensors are usually installed in a centralized hub. For example, CTs are installed in the substations, and the electricity meters are installed at customers' premises to measure the energy consumption for billing. With the advancement of home automation, many residential appliances will be networked together and operated through the energy management system (EMS). The electric appliances will not only respond to on-and-off commands but also operate according to the signals indicating the electricity usage condition of each device under EMS management. All these depend on a current sensing network on the appliances. Moreover, these current sensors must be able to detect the currents in multiple-conductor cables because the electric cables connecting with the appliances are typically composed of more than one conductor.

Spintronic sensors are capable of measuring the currents in multiple-conductor cables without the need to remove insulation from the cable, whereas traditional current clamps cannot measure the currents in multiple-conductor cables [57], [58]. In [57], four spintronic sensors encircle two-conductor cable of any type, and these four sensors are 90° rotationally symmetric around the central axis of the power cable (as shown in Fig. 3). Due to the symmetric magnetic field distribution for the currents in opposite directions, the magnetic field can be measured by four spintronic sensors and then decomposed. Hence, the currents in power cable and the rotation angle of the power cable around its central axis can be resolved from the magnetic field measured. With this technique, spintronic sensors can be implemented to measure the current of power cables connected to domestic appliances or a household which are typically two-conductor cable. Meanwhile, non-contact voltage sensors are utilized to detect the real-time voltages of these cables [59], [60], and thus the instantaneous power can be determined by multiplying the current with the voltage. Using this convenient technique, the power consumption of each individual electric appliance in a household or building can be monitored. Spintronic sensors have the potential to be embedded in a large amount of the appliances to monitor their usage of electricity with great convenience and little power consumption.

B. Transmission/Distribution Lines Monitoring

Transmission and distribution lines are the critical elements in a power system to transfer the electricity from the generation side to the consumption load over long distances. Overhead transmission lines are usually deployed for the transmission network while underground power cables are frequently used in the distribution network. Conventionally, the operating currents of the overhead transmission lines and underground cables are monitored by the CTs at the substations. Apart from the drawbacks such as limited measurement range and frequency bandwidth, CTs are costly (typically over the U.S. \$100k), bulky (with volume size in the order of m^3), and need regular maintenance (e.g., insulation oil replacement). Great care must be taken to ensure the secondary side never open-circuited. Spintronic sensors can overcome the above weaknesses of CTs in transmission-and-distribution-lines monitoring.

A non-contact platform to monitor the currents of overhead transmission lines and underground cables by employing spintronic sensors has been developed [61]–[64]. The configuration of the overhead transmission lines and the deployment of spintronic sensors are shown in Fig. 4(a). The three-phase high-voltage conductors of the overhead transmission lines are current-energized. The spintronic sensor arrays can be deployed either on the ground level [61] or installed on the transmission towers [64] (as sometimes the geographical condition does not allow them to be deployed on the ground). The magnitude of the magnetic field at the ground level under a transmission line is typically on the order of 10^{-5} T while it is on the order of 10^{-4} T on the transmission towers, and currently, spintronic sensors are sensitive enough to measure these transmission-line magnetic fields. The configuration of the underground power cables and the deployment of spintronic sensors are shown in Fig. 4(b). The spintronic sensor arrays are installed around the cable surface to measure the magnetic fields generated by the three-phase conductors of the cable. An array of spintronic sensors in a circle is installed around the cable surface to measure the comprehensive magnetic information. The magnitude of the magnetic field around underground power cable surface is at the level of mT, which is detectable

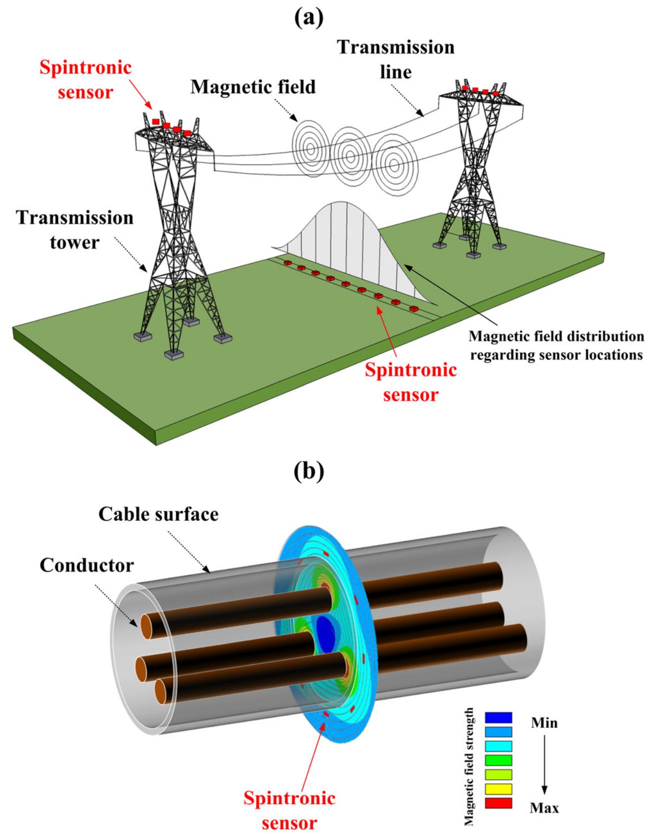

Fig. 4. Spintronic sensors for monitoring transmission and distribution lines. (a) Configuration of three-phase overhead transmission lines and spintronic sensors. (b) Configuration of underground power cable and spintronic sensors.

by spintronic sensors. The currents can be reconstructed from the measured magnetic field by the stochastic optimization algorithm. The stochastic optimization algorithm is adopted since the individual currents cannot be solved easily from the magnetic field information in an analytical way. The reconstructed results resemble the actual ones with very small errors, as demonstrated in [61] and [63].

Meanwhile, the sag characteristic of transmission lines can also be estimated using the measured magnetic field [65], [66]. A uniaxial spintronic sensor can be deployed along the x-axis at the transmission tower to detect the sagged conductors and galloping conductors [65]. In addition, locating corona discharge in power grid has been achieved using a dual-axial TMR sensor array [67] since the corona discharge emanates magnetic field which is inversely proportional to the third power of distance from the discharge point.

This spintronic sensor platform is compact and low cost. It is easy to be installed on the transmission or distribution lines because of its noncontact current measurement. Spintronic sensors do not need regular maintenance. The sensing platform is entirely isolated from the primary circuit; thus, the reconstruction of currents and spatial parameters based on magnetic field sensing does not disturb the operation of transmission lines and underground cables. The spintronic sensors also show the enhanced measurement range and frequency bandwidth than traditional CTs. By virtue of low cost and compact size, the platform can be extensively deployed over transmission lines to establish the sensing network over a large area [68]. It should also be noted that the developed platform excels the existing current clamps because it can carry out current sensing for each individual conductor in a multi-core cable. A current clamp measures the vector sum of all currents together, and thus there would be a net current of zero when it clamps around a cable with the three-phase balanced currents. This problem can be overcome by having a current clamp to clamp around each conductor individually; however, it will involve removing the insulating layers of the multi-core underground power cable which is difficult and dangerous.

The research studies [19], [62]–[64], [67] show that GMR sensors and especially TMR sensors are more popular sensing technologies beyond AMR sensors for the transmission and distribution lines monitoring systems. They require less complex circuitry (e.g., for recalibration) and perform better in aspects like sensitivity, bandwidth, and broad field range [69], [70]. GMR and TMR sensors are certainly capable for current sensing applications such as overload detection that do not require high precision; for precise applications such as metering the power consumption, perhaps AMR sensors still have advantages, and GMR and TMR sensors are catching up.

C. Vehicle Detection

An intelligent transport system (ITS) integrates the information and communication technologies into the transport infrastructure, aiming to deliver innovative services for various modes of transport with improved safety, security, efficiency, mobility, and environmental performance [71]. In recent years, the ITS has attracted widespread attention from both government and motor corporations. Vehicle detection, as the most fundamental element of the ITS, collects traffic information such as vehicle speed, occupancy rate, and traffic volume. Vehicle detectors based on spintronic sensors including AMR, GMR, and TMR sensors have been widely used for vehicle detection applications [72]–[75].

The earth provides a uniform and stable magnetic field over the planet surface. A ferrous or metal object, like a vehicle, can be considered as a model consisting of a number of bipolar magnets with the N-S polarization direction. A vehicle can cause a local disturbance in the earth's field when it moves or stands still as shown in Fig. 5(a). The disturbance depends on the ferrous material, the size, and the moving orientation [76]. The disturbances are most obvious on the engine and wheels. In [75], the magnetic signature of a vehicle is described as a magnetic point dipole with a magnetic moment m centered in the vehicle. It was reported that a typical vehicle has a magnetic moment of 100–300 A·m^2 [77]. In [78]–[80], triaxial spintronic sensors were employed at the center of the road lane or the roadside to detect the disturbance of magnetic field in each axis direction (B_x, B_y, and B_z). Here, the x-axis is parallel to the vehicle moving detection, the y-axis is perpendicular to the vehicle moving detection, and the z-axis is perpendicular to the road surface. The relation between the magnetic moment and the magnetic field can be described

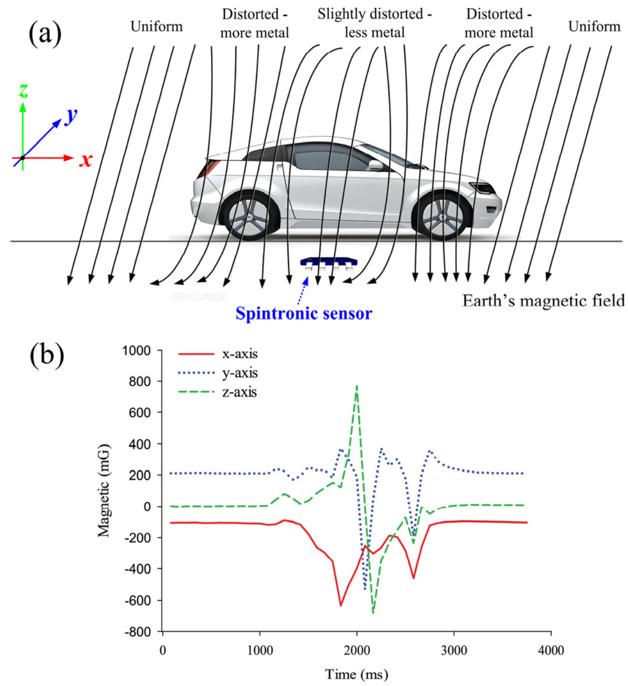

Fig. 5. Basic principle of vehicle detection by magnetic field sensing. (a) Disturbance of the earth's magnetic field by a passing vehicle. (b) Magnetic field reading when a vehicle passes over a triaxial AMR sensor (permission obtained from [75]).

according to Maxwell's Equations [75]

$$B_x = \frac{\mu_0 \times (m_x(2x^2 - y^2 - z^2) + 3m_y xy + 3m_z xz)}{4\pi r^5} \quad (3a)$$

$$B_y = \frac{\mu_0 \times (m_y(2y^2 - x^2 - z^2) + 3m_x xy + 3m_z yz)}{4\pi r^5} \quad (3b)$$

$$B_z = \frac{\mu_0 \times (m_z(2z^2 - x^2 - y^2) + 3m_x xz + 3m_y yz)}{4\pi r^5} \quad (3c)$$

where m_x, m_y, and m_z are the magnetic moments in each axis direction, respectively, μ_0 is the permeability of air, and r is the distance between the sensor (x_0, y_0, z_0) and the dipole point (x, y, z). The magnetic field strength reading in the x-, y-, and z-axes when a moving vehicle passes over an AMR sensor can be shown in Fig. 5(b) [75]. When there is no vehicle, the sensor outputs the uniform earth's magnetic field as the initial value. As the vehicle approaches the spintronic sensor, the magnetic field distribution is distorted towards the ferrous vehicle. By analyzing the disturbance signal, the vehicle presence, moving speed, direction, and classification of this vehicle can be determined. To obtain a smoother magnetic field signal, a digital filtering algorithm is usually used to eliminate noise, which may utilize fast Fourier transform, median filter, Gaussian filter, etc.

The arrival and departure of a vehicle can be determined by comparing the square deviation of measured signal SD(t) with the pre-defined high threshold and low threshold, respectively. The SD(t) is defined as

$$\text{SD}(t) = \sqrt{(B_x - B_{x0})^2 + (B_y - B_{y0})^2 + (B_z - B_{z0})^2} \quad (4)$$

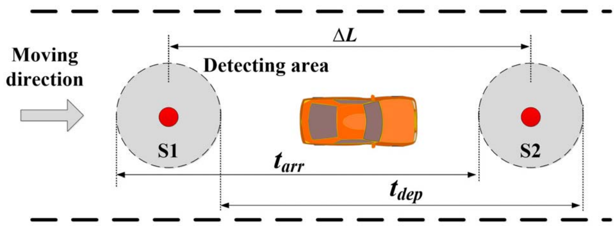

Fig. 6. Configuration for vehicle speed estimation.

where B_{x0}, B_{y0}, and B_{z0} are the baseline values of three axes when no vehicles pass over the sensor. The variance-based multi-state machine adaptive threshold algorithm in [81] uses the historical data variance to calculate the real-time data fluctuation, and then predict the new thresholds. This algorithm can detect the vehicle on urban streets with a precision of 97.3%. In [79], the algorithm uses the deviation of processed magnetic field intensity from a baseline to drive a fixed threshold state machine, which can detect the low-speed vehicles with an accuracy of 99.05%. Meanwhile, several other algorithms in recent literature including threshold-based algorithms, state machine algorithms, and cross-correlation-based algorithms have been proposed with good results [75], [76], [82], [83].

For the vehicle speed estimation, at least two sensor nodes (S1 and S2) are employed [75], [84], as shown in Fig. 6. The distance between S1 and S2 is known as ΔL, and the travel time from S1 to S2 is δt. The average speed is determined as $\bar{v} = \Delta L/\delta t$. As the time of arrival and departure points of S1 ($t_{\text{arr\_s1}}$, $t_{\text{dep\_s1}}$) and S2 ($t_{\text{arr\_s1}}$, $t_{\text{dep\_s1}}$) can be obtained, respectively, the travel time can be calculated as

$$\begin{aligned}\delta t &= 0.5(t_{\text{arr}} + t_{\text{dep}}) \\ &= 0.5[(t_{\text{arr\_2}} - t_{\text{arr\_1}}) + (t_{\text{dep\_2}} - t_{\text{dep\_1}})]. \end{aligned} \tag{5}$$

The vehicle speed can also be estimated by the measurement of the signal time delay between S1 and S2 using the cross correlation algorithm [75].

Each category of vehicle signal has its own characteristics due to different structures and sizes. The vehicle classification can be implemented based on a hierarchical tree methodology. First, the vehicle features are extracted through time-domain waveform structure after signal segmentation. The vehicle signal duration L, the signal energy E, the average energy EV, the ratio of positive and negative energy of x-axis VX, and the ratio of positive and negative energy of y-axis VY are several main parameters to classify a vehicle [79], [85]. In [79], based on a three-layer hierarchical tree model shown in Fig. 7, the detected vehicles can be classified as a motorcycle, two-box car, saloon car, bus, and sport utility vehicle with the precision of 93.66% for low-speed congested traffic. On the other hand, Dong *et al.* [86] developed the gradient tree boosting algorithm for vehicle identification using a single AMR sensor, as illustrated in Fig. 8. The 42-D features are first extracted from every vehicle signal comprising statistical features of the whole waveform and short-term features of fragment signal. Then, the gradient tree boosting algorithm is used to identify four vehicle categories. The experimental results

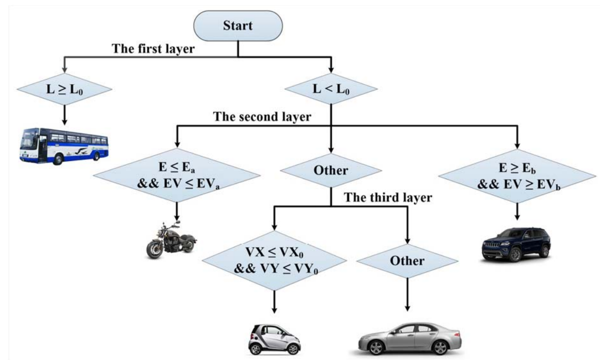

Fig. 7. Schematic of a three-layer vehicle classification algorithm in [79].

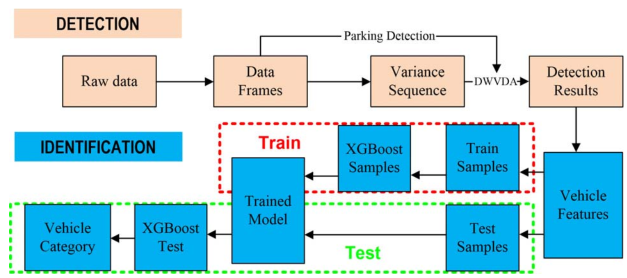

Fig. 8. Framework of vehicle detection/identification algorithm in [86].

based on 4507 vehicles with 80.5% accuracy rate on vehicle identification have approved its effectiveness [86].

In contrast to conventional detectors including inductive loops, radar sensors, and video cameras, spintronic sensors are easy to install, compact in size, low cost, and immune to environment conditions such as fog, rain, and wind [84], [91]. As a result, spintronic sensors have great potential to be employed as the sensor nodes in a large scale combined with the WSN for traffic monitoring.

D. Biodetection

Spintronic sensors are becoming increasingly popular in biomedical applications. Spintronic-based devices have been used in highly sensitive and rapid biological non-destructive detections, which provide immense help to the doctors for tracing the metallic shrapnel during surgery [87]. More promisingly, spintronic biodetection technologies are widely used to measure the concentration of target analyte molecules in solutions, such as DNAs and proteins [88]. In the spintronic biodetection process, magnetic labels are utilized to tag the target analyte molecules, and then spintronic sensors are used to detect the magnetic signals generated from the labels [89]. From [90]–[93], typically high-sensitivity spin-valve GMR and TMR sensors are used to detect the weak magnetic field (e.g., from brain and heart) for biodetection at room temperature and they can be fabricated down to nanometer level to match with the size of target analyte molecules for better detection.

The schematic of biodetection using spintronic sensors is illustrated in Fig. 9. Spintronic biodetection is implemented on the surface of a single spintronic sensor or a patterned spintronic sensor array. First, the surface of the sensing area

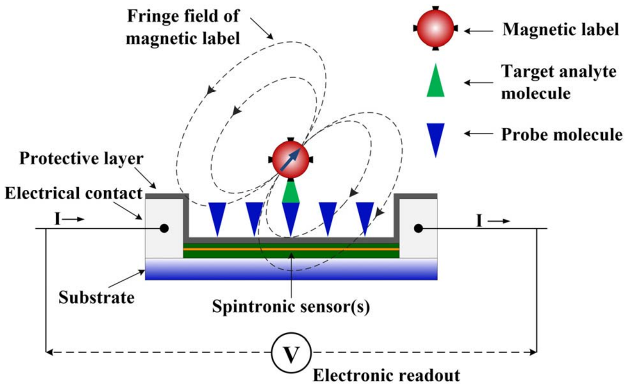

Fig. 9. Cross-sectional view of biodetection using spintronic sensors [88].

is functionalized with the probe molecules, which can specifically bind to the target analyte molecules. The target analytes in recent researches are dominantly DNAs or proteins, and the probe molecules used to capture them are different. In DNA sequence detection, the complementary DNA chains are used as probes to capture the target DNA chain [94]. On the other hand, for the detection of protein molecules, antibodies are employed to bind to the target protein through the specific immune (antigen-antibody) recognition [95]. Then, the sample solution (e.g., plasma, sera, and urine) is applied to the sensor surface. After the interrogation of the probe array, the target analyte molecules in the solution are specifically captured onto the sensor surface. The target analyte molecules are tagged by the magnetic labels before or after the capturing process depending on different mechanisms (direct labeling or indirect labeling) [96]. As a result, the magnetic labels are attached to the sensor surface. By exciting with the applied magnetic field, the magnetic labels produce a fringe field that is detectable by the underneath sensors. This detected magnetic signal quantitatively represents the concentration level of the target analytes in the sample solution [93].

It is noted that choosing appropriate magnetic labels is a vital aspect of the spintronic biodetection. Different magnetic labels distinctly affect the final detection signal, depending on the magnetic moment, size, structure, and surface-based binding ability [90]. Magnetic labels are normally functionalized magnetic micro-particles or nano-particles. Large magnetic particles can provide a higher magnetic moment which enables detection with a small number of particles. However, they are mismatched in size with the biomolecules and thus jeopardize the quantitative capability of the biodetection. Recently, magnetic nanoparticles (MNPs) with diameters under 100 nm have been widely used, as their size is comparable to the target biomolecules and are less prone to particle clustering in the applied magnetic field since they are superparamagnetic [96]–[98].

Conventional biodetection technology utilizes fluorescent labeling to quantify the concentration of target biomolecules. This technology requires an expensive and bulky optical system, and the sensitivity is limited [99]. Hence, it is difficult to integrate this fluorescence-based assay into a portable point-of-care (POC) device. In contrast, the spintronic biodetection technology using spintronic sensors demonstrate high sensitivity, compact size, and low cost [91]. Most importantly, the spintronic sensors provide a fully electronic readout, which can be easily integrated into electronics to detect multiple analytes on a single chip [100], [101]. Thus, this spintronic biodetection technology is a promising candidate for building portable POC devices. Actually, in recent researches, several POC devices based on spintronic biodetection have been developed [102], [103]. In [92], a portable, quantitative immunoassay platform based on GMR biosensor technology can display quantitative results in less than 15 min with one-time user involvement, and each test costs less than the U.S. $4. In addition, among various target analytes, the protein biomarkers in plasma for early diagnosis of diseases (e.g., cancer and cardiovascular disease [96], [97]) have attracted much interest. These handheld biodetection devices for protein biomarkers can provide a great convenience for users to realize daily diagnostic or health monitoring at the hospital, home, or outdoor environment.

IV. Combination of IoT and Spintronic Sensors

The IoT paradigm envisions connecting billions of "Things" surrounding us to the Internet and expects to use the information of these "Things" to enhance effectiveness and efficiency of various public resources, thus accelerating the actualization of smart living. Spintronic sensors, as introduced in Sections II and III, can provide the information of magnetic field and magnetic-field-related parameters (i.e., current, vehicle speed, and analyte concentration) in many practical applications, which can be a sensor node for the IoT. A massive network of spintronic sensor nodes connected together wirelessly can seamlessly integrate spintronic sensors into the IoT platform, which will be discussed in this section. This combination of the IoT and spintronic sensors has great potential to tackle roadblock challenges in the fields of building, power grid, transport, and healthcare. In this section, we present a brief introduction of the IoT concept and architecture and then discuss the construction of a spintronic sensor node and the proposal of the WSSN. Note that it is not our purpose to provide a comprehensive survey of the IoT in this section. We aim at emphasizing how the spintronic sensors can work with the IoT platform.

A. IoT Architecture

Since the term of IoT was first coined by Ashton [104] in 1999, a number of definitions of the IoT have been proposed. In [105], the IoT can be defined from three visions: internet-oriented, things-oriented, and semantic-oriented, derived from the perspectives of middleware, sensors, and knowledge, respectively. Actually, the IoT paradigm is the result of the convergence of these three visions. It is commonly accepted that IoT is a global infrastructure where day-to-day digitally augmented objects can be equipped with the capabilities of sensing, identifying, processing and networking; then, they can communicate with other devices over the Internet, and finally accomplish specialized objectives [106].

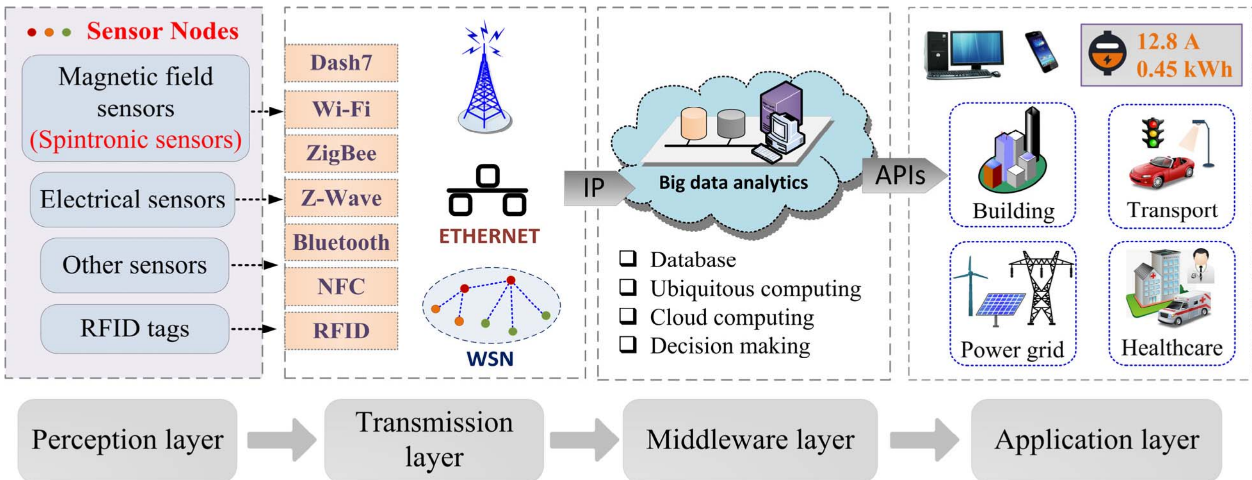

Fig. 10. Four-layer IoT architecture with sensor nodes.

Standardizing a common architecture for the IoT is a very complex task as billions or trillions of heterogeneous objects, various link layer technologies, and diverse services may be involved in the IoT system and many factors, such as security, privacy, reliability, scalability, interoperability, and quality of service (QoS), should be considered. To build such a common architecture, manifold architectures frameworks for the IoT have been attempted in recent literature. At the initial development stage, the three-layer architecture composed of the perception layer, network layer, and application layer is widely adopted [107], [108]. However, this IoT architecture lacks effective management methods and business models. Afterward, to obtain a more reasonable architecture for IoT, several architectures including the middleware-based, service-oriented architecture (SOA) based, and five-layer architecture have been proposed [109], [110]. Among these architectures, the four-layer architecture is established by combining the transmission control protocol/internet protocol (TCP/IP) model, Telecommunications Management Network (TMN) model, and features of the IoT. The common four-layer IoT architecture is illustrated in Fig. 10, and each layer is briefly described as follows.

1) Perception layer represents the physical objects, such as various sensors, actuators, and RFID tag, which aims to recognize things, collect information of interest, and convert this information into digital data. Depending on the type of sensors, the collected information can be temperature, humidity, location, current, solution concentration, etc. This paper focuses on the spintronic sensors, which collect the information of the magnetic field and magnetic-field-related parameters. The digitalized signal is then passed to the transmission layer through secure channels.
2) Transmission layer (or called network layer) securely transfers the data passed from the perception layer to the middleware layer through various networking technologies. The primary communication technologies can be classified as home area networks (HANs), field area network (FAN), and wide area networks (WANs), depending on the practical requirements of location, data rate, and coverage range [111], [112]. The communication technologies for various IoT applications will be further discussed in Section IV-C.
3) Middleware layer is a software layer interposed between the transmission layer and application layer, which can directly match services with the corresponding requesters and has a link to the database. The database, ubiquitous computing, cloud computing, and decision-making can take place in this layer [107]. For instance, in the scenario of smart transport, the middleware layer can process the received data about the traffic information (e.g., traffic flow, and occupancy rate) to predict the future traffic conditions.
4) The application layer provides various high-quality services and applications to users or customers according to the processed data in the middleware layer. Smart applications such as smart building, smart grid, smart transport, and smart healthcare (which are discussed in detail in Section IV) are implemented in this layer. This layer also can provide the interface for customers to interact with a physical device or to access the designated data.

The multi-layered architecture of the IoT clearly indicates that the realization of the IoT relies on the integration of multiple enabling elements. These IoT elements can be categorized as hardware (e.g., identification, sensors, actuators, communication), middleware (data storage and analytics), and presentation (which presents meaningful information and services to the end users) [113], [114]. Among these enabling elements, WSN [115] plays an especially important role as hardware to support the IoT. A WSN is a network formed by extensive specialized sensor nodes with a communication infrastructure, which monitors physical or environmental conditions at diverse locations and cooperatively transfers the collected data through the network to the main location. One way to realize IoT is by connecting WSNs to the Internet. Nowadays, the WSN-based IoT platform is a popular solution in remote monitoring and management applications. In this

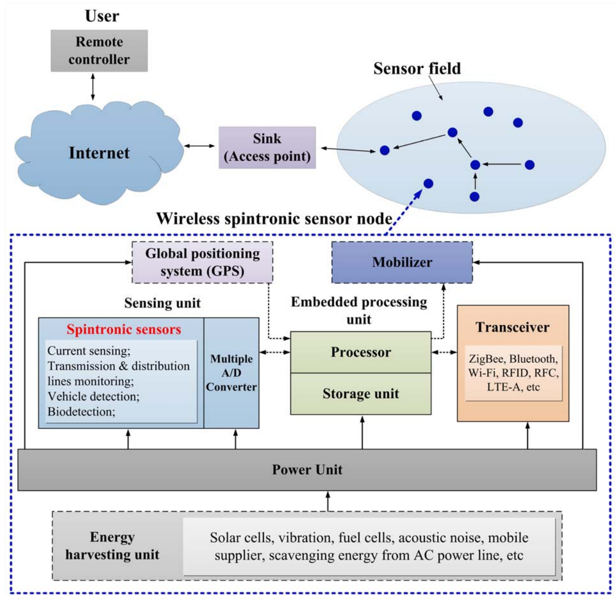

Fig. 11. Hardware structure of a wireless spintronic sensor node.

review, we propose a WSSN composed of spintronic sensor nodes for the collection of information of interest.

B. Spintronic Sensor Node

The general hardware structure of a wireless spintronic sensor node is illustrated in Fig. 11. A standard wireless spintronic sensor node is composed of four essential components: a spintronic sensor unit, an embedded processing unit, a transceiver unit, and a power unit. Depending on the practical applications, additional components such as global positioning system (GPS), energy harvesting unit, and mobilizer are also required [115]. A spintronic sensor unit consists of spintronic sensors and multiple A/D converters. The spintronic sensors can sense the magnetic field signals in the applications, and then these analog signals are converted to digital data by the A/D converters. The microprocessor in the embedded processing unit can process the digital data and arrange this sensor node to collaborate with other nodes. Generally, this processing unit associates with a storage unit. Nodes report the detected information to a small number of special nodes called sinks (access points). Here, the transceiver unit can connect this node to the sinks through various wireless communication technologies. Most importantly, a power unit, commonly battery power, provides the energy of all the system. It should ensure a sufficiently long lifetime of the sensor node. Moreover, the power unit can be supported by an energy harvesting unit that scavenges energy from the external sources, such as solar cells, fuel cells, vibration, acoustic noise, a mobile supplier, and ac power line [115]–[117]. Certain remote monitoring tasks (e.g., in power grid and transport monitoring systems) require the information of position at high accuracy. Hence, a GPS with at least 5 m of accuracy is commonly deployed within the sensor node [118]. Furthermore, sometimes, a mobilizer may be needed to move the sensor

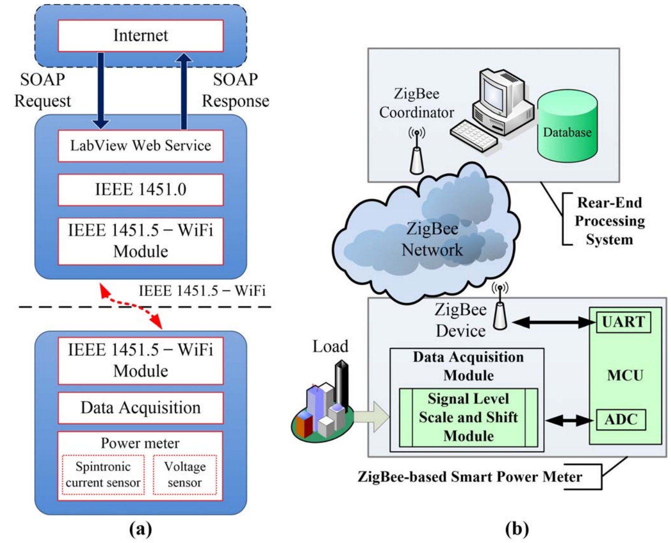

Fig. 12. Smart power meter architectures in [120] and [121] for building energy monitoring system.

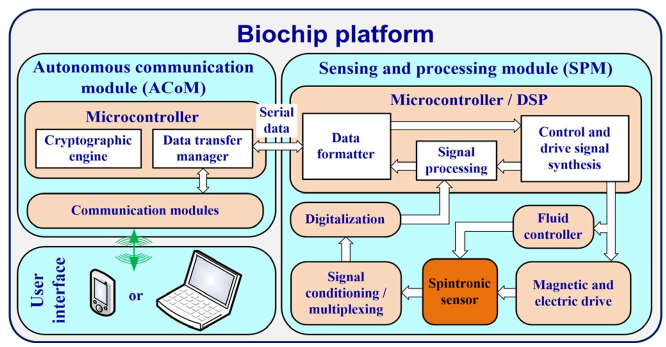

Fig. 13. Spintronic-sensor-node architecture for biodetection [122].

nodes in some particular tasks (e.g., changing the antenna's orientation [119]).

Following the above hardware structure, spintronic sensor nodes can be built in compliance with various IoT application standards. In [120], a spintronic sensor node that fulfills the IEEE 21451.5 standard specification was developed as a smart power meter for the building energy monitoring system [see Fig. 12(a)]. Besides the power consumption data, the other information of interest such as meter identification, calibration data, correction data, and manufacture-related information for each power meter node has been stored using a transducer electronic data sheet (TEDS). Similarly, a system architecture of the ZigBee-based smart power meter and outage recording system has been proposed in [121]. The smart meter node equipped with a ZigBee device communicates with the ZigBee coordinator through the ZigBee network to fulfill the meter-reading function [see Fig. 12(b)]. In addition, the spintronic sensor node for biodetection has been established in [122], as depicted in Fig. 13. Four requirements for spintronic biodetection uses have been taken into account: (i) real-time signal processing; (ii) standard communication interfaces for lowering the development time and increasing compatibility; (iii) transmitted data encryption; (iv) graphical user interface on a personal digital assistant (PDA) or a laptop. Meanwhile, the battery-powered spintronic sensor node named iVCCS in [84] was deployed in the lane for the vehicle detection uses, which also ensures the highly accurate time-synchronization and auto-localization using a low-power embedded GPS receiver module.

As described in Section III, spintronic sensors are compact in size, low cost, low energy consumption, and highly robust. As a result, spintronic sensors can meet the requirements of a WSN for larger scale applications. These spintronic sensor nodes with four sensing capabilities elaborated in Section II are applicable for diverse smart-living applications such as in buildings, power grid, transport, and healthcare. In order to achieve these applications, a massive network of WSNs made of spintronic sensor nodes with wireless connectivity is proposed to form a WSSN.

C. Wireless Spintronic Sensor Network

A common WSN-based monitoring network is mainly composed of four components [123]: (a) hardware—a typical wireless sensor node contains sensors, processing units, transceiver units, power source, etc., as described in Section IV-B. Commonly, the sensor nodes are of small size, lightweight, and low power consumption. (b) Communication stack—WSN nodes communicate among themselves to transmit data in a single- or multi-hop fashion to a base station. (c) Middleware—a platform-independent middleware can combine infrastructure with an SOA and sensor networks to provide access to heterogeneous sensor resources. (d) Data aggregation—an efficient and secure data aggregation method can extend the lifetime of the network and ensure reliable data collected from sensors.

A pervasive monitoring system is conceptualized as a system to deliver accurate information of interest anytime and anywhere, which can be enabled by the wide-scale deployment of WSNs [124]. As a bunch of wireless spintronic sensor nodes can constitute an interconnected WSSN, combining the excellent measuring capabilities of spintronic sensors and the pervasive monitoring ability of WSN, the WSSNs have great potentials in the monitoring applications which are related to the measurement of the magnetic field. On the other hand, energy efficiency, scalability, reliability, and robustness should be considered when designing a WSSN solution [105]. To develop a large-scale, cost-effective, and reliable WSSN platform for a wide variety of smart-living applications, the major challenges and requirements should be considered as follows.

1) *Scalability:* In order to provide a pervasive monitoring solution, the number of wireless spintronic sensor nodes deployed in a sensing area such as building or urban cross may be in the order of higher than thousands [123]. The sensor network protocols should be capable of adequately operating and flexibly adding/removing sensor nodes. An IP-based network can provide an effective network solution with low-cost deployment and maintenance [125].
2) *Energy Efficiency:* Energy-efficient wireless sensor nodes are expected to operate for 10–15 years without replacement [126]. One possible solution is to use energy harvesting from the operating environments of sensors nodes, especially the outdoor environments. For traffic monitoring uses, energy harvesting from the road environment based on vibration source using piezoelectric devices or solar energy is a possible way to power the sensor nodes. Similarly, energy harvesting in the power grid environment is also needed to ensure the wireless sensor nodes to autonomously operate for long lifetime. Recent finding [127] shows that the magnetic field energy harvesting and part of solar energy harvesting are the best candidates for power grid applications. Several successful cases of magnetic energy harvesting from the ac power lines in [128]–[131] have been demonstrated with advantages of ease of installation, low cost, and compactness. On the other hand, lower power operation or configuration like low-power wireless communication protocols (e.g., time division multiple access protocol) can significantly minimize the active time of wireless communications [132].
3) *Wireless Communication Networks:* Wireless communication provides a solution that is easy for installation for sensor networks compared to wired communication technologies, and it is particularly suitable for large-scale deployment. The selection of the best available wireless communication technologies depends on the target smart-living application. Several key limiting factors need to be considered for the choice of wireless technology such as time of implementation, operational costs, the availability of infrastructure, and operation environment [133]. Both short-range and long-range wireless communication technologies are possibly required for a WSSN. A brief summary of common wireless networks and communication technologies for WSSN is shown in Table I. The infrastructure-less short-range communication technologies including ZigBee, Z-Wave, Bluetooth, Wi-Fi, and Dash7 do not require any infrastructure to operate, which have the features of easy-to-installation, short setup time, and relatively low data rate. Thus, they are commonly used to provide wireless connectivity from the sensor nodes to the access points. Infrastructure-based cellular network technologies (e.g., GPRS, CDMA, 3G, and LTE) support point-to-point long-range communication [134] as they are equipped with base stations to relay communication signals. WiMAX based on the IEEE 802.16 standard can also be used to provide wireless data over a long distance, which offers portable connectivity and high-speed data transfer rate. These long-range communication technologies are usually adopted to transfer the collected data from the access points to the remote servers.
4) *Reliable Data Delivery*: The multi-hop communication may be required to ensure reliable data delivery to the access point for nodes with a limited transmission range. In some scenarios, specialized multi-hop protocols need to be designed to enable reliable data connectivity. A fast and reliable MAC access protocol and data forwarding mechanisms to ensure the timely transmission of critical

TABLE I
COMMON COMMUNICATION TECHNOLOGIES FOR IoT APPLICATIONS

Networks	Technology	Typical frequency	Range	Data rate	Unique features
HAN	RFID	13.56 MHz	< 1m	6.6–26.5 Kbps	Possibility of unique IDs; high speed data capture; simultaneous multi-tag reading;
	NFC	13.56 MHz	< 10 cm	Up to 424 Kbps	Peer-to-peer communication; short set-up time;
	ZigBee	868/915/2400 MHz	50–300 m	20 Kbps, 40 Kbps, 250 Kbps	Self-deployment; support of addressing and routing for Ad hoc, tree and mesh topologies, providing flexible network structure;
	Z-Wave	868/908/2400 MHz	30–100 m	9.6 Kbps, 40 Kbps, 200 Kbps	Low powered RF communication; support of full mesh networks;
	Bluetooth	2.4/5 GHz	10–100 m	1 Mbps, 24 Mbps	Complicated set-up procedure; Ad hoc topology;
	Wi-Fi	2.4/5 GHz	< 300 m	< 300 Mbps	The most widely used WLAN technology; high data rate;
	Dash7	433/868/915 MHz	< 5 km	< 10 Kbps	Low energy standby mode; support of peer-to-peer, star, and mesh topologies;
FAN	PLC (Power line communication)	1–30 MHz	1–3 km	2–3 Mbps	Using existing power cables to simulteneously carry both data and electricity current;
WAN	Cellular (GSM, GPRS, 3G, LTE)	700 MHz – 2.7 GHz	< 50 km	< 300 Mbps	Existing communication infrastructure; widespread and cost-effective;
	WiMAX	2.5/3.5/5.8 GHz	< 50 km	< 75 Mbps	Advanced IP-based architecture; flexible channel bandwidth to facilitate long range transmission;

messages (e.g., emergency events like traffic accidents) are also highly required [135].

5) *Time Synchronization:* All spintronic sensor nodes need to be time-synchronized for data acquisition and communication. The synchronization can be possibly achieved by using a time reference signal with the repetition rate of 1 pulse per second (i.e., 1 PPS) which is provided by a GPS receiver 136] or by adopting synchronized protocols such as flooding time synchronization protocol [137], [138].

V. SMART-LIVING APPLICATIONS

This section presents four practical smart-living scenarios in which the IoT platform based on WSSNs can constitute pervasive monitoring systems for smart building, smart grid, smart transport, and smart healthcare. Such monitoring systems can collect information of interest in real time for the administrators and end users. Successful implementation examples and experimental evidence are also presented.

A. Smart Building

Buildings are the largest energy-consuming sector, which contributes to about 40% of the global energy consumption and 30% CO_2 emissions. One major challenge for the smart building is reducing the overall energy consumption and carbon footprint of buildings without compromising comfort. Real-time energy metering is needed to achieve the non-intrusive load monitoring (NILM) in buildings. A recent study shows that 5%–20% of building energy can be saved with real-time feedbacks of energy consumption to the end users [139]. Moreover, smart power meters with the utility can facilitate demand response (DR) so that the consumers can reduce demand during peak load times.

As reported in the recent literature, spintronic sensors can work as smart power meters, collecting the real-time energy consumption of electrical appliances in residential or commercial buildings. The spintronic power meters provide advantages including low cost, compactness, non-intrusive measurement, and ease of installation and they are ideal for the pervasive building energy monitoring. In [59], the high-sensitivity TMR-based current sensing (i.e., STJ-340 sensor) was used to monitor the three-phase power line and circuit-breaker panel. Sensor arrays including GMR sensors were also developed to measure the currents through the enclosed multi-conductor systems for energy monitoring in [140]–[142]. In addition, the wattmeters based on the Wheatstone-type MR sensors were also designed to directly measure the active power with uncertainty less than 1.5% [143]–[146].

The IoT platform with smart power meters provides a pervasive building energy monitoring system, as illustrated in Fig. 14. Smart power meters are conveniently deployed

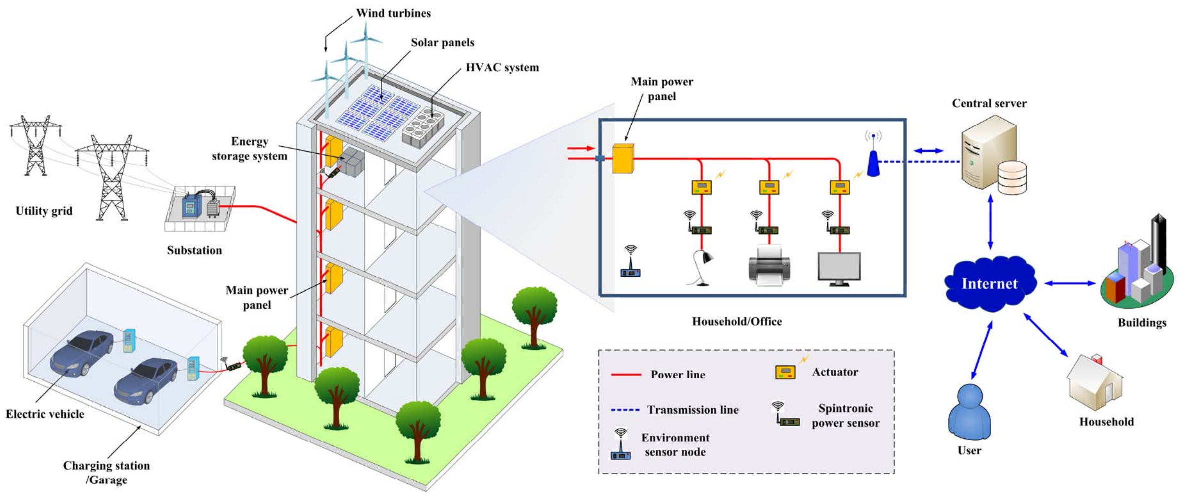

Fig. 14. Architecture of the pervasive energy monitoring system for smart building.

around the power cords connecting to electrical appliances or equipment in buildings, measuring the current and power. The data collected by spintronic power meters are wirelessly transmitted to the WSN access point located in the same household or floor and then conveyed to a central server via a data transmission line. The central server has the responsibility to perform the aggregation, process, and storage of the instantaneous and historical data. By virtue of the specialized user interface (e.g., RESTful Application Programming Interface in [147]) and the Internet, the consumers can visually access the power consumption/generation and status (i.e., ON/OFF/standby) of each appliance through a web browser. The historical information on building energy consumption (e.g., 1-year-long building energy usage) provides weekly, monthly, and seasonal patterns and gives even the forecasting of the short-term energy demand. This will enable power companies to offer the up-to-date tariff options such as time-of-use rates, critical peak pricing, and real-time pricing, which will encourage consumers to migrate their electricity usage to the off-peak period [148].

The smart-building applications supported by the pervasive energy monitoring systems have been demonstrated in several recent research works. A TMR wattmeter-based WSSN for smart energy metering has been introduced in [149], which achieves the web page display of active and apparent powers from five wattmeter nodes. An Internet-based home energy use tracking system named the EnerTracker with magnetic sensor array has been reported in [150]. It collects the current data of residential houses in a non-invasive way and achieves the data refresh rate of 1 sample/s. In both laboratory and field tests, the EnerTracker system has been demonstrated to track the power/energy use characteristics of a group of electrical appliances with satisfactory performance. In addition, an NILM system framework for DR in building level has been established in [151] from both hardware and software aspects, which achieves the multiple data logs of current waveforms for electrical appliances in circuit breaker level and strip level.

However, the smart-building protocols enabled by the pervasive building energy monitoring system are facing several challenges at the present stage. While smart power meters are commonly used to measure the energy use of large individual appliances with high power consumption, it is also required to estimate the energy use of different groups of appliances (e.g., medium to low power consumption). It is still not convenient to install a smart power meter for each appliance in buildings as the large-scale deployment of smart power meters requires proper data storage, computational ability, as well as power supply [152], [153]. The approach of monitoring energy use for multiple similar appliances as one group in [154] can be a viable solution. Self-powering of the pervasive smart power meters is also highly imperative to develop wireless power meters without wired power supply for multi-conductor power cords in buildings [155].

B. Smart Grid

Smart grid, characterized by the bidirectional flow of electricity and information, is to modernize the transmission and distribution grids for improved efficiency, reliability, and safety that meets the future demand and achieves intelligent control. Traditional power-grid monitoring and diagnostic systems are typically established in a centralized way through wired communications (e.g., with monitoring sensors mainly deployed in substations) and cannot efficiently collect the key parameters of electricity phasor and frequency over the grid. The IoT platform (e.g., the 61850 GOOSE protocol) combined with various smart sensors can be a promising solution to realize the smart grid.

As reported in Section III-B, spintronic sensors possess sensing capability for monitoring transmission and distribution lines in power systems. Spintronic sensors are suitable for large-scale non-invasively monitoring of both the electrical parameters (e.g., phase currents of overhead transmission lines [64]) and spatial parameters (e.g., conductor sagging and galloping [61], [156]) of the power grids based on magnetic field sensing, as opposed to traditional CTs which are bulky, expensive, requiring regular maintenance, and making contact with live conductors. Hence, the phase measurement units (PMUs), which provide wide-area information for the wide-area monitoring (WAM) of the power grid [157], can

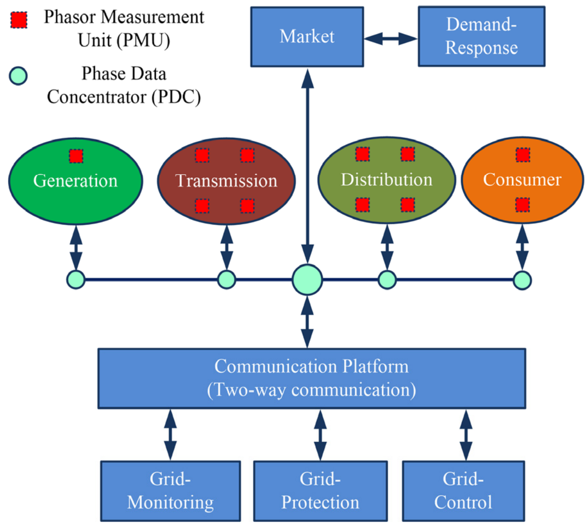

Fig. 15. WAM-based smart grid architecture using PMUs and PDCs.

be constructed by spintronic sensor nodes. The WAM-based smart-grid architecture illustrated in Fig. 15. The PMUs are possibly interfaced with spintronic sensors for collecting various information such as current phasors, frequency, change rate of frequency, over-current, and sagging conditions, and then these collected information are aggregated in phase data concentrators (PDCs) [158].

Similar to in the smart-building applications, WSSN can be applied in the WAM system of smart grid to realize pervasive monitoring of power systems. More explicitly, a WAM case that uses the spintronic-based PMUs for the transmission and distribution network monitoring is depicted in Fig. 16. The electrical parameters, as well as spatial parameters for overhead transmission lines and underground distribution cables, can be collected using the wireless spintronic sensor nodes. Combining with the real-time environmental information from the environment sensors nodes, the collected data are periodically transmitted to the access points using the short-range wireless communication technologies. Then, the WAN transfer it to the central control and data acquisition (SCADA) using cellular technology or Ethernet.

By virtue of the collected real-time information of power grids, several challenging problems such as integration of renewable energy, dynamic line rating (DLR), and self-healing can be tackled. Some proof-of-concept experimental examples have also been presented in recent works to validate the WSSN-based smart-grid application protocol [159]–[161]. A WSSN-based transmission line monitoring system reported in [160] can realize the real-time system state estimation and early fault location via the data visualization application. Similarly, a smart-grid scenario with wireless spintronic sensor nodes has been demonstrated to monitor key parameters (e.g., current) in the transmission and distribution segments in Portugal [161].

Apart from those described in Section IV-C, the WSSN-based smart grid application is also facing other challenges. The sensor networks in the harsh electric-power-system environments may suffer from several conditions that affect the performances [162], [163], such as background noises, RF interferences, high humidity, highly corrosive environments, vibrations, and limited battery energy supply. It is required to conduct large-scale field tests to decide the optimal configuration for different sensor networks. For example, the lifetime of wireless spintronic sensor nodes in harsh power grid environments should be properly estimated [164].

C. Smart Transport

The increasing population and growing size of cities lead to a rapid increase in the amount of vehicles on the roads. One of the most critical consequences is the management problem of traffic congestion. Traffic congestion has caused huge economic losses worldwide (U.S. $101 billion for the USA and €200 billion for Europe in 2012). Smart transport is expected to facilitate traffic management through the integration of smart sensors, advanced wireless communications, and information technologies with transport engineering. An intelligent WSSN-based traffic monitoring system can provide a solution to reduce traffic congestion, providing detailed dynamic traffic information and consequently facilitating the highly efficient management of road traffic.

As described in Section III-C, spintronic sensor nodes can detect vehicles and provide information on vehicle presence, speed, and vehicle categories. Spintronic sensors are the promising candidates for vehicle detection applications due to their advantages such as compactness, ease to installation, and high detection accuracy, comparing the conventional inductive loop detectors. The testing accuracies of vehicle detection and parking occupancy detection can even reach more than 98% by using spintronic sensors [72], [75], [79], [84].

A network of wireless spintronic sensor nodes installed on the roadway surface or roadsides can collect and deliver useful dynamic traffic information including occupancy rate, traffic volume, congestion, accidents, and vehicle statistics. The schematic architecture of a WSSN-based traffic management system is illustrated in Fig. 17. Through the short-range radio communications (e.g., ZigBee, Dash7, and NFC), each sensor node containing GPS reports the traffic data to the access point (namely, gateway station) is normally located at the roadside. The access point then transmits the data packet to a remote server via cellular network communication. After the data aggregation, process, and storage by the server, the processed traffic information ultimately can be accessed by the traffic management center (TMC), users, and vehicles. In addition, vehicle-to-infrastructure (V2I) communications also enable the sensing nodes to deliver timely traffic information directly to nearby vehicles [134]. By virtue of the dynamic traffic data from the high-density spintronic sensor nodes, the WSSN-based traffic management system can achieve the following functions.

1) *Traffic Light Control:* The real-time adaptive traffic light control achieve more balanced traffic conditions by minimizing the light delays and unnecessary stoppages for vehicles [126], [165].
2) *Traffic Prediction and Routing:* The short-time traffic evolution can be performed according to the real-time

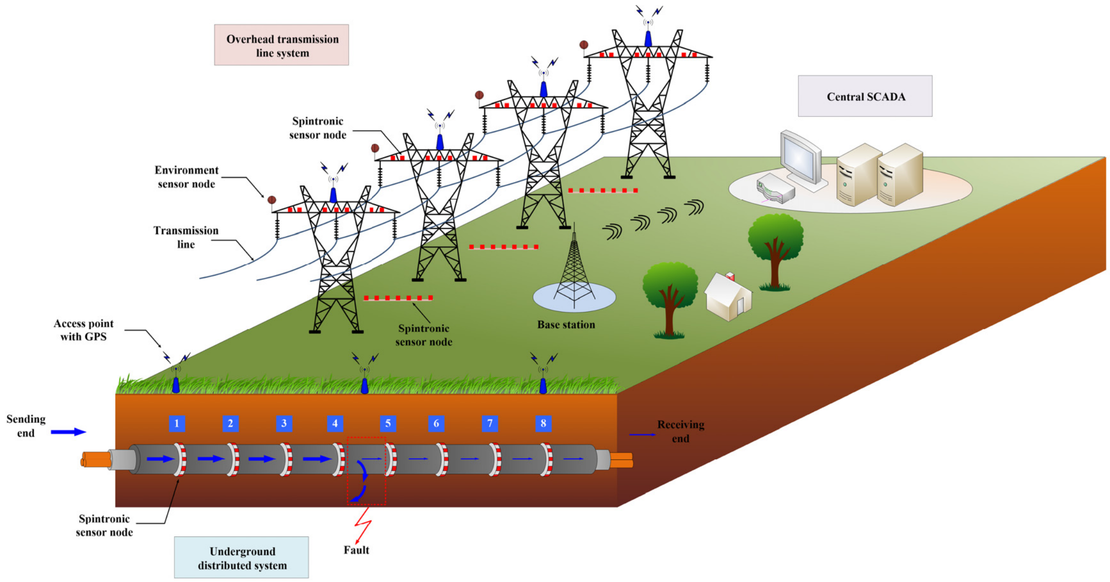

Fig. 16. Schematic diagram of wide-area transmission and distribution monitoring systems by deploying spintronic sensors with IoT technology.

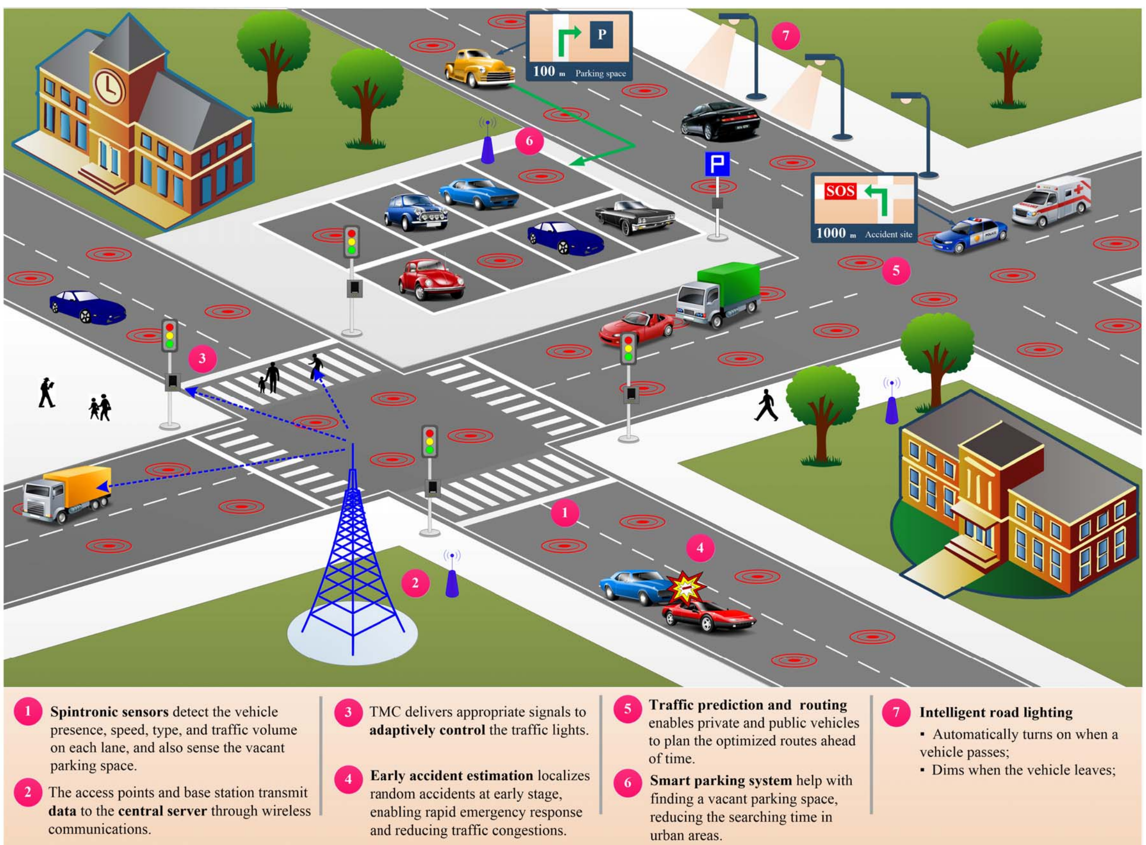

Fig. 17. System architecture of the WSSN-based traffic monitoring system.

and historical traffic information, which provides a dynamic traffic routes planning for the drivers [166].

3) *Early Accident Estimation:* The random traffic incidents are detected and the incident location and time are immediately reported to TMC. This will enable faster and more efficient emergency services dispatch to the incident point in optimized routes [167].

4) *Speed Limiting:* Variable speed limits are adjusted on the motorways depending on the real-time traffic volumes, improving the traffic flow and alleviating the traffic congestion [168].

5) *Parking Space Management:* WSSNs detect the occupancies of parking space and then provide real-time information on parking slots to the drivers 72]. This

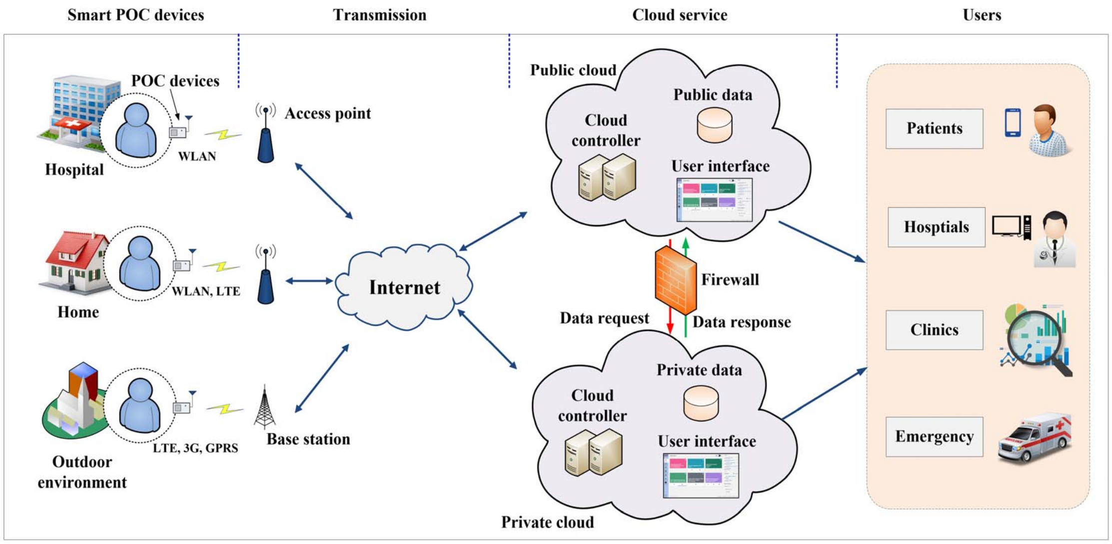

Fig. 18. Architecture of the pervasive diagnosis system for smart healthcare protocol.

smart-parking protocol has been demonstrated and verified in a smart city project in Santander, Spain [169].

6) *Road Lighting Control:* Vehicle detection can be applied to control the road lighting adaptively in spare suburban roads at night during low traffic period. Such an intelligent road lighting system can achieve over 90% energy saving [170].

However, the large-scale deployment of wireless spintronic sensor nodes in the road environment to realize the above-mentioned smart-transport applications faces several technical challenges. Traffic flows need to be sampled every 20–200 m, depending on the specific mobility context [126], in order to provide accurate and virtually continuous monitoring. For example, high-density spintronic sensor nodes should be deployed in urban crosses, whereas the lower density of nodes is needed for extra-urban areas. On the other hand, reliable data analysis for traffic estimation (e.g., mathematical models of traffic flows) are required to integrate the data from high-density sensor nodes and extend the observation capability to regions with poor or missing data [167].

D. Smart Healthcare

The need for delivering quality healthcare to a rapidly growing population (especially the elderly populations) while reducing the healthcare costs in modern-day society is a challenging issue [179]. In the existing healthcare systems, patients have to be monitored or diagnosed in the premises of healthcare such as hospitals. Moreover, the limited quality healthcare services and the growing healthcare costs are universal concerns. An enabling component of affordable global healthcare is the pervasive health diagnosis systems with the help of the POC healthcare technologies supported by smart portable biosensors and the advanced IoT platform.

The POC technology is considered as an effective means of reducing healthcare costs and improving diagnostic efficiency. Spintronic biodetection capability as discussed in Section III-D can enable POC devices. The POC devices can comprise single or multiple spintronic sensors, and they can detect the versatile target biomolecules, predominately DNA and protein in present researches. Up to now, the research groups from the USA [106] and Portugal [102] have built prototypes of POC device by miniaturizing the spintronic biodetection platform into a handheld and battery powered device, and the detection of protein and DNA was realized. These low-cost and highly portable POC devices can be widely operated in the hospital and at home for users' personalized health management, or even in the outdoor environment as part of the emergency medical services (EMS). By now, the classes of analytical targets in spintronic biodetection are expanding from proteins and nucleic acids to metabolites, drugs, and even cells [181]. By testing the samples which are relatively easy to obtain, such as blood, saliva, and urine, the POC testing can acquire various health information "near-patient" whenever it is needed. Meanwhile, the POC diagnostics are widely self-administered without the need of complex operations, and thus patients can conveniently realize their health conditions at home or outdoor environment, reducing the frequency of hospital visits and travel expenses. This kind of spintronic POC system will be robust, low-cost, with no requirement for maintenance or calibration, and transmit data wirelessly. All these are favorable for its pervasiveness in smart healthcare.

A feasible pervasive diagnostic diagnosis system based on spintronic detection and cloud services is illustrated in Fig. 18, which typically consists of smart POC devices, data transmission, cloud services, and multiple end users [180]. Portable POC devices are used to detect the information of versatile target biomolecule, DNA, and protein. The test data from POC devices are then transmitted to the "cloud" through wireless communication and the Internet. More importantly, the hybrid cloud composed of public cloud and private cloud can make full use of the abundant monitoring data from the pervasive POC devices. Multiple cloud services including automatic diagnosis and medical decision-making can be rapidly provided. Different end users, such as patients, clinicians, and hospitals, can ubiquitously obtain these cloud services through user interfaces in their PCs or smartphones. Hospitals and healthcare facilities can provide high-efficient healthcare services benefiting from this pervasive diagnosis system. The information of patients can be remotely accessed by the designated hospitals. Such information could be useful for maintaining patients' health, managing disease, or monitoring therapy. Hence, doctors or healthcare staff can directly provide professional help to patients over the Internet. Meanwhile, the user's profile and medical history data are maintained by the management center for local private use. The doctor may access the user's information as needed when making clinical decisions. Moreover, automated notifications or alarms can be issued to his/her relatives according to the diagnosis results via various telecommunication means. In addition, EMS also benefit from this pervasive diagnosis system. Traditional EMS starts with a 911 call followed by ground ambulance dispatch, patient evaluation, treatment by EMS personnel, and transport to a hospital facility [182]. Time available for EMS patient evaluation and treatment varies with geography and patient condition. The pervasive diagnosis system can offer the long-term and recent diagnosis records of the patient. This will be beneficial to the clinical decision-making and EMS arrangement at an early stage, shortening the waiting time.

The smart healthcare applications supported by the spintronic-sensor-based POC devices and IoT platforms are still limited by several challenges at the present stage. Most of the demonstrated spintronic POC devices [92], [103], [122], with the exception of biochip-based platforms, are still at the proof-to-concept level or small-scale laboratory evaluation level. More effort needs to be made to advance the realization of affordable and clinically accurate POC devices. From the respective of the IoT platforms for smart healthcare, several open issues in the previous applications including privacy, data analytics and cloud computing, energy efficiency, and security should be also taken into consideration.

VI. Conclusion and Outlook

This paper focuses on the promising combination of spintronic sensors and IoT that enables the realization of smart living. Spintronic sensors, working as sensing devices, possess superb measuring abilities, and they are of small size and low cost. They can be used as pervasive magnetic field sensors in electrical current measurement, transmission and distribution lines monitoring, vehicle detection, and biodetection. Spintronic sensors are seamlessly integrated into WSNs by virtue of the IoT technologies, providing the pervasive WSSN monitoring systems for smart living. These WSSN based or related solutions enable the pervasive building EMS, the wide-area transmission and distribution network monitoring system, the all-round traffic monitoring and management system, and the pervasive health diagnosis system. Indeed, the applications of WSSNs are not limited to the domains above. In the future, the development of spintronic sensors with wider linear measuring range, higher sensitivity, and lower noise will create even more opportunities in sensing ultra-weak or transient signals (e.g., in detecting low-concentration target analyte molecules and tracking high-speed motion). Note that there is no single universal sensor solution to all sensing problems. Nevertheless, the unique advantages and features of spintronic sensors, combining with other competing or complementary sensing technologies (i.e., sensor fusion), will go a long way in stimulating the advancement of smart living in all aspects. Multiple-source data fusion will combine spintronic sensors with other sensing technologies such as environmental sensors to reach a comprehensive platform to extend smart sensing into an even broader regime. Meanwhile, the advancement of cloud computing and big data technologies will hold great promise to provide trend prediction based on the historical data, facilitating the policy-making at the early stage.

Acknowledgment

This work was supported in part by the Seed Funding Program for Basic Research, in part by the Seed Funding Program for Applied Research, in part by the Small Project Funding Program from the University of Hong Kong, in part by ITF Tier 3 funding under Grant ITS/203/14, Grant ITS/104/13, and Grant ITS/214/14, in part by RGC-GRF under Grant HKU 17210014 and Grant HKU 17204617, and in part by the University Grants Committee of Hong Kong under Contract AoE/P-04/08.

References

[1] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, "Sensing as a service model for smart cities supported by Internet of Things," *Trans. Emerg. Telecommun. Technol.*, vol. 25, no. 1, pp. 81–93, 2014.

[2] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[3] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2347–2376, 4th Quart., 2015.

[4] J. Pan, R. Jain, S. Paul, T. Vu, A. Saifullah, and M. Sha, "An Internet of Things framework for smart energy in buildings: Designs, prototype, and experiments," *IEEE Internet Things J.*, vol. 2, no. 6, pp. 527–537, Dec. 2015.

[5] Z. Ruihua, D. Yumei, and L. Yuhong, "New challenges to power system planning and operation of smart grid development in China," in *Proc. Int. Conf. Power Syst. Technol. (POWERCON)*, Hangzhou, China, Oct. 2010, pp. 1–8.

[6] M. Tubaishat, P. Zhuang, Q. Qi, and Y. Shang, "Wireless sensor networks in intelligent transportation systems," *Wireless Commun. Mobile Comput.*, vol. 9, no. 3, pp. 287–302, 2009.

[7] T. W. Wlodarczyk, C. Rong, and D. Waage, "Challenges in healthcare and welfare intercloud," in *Proc. 7th Int. Conf. Digit. Content, Multimedia Technol. Appl. (IDCTA)*, Busan, Korea, Sep. 2011, pp. 45–48.

[8] R. Bogue, "Towards the trillion sensors market," *Sensor Rev.*, vol. 34, no. 2, pp. 137–142, 2014.

[9] Libelium. *50 Sensor Applications for a Smarter World*. Accessed: Jan. 2019. [Online]. Available: http://www.libelium.com/50_sensor_applications/

[10] Yole Development. *Magnetic Sensors Market and Technologies 2017 Report*. Accessed: Jan. 2019. [Online]. Available: http://www.yole.fr/

[11] TMR9001 TMR Linear Sensor Datasheet. *Multidimension Technology*. Accessed: Sep. 2018. [Online]. Available: http://www.dowaytech.com/en/1866.html

[12] S. H. Liou *et al.*, "Picotesla magnetic sensors for low-frequency applications," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 3740–3743, Oct. 2011.

[13] M. Tondra, J. M. Daughton, D. Wang, R. S. Beech, A. Fink, and J. A. Taylor, "Picotesla field sensor design using spin-dependent tunneling devices," *J. Appl. Phys.*, vol. 83, no. 11, pp. 6688–6690, 1998.

[14] S. J. Nibir, E. Hurwitz, M. Karami, and B. Parkhideh, "A technique to enhance the frequency bandwidth of contactless magnetoresistive current sensors," *IEEE Trans. Ind. Electron.*, vol. 63, no. 9, pp. 5682–5686, Sep. 2016.

[15] C. Reig, M.-D. Cubells-Beltrán, and D. R. Muñoz, "Magnetic field sensors based on giant magnetoresistance (GMR) technology: Applications in electrical current sensing," *Sensors*, vol. 9, no. 10, pp. 7919–7942, Oct. 2009.

[16] L. Jogschies *et al.*, "Recent developments of magnetoresistive sensors for industrial applications," *Sensors*, vol. 15, no. 11, pp. 28665–28689, 2015.

[17] Y. Kang, J. Bokor, and V. Stojanović, "Design requirements for a spintronic MTJ logic device for pipelined logic applications," *IEEE Trans. Electron Devices*, vol. 63, no. 4, pp. 1754–1761, Apr. 2016.

[18] J.Včelák, P. Ripka, A. Platil, J. Kubik, and P. Kašpar, "Errors of AMR compass and methods of their compensation," *Sens. Actuators A, Phys.*, vol. 129, nos. 1–2, pp. 53–57, 2006.

[19] A. H. Khawaja, Q. Huang, and L. Lian, "Experimental study of tunnel and anisotropic magnetoresistive sensor for power system magnetic field measurement applications," in *Proc. IEEE 3rd Int. Conf. Smart Instrum., Meas. Appl. (ICSIMA)*, Nov. 2015, pp. 1–5.

[20] A. Fert, "Nobel lecture: Origin, development, and future of spintronics," *Rev. Mod. Phys.*, vol. 80, no. 4, pp. 1517–1530, 2008.

[21] P. A. Grünberg, "Nobel lecture: From spin waves to giant magnetoresistance and beyond," *Rev. Mod. Phys.*, vol. 80, pp. 1531–1540, Dec. 2008.

[22] J. M. Daughton, "GMR applications," *J. Magn. Magn. Mater.*, vol. 192, no. 2, pp. 334–342, Feb. 1999.

[23] B. Dieny *et al.*, "Magnetotransport properties of magnetically soft spin-valve structures," *J. Appl. Phys.*, vol. 69, no. 8, pp. 4774–4779, 1991.

[24] Y. Sakuraba *et al.*, "Fabrication of fully-epitaxial $Co_2MnSi/Ag/Co_2MnSi$ giant magnetoresistive devices by substrate-heating deposition," *IEEE Trans. Magn.*, vol. 49, no. 11, pp. 5464–5468, Nov. 2013.

[25] S. Li, Y. K. Takahashi, T. Furubayashi, and K. Hono, "Enhancement of giant magnetoresistance by $L2_1$ ordering in $Co_2Fe(Ge_{0.5}Ga_{0.5})$ Heusler alloy current-perpendicular-to-plane pseudo spin valves," *Appl. Phys. Lett.*, vol. 103, no. 4, p. 042405, Jul. 2013.

[26] S. Jo, O. Mikihiko, N. Hiroshi, and A. Yasuo, "Large magnetoresistance effect in epitaxial $Co_2Fe_{0.4}Mn_{0.6}Si/Ag/Co_2Fe_{0.4}Mn_{0.6}Si$ devices," *Appl. Phys. Exp.*, vol. 4, no. 11, p. 113005, 2011.

[27] H. N. Fuke *et al.*, "Magnetoresistance of FeCo nanocontacts with current-perpendicular-to-plane spin-valve structure," *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2848–2850, Jun. 2007.

[28] H. Fukuzawa *et al.*, "MR ratio enhancement by NOL current-confined-path structures in CPP spin valves," *IEEE Trans. Magn.*, vol. 40, no. 4, pp. 2236–2238, Jul. 2004.

[29] J. Son, J. Lim, J. Ko, S. Kim, S. Lee, and J. Hong, "A study on the sensitivity of a spin valve with conetic-based free layers," *Jpn. J. Appl. Phys.*, vol. 51, no. 3, p. 033002, 2012.

[30] P. Coelho, D. C. Leitao, J. Antunes, S. Cardoso, and P. P. Freitas, "Spin valve devices with synthetic-ferrimagnet free-layer displaying enhanced sensitivity for nanometric sensors," *IEEE Trans. Magn.*, vol. 50, no. 11, pp. 1–4, Nov. 2014.

[31] C. Reig, D. Ramirez, H. H. Li, and P. P. Freitas, "Low-current sensing with specular spin valve structures," *IEE Proc.–Circuits, Devices Syst.*, vol. 152, no. 4, pp. 307–311, Aug. 2005.

[32] M.-D. Cubells-Beltrán *et al.*, "Monolithic integration of giant magnetoresistance (GMR) devices onto standard processed CMOS dies," *Microelectron. J.*, vol. 45, no. 6, pp. 702–707, Jun. 2014.

[33] C. Reig, S. Cardoso, and S. C. Mukhopadhyay, "Giant magnetoresistance (GMR) sensors," in *Smart Sensors, Measurement and Instrumentation*, vol. 6. New York, NY, USA: Springer, 2013, pp. 80–157.

[34] M.-D. Cubells-Beltrán *et al.*, "Integration of GMR sensors with different technologies," *Sensors*, vol. 16, no. 6, p. 939, 2016.

[35] NVE Magnetic Sensor Catalog. *NVE Corporation*. Accessed: Sep. 2018. [Online]. Available: https://www.nve.com/sensorcatalog.php

[36] F. Xie, R. Weiss, and R. Weigel, "Simple mathematical operation-based calibration method for giant magnetoresistive current sensor applying B-spline modeling," *IEEE Sensors J.*, vol. 16, no. 12, pp. 4733–4739, Apr. 2016.

[37] D. R. Muñoz, J. S. Moreno, S. C. Berga, E. C. Montero, C. R. Escrivà, and A. E. N. Antón, "Temperature compensation of wheatstone bridge magnetoresistive sensors based on generalized impedance converter with input reference current," *Rev. Sci. Instrum.*, vol. 77, no. 10, p. 105102, Oct. 2006.

[38] J. S. Moreno *et al.*, "A non-invasive thermal drift compensation technique applied to a spin-valve magnetoresistive current sensor," *IEEE Sensors J.*, vol. 11, no. 3, pp. 2447–2458, Mar. 2011.

[39] S. Yuasa, A. Fukushima, H. Kubota, Y. Suzuki, and K. Ando, "Giant tunneling magnetoresistance up to 410% at room temperature in fully epitaxial Co/MgO/Co magnetic tunnel junctions with bcc Co(001) electrodes," *Appl. Phys. Lett.*, vol. 89, no. 4, p. 042505, 2006.

[40] D. D. Djayaprawira *et al.*, "230% room-temperature magnetoresistance in CoFe/MgO/CoFeB magnetic tunnel junctions," *Appl. Phys. Lett.*, vol. 86, no. 9, p. 092502, 2005.

[41] H. Yang, S.-H. Yang, S. S. Parkin, T. Leo, and D. J. Smith, "Optimized thickness of superconducting aluminum electrodes for measurement of spin polarization with MgO tunnel barriers," *Appl. Phys. Lett.*, vol. 90, no. 20, p. 202502, 2007.

[42] M. Tsunoda, K. Nishikawa, S. Ogata, and M. Takahashi, "60% magnetoresistance at room temperature in Co-Fe/Al-O/Co-Fe tunnel junctions oxidized with Kr-O_2 plasma," *Appl. Phys. Lett.*, vol. 80, no. 17, pp. 3135–3137, 2002.

[43] S. Cardoso, P. P. Freitas, C. de Jesus, P. Wei, and J. C. Soares, "Spin-tunnel-junction thermal stability and interface interdiffusion above 300° C," *Appl. Phys. Lett.*, vol. 76, no. 5, pp. 610–612, 2000.

[44] T. Miyazaki and N. Tezuka, "Giant magnetic tunneling effect in $Fe/Al_2O_3/Fe$ junction," *J. Magn. Magn. Mater.*, vol. 139, no. 3, pp. L231–L234, 1995.

[45] D. Wang, C. Nordman, J. M. Daughton, Z. Qian, and J. Fink, "70% TMR at room temperature for SDT sandwich junctions with CoFeB as free and reference Layers," *IEEE Trans. Magn.*, vol. 40, no. 4, pp. 2269–2271, Jul. 2004.

[46] S. Yuasa, "Giant tunneling magnetoresistance in MgO-based magnetic tunnel junctions," *J. Phys. Soc. Jpn.*, vol. 77, no. 3, p. 031001, 2008.

[47] S. Ikeda *et al.*, "Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature," *Appl. Phys. Lett.*, vol. 93, no. 8, p. 082508, 2008.

[48] P. P. Freitas, R. Ferreira, S. Cardoso, and F. Cardoso, "Magnetoresistive sensors," *J. Phys., Condens. Matter*, vol. 19, no. 16, p. 165221, 2007.

[49] C. Fermon and M. Pannetier-Lecoeur, "Noise in GMR and TMR sensors," in *Giant Magnetoresistance (GMR) Sensors*, vol. 6. Berlin, Germany: Springer, 2013, pp. 47–70.

[50] J. Han, J. Hu, Y. Ouyang, S. X. Wang, and J. He, "Hysteretic modeling of output characteristics of giant magnetoresistive current sensors," *IEEE Trans. Ind. Electron.*, vol. 62, no. 1, pp. 516–524, Jan. 2015.

[51] Z. Li and S. Dixon, "A closed-loop operation to improve GMR sensor accuracy," *IEEE Sensors J.*, vol. 16, no. 15, pp. 6003–6007, Aug. 2016.

[52] T. Y. Poon, N. C. F. Tse, and R. W. H. Lau, "Extending the GMR current measurement range with a counteracting magnetic field," *Sensors*, vol. 13, no. 6, pp. 8042–8059, 2013.

[53] X. Yang *et al.*, "A giant magneto resistive (GMR) effect based current sensor with a toroidal magnetic core as flux concentrator and closed-loop configuration," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1–5, Jun. 2014.

[54] F. Xie, R. Weiss, and R. Weigel, "Hysteresis compensation based on controlled current pulses for magnetoresistive sensors," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7804–7809, Dec. 2015.

[55] P. Ripka, "Advances in fluxgate sensors," *Sens. Actuators A, Phys.*, vol. 106, nos. 1–3, pp. 8–14, 2003.

[56] Texas Instruments. *DRV425 Fluxgate Magnetic-Field Sensor Datasheet*. Accessed: Dec. 2018. [Online]. Available: http://www.ti.com/lit/ds/symlink/drv425.pdf

[57] J. Zhang, Y. Wen, and P. Li, "Nonintrusive current sensor for the two-wire power cords," *IEEE Trans. Magn.*, vol. 51, no. 11, Nov. 2015, Art. no. 4005304

[58] G. Geng, X. Yang, Y. Gao, W. Hammond, and W. Xu, "Non-invasive current sensor for multi-core cables," *IEEE Trans. Power Del.*, vol. 33, no. 5, pp. 2335–2343, Oct. 2018.

[59] J. S. Donnal and S. B. Leeb, "Noncontact power meter," *IEEE Sensors J.*, vol. 15, no. 2, pp. 1161–1169, Feb. 2015.

[60] Y. C. Chen, W.-H. Hsu, S.-H. Cheng, and Y. T. Cheng, "A power sensor tag with interference reduction for electricity monitoring of two-wire household appliances," *IEEE Trans. Ind. Electron.*, vol. 61, no. 4, pp. 2062–2070, Apr. 2014.

[61] X. Sun, Q. Huang, Y. Hou, L. Jiang, and P. W. T. Pong, "Noncontact operation-state monitoring technology based on magnetic-field sensing for overhead high-voltage transmission lines," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2145–2153, Oct. 2013.

[62] X. Sun *et al.*, "Operation-state monitoring and energization-status identification for underground power cables by magnetic field sensing," *IEEE Sensors J.*, vol. 13, no. 11, pp. 4527–4533, Nov. 2013.

[63] X. Sun, W. K. Lee, Y. Hou, and P. W. T. Pong, "Underground power cable detection and inspection technology based on magnetic field sensing at ground surface level," *IEEE Trans. Magn.*, vol. 50, no. 7, Jul. 2014, Art. no. 6200605.

[64] X. Sun, Q. Huang, L. J. Jiang, and P. W. Pong, "Overhead high-voltage transmission-line current monitoring by magnetoresistive sensors and current source reconstruction at transmission tower," *IEEE Trans. Magn.*, vol. 50, no. 1, Jan. 2014, Art. no. 4000405.

[65] A. H. Khawaja and Q. Huang, "Characteristic estimation of high voltage transmission line conductors with simultaneous magnetic field and current measurements," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, Taipei, Taiwan, May 2016, pp. 1–6.

[66] A. H. Khawaja, Q. Huang, J. Li, and Z. Zhang, "Estimation of current and sag in overhead power transmission lines with optimized magnetic field sensor array placement," *IEEE Trans. Magn.*, vol. 53, no. 5, May 2017, Art. no. 6100210.

[67] G. Zhao, J. Hu, Y. Ouyang, Z. Wang, S. X. Wang, and J. He, "Tunneling magnetoresistive sensors for high-frequency corona discharge location," *IEEE Trans. Magn.*, vol. 52, no. 7, Jul. 2016, Art. no. 4001804.

[68] J. Engelhardt and S. Basu, "Design, installation, and field experience with an overhead transmission dynamic line rating system," in *Proc. IEEE Conf. Trans. Distrib.*, Sep. 1996, pp. 366–370.

[69] J. M. Daughton, "GMR and SDT sensor applications," *IEEE Trans. Magn.*, vol. 36, no. 5, pp. 2773–2778, Sep. 2000.

[70] K.-M. H. Lenssen, D. J. Adelerhof, H. J. Gassen, A. E. T. Kuiper, G. H. J. Somers, and J. B. A. D. van Zon, "Robust giant magnetoresistance sensors," *Sens. Actuators A, Phys.*, vol. 85, nos. 1–3, pp. 1–8, 2000.

[71] P. K. Sarkar and A. K. Jain, *Intelligent Transport Systems*. New Delhi, India: PHI Learning, 2017.

[72] Z. Zhang, M. Tao, and H. Yuan, "A parking occupancy detection algorithm based on AMR sensor," *IEEE Sensors J.*, vol. 15, no. 2, pp. 1261–1269, Feb. 2015.

[73] X. Guan, Z. Zhang, J. Zhou, and F. Yu, "A vehicle detection algorithm based on wireless magnetic sensor networks," in *Proc. 8th Int. Conf. Commun. Netw. China (CHINACOM)*, Guilin, China, Aug. 2013, pp. 669–674.

[74] S. Taghvaeeyan and R. Rajamani, "The development of vehicle position estimation algorithms based on the use of AMR sensors," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1845–1854, Dec. 2012.

[75] H. Zhu and F. Yu, "A cross-correlation technique for vehicle detections in wireless magnetic sensor network," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4484–4494, Jun. 2016.

[76] A. Haoui, R. Kavaler, and P. Varaiya, "Wireless magnetic sensors for traffic surveillance," *Transp. Res. C, Emerg. Technol.*, vol. 16, pp. 294–306, Jun. 2008.

[77] S. Marshall, "Vehicle detection using a magnetic field sensor," *IEEE Trans. Veh. Technol.*, vol. VT-27, no. 2, pp. 65–68, May 1978.

[78] S. Taghvaeeyan and R. Rajamani, "Portable roadside sensors for vehicle counting, classification, and speed measurement," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 73–83, Feb. 2014.

[79] B. Yang and Y. Lei, "Vehicle detection and classification for low-speed congested traffic with anisotropic magnetoresistive sensor," *IEEE Sensors J.*, vol. 15, no. 2, pp. 1132–1138, Feb. 2015.

[80] M. J. Caruso and L. S. Withanawasam, "Vehicle detection and compass applications using AMR magnetic sensors," *Sensors Expo Proc.*, vol. 499, pp. 477–489, May 1999.

[81] Y. Bo and N. Wenbin, "Vehicle detection and classification algorithm based on anisotropic magnetoresistive sensor," *Chin J. Sci. Instrum.*, vol. 34, no. 3, pp. 537–544, 2013.

[82] V. Markevicius, D. Navikas, M. Zilys, D. Andriukaitis, A. Valinevicius, and M. Cepenas, "Dynamic vehicle detection via the use of magnetic field sensors," *Sensors*, vol. 16, no. 1, p. 78, 2016.

[83] S. Cheung, S. Coleri, B. Dundar, S. Ganesh, C.-W. Tan, and P. Varaiya, "Traffic measurement and vehicle classification with single magnetic sensor," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1917, pp. 173–181, Jan. 2005.

[84] W. Balid, H. Tafish, and H. H. Refai, "Intelligent vehicle counting and classification sensor for real-time traffic surveillance," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 6, pp. 1784–1794, Jun. 2018.

[85] S. Kaewkamnerd, R. Pongthornseri, J. Chinrungrueng, and T. Silawan, "Automatic vehicle classification using wireless magnetic sensor," in *Proc. 5th IEEE Int. Workshop Intell. Data Acquisition Adv. Comput. Syst., Technol. Appl. (IDAACS)*, Berlin, Germany, Sep. 2009, pp. 420–424.

[86] H. Dong, X. Wang, C. Zhang, R. He, L. Jia, and Y. Qin, "Improved robust vehicle detection and identification based on single magnetic sensor," *IEEE Access*, vol. 6, pp. 5247–5255, 2018.

[87] M. Sakthivel, B. George, and M. Sivaprakasam, "A novel GMR-based eddy current sensing probe with extended sensing range," *IEEE Trans. Magn.*, vol. 52, no. 4, Apr. 2016, Art. no. 4000512.

[88] L. Li, K. Y. Mak, C. W. Leung, S. M. Ng, Z. Q. Lei, and P. W. T. Pong, "Detection of 10-nm superparamagnetic iron oxide nanoparticles using exchange-biased GMR sensors in Wheatstone bridge," *IEEE Trans. Magn.*, vol. 49, no. 7, pp. 4056–4059, Jul. 2013.

[89] D. L. Graham, H. A. Ferreira, and P. P. Freitas, "Magnetoresistive-based biosensors and biochips," *Trends Biotechnol.*, vol. 22, pp. 455–462, Sep. 2004.

[90] W. Wang, Y. Wang, L. Tu, Y. Feng, T. Klein, and J.-P. Wang, "Magnetoresistive performance and comparison of supermagnetic nanoparticles on giant magnetoresistive sensor-based detection system," *Sci. Rep.*, vol. 4, p. 5716, Jul. 2014.

[91] J. Germano *et al.*, "A portable and autonomous magnetic detection platform for biosensing," *Sensors*, vol. 9, no. 6, pp. 4119–4137, 2009.

[92] J. Choi, A. W. Gani, D. J. Bechstein, J. R. Lee, P. J. Utz, and S. X. Wang, "Portable, one-step, and rapid GMR biosensor platform with smartphone interface," *Biosen. Bioelectron.*, vol. 85, pp. 1–7, Nov. 2016.

[93] W. Shen, B. D. Schrag, M. J. Carter, and G. Xiao, "Detection of DNA labeled with magnetic nanoparticles using arrays of MgO-based magnetic tunnel junction sensors," *J. Appl. Phys.*, vol. 103, no. 7, p. 07A306, 2008.

[94] L. Xu *et al.*, "Giant magnetoresistive biochip for DNA detection and HPV genotyping," *Biosensors Bioelectron.*, vol. 24, no. 1, pp. 99–103, 2008.

[95] X. Sun, D. Ho, L. M. Lacroix, J. Q. Xiao, and S. Sun, "Magnetic nanoparticles for magnetoresistance-based biodetection," *IEEE Trans. Nanobiosci.*, vol. 11, no. 1, pp. 46–53, Mar. 2012.

[96] S. X. Wang and G. Li, "Advances in giant magnetoresistance biosensors with magnetic nanoparticle tags: Review and outlook," *IEEE Trans. Magn.*, vol. 44, no. 7, pp. 1687–1702, Jul. 2008.

[97] M. Colombo *et al.*, "Biological applications of magnetic nanoparticles," *Chem. Soc. Rev.*, vol. 41, no. 11, pp. 4306–4334, 2012.

[98] I. Koh and L. Josephson, "Magnetic nanoparticle sensors," *Sensors*, vol. 9, pp. 8130–8145, Oct. 2009.

[99] K. N. Vyas, B. Hong, J. F. K. Cooper, J. J. Palfreyman, and C. H. W. Barnes, "Detection of magnetically labelled microcarriers for suspension based bioassay technologies," *IEEE Trans. Magn.*, vol. 47, no. 6, pp. 1571–1574, Jun. 2011.

[100] F. Cardoso *et al.*, "Integration of magnetoresistive biochips on a CMOS circuit," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 3784–3787, Nov. 2012.

[101] R. Gaster *et al.*, "Matrix-insensitive protein assays push the limits of biosensors in medicine," *Nature Med.*, vol. 15, no. 11, pp. 1327–1332, 2009.

[102] S. J. Osterfeld *et al.*, "Multiplex protein assays based on real-time magnetic nanotag sensing," *Proc. Natl. Acad. Sci. USA*, vol. 105, no. 52, pp. 20637–20640, 2008.

[103] R. S. Gaster, D. A. Hall, and S. X. Wang, "nanoLAB: An ultraportable, handheld diagnostic laboratory for global health," *Lab Chip*, vol. 11, no. 5, pp. 950–956, 2011.

[104] K. Ashton, "That 'Internet of Things' thing," *RFiD J.*, vol. 22, no. 7, pp. 97–114, 2009.

[105] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[106] A. Whitmore, A. Agarwal, and L. Da Xu, "The Internet of Things—A survey of topics and trends," *Inf. Syst. Frontiers*, vol. 17, no. 2, pp. 261–274, 2015.

[107] M. Wu, T.-L. Lu, F.-Y. Ling, L. Sun, and H.-Y. Du, "Research on the architecture of Internet of Things," in *Proc. 3rd Int. Conf. Adv. Comput. Theory Eng. (ICACTE)*, Chengdu, China, vol. 5, pp. 484–487, Aug. 2010.

[108] Z. Yang, Y. Peng, Y. Yue, X. Wang, Y. Yang, and W. Liu, "Study and application on the architecture and key technologies for IoT," in *Proc. Int. Conf. Multimedia Technol. (ICMT)*, Hangzhou, China, Jul. 2011, pp. 747–751.

[109] L. Tan and N. Wang, "Future Internet: The Internet of Things," in *Proc. 3rd Int. Conf. Adv. Comput. Theory Eng. (ICACTE)*, Chengdu, China, vol. 5, pp. 376–380, Aug. 2010.

[110] R. Khan, S. U. Khan, R. Zaheer, and S. Khan, "Future Internet: The Internet of Things architecture, possible applications and key challenges," in *Proc. 10th Int. Conf. FIT*, Islamabad, Pakistan, Dec. 2012, pp. 257–260.

[111] G. P. Hancke, B. de Carvalho e Silva, and G. P. Hancke, "The role of advanced sensing in smart cities," *Sensors*, vol. 13, no. 1, pp. 393–425, 2012.

[112] V. C. Gungor *et al.*, "A survey on smart grid potential applications and communication requirements," *IEEE Trans. Ind. Informat.*, vol. 9, no. 1, pp. 28–42, Feb. 2013.

[113] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Generat. Comput. Syst.*, vol. 29, no. 7, pp. 1645–1660, 2013.

[114] L. Da Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[115] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002.

[116] J. Han, J. Hu, Y. Yang, Z. Wang, S. X. Wang, and J. He, "A nonintrusive power supply design for self-powered sensor networks in the smart grid by scavenging energy from AC power line," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4398–4407, Jul. 2015.

[117] D. Porcarelli, D. Balsamo, D. Brunelli, and G. Paci, "Perpetual and low-cost power meter for monitoring residential and industrial appliances," in *Proc. Design, Automat. Test Eur. Conf. Exhib. (DATE)*, Mar. 2013, pp. 1155–1160.

[118] L. Li and J. Y. Halpern, "Minimum-energy mobile wireless networks revisited," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Helsinki, Finland, Jun. 2001, pp. 278–283.

[119] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Netw.*, vol. 7, no. 3, pp. 537–568, May 2009.

[120] C. De Capua, G. Lipari, M. Lugarà, and R. Morello, "A smart energy meter for power grids," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, Auckland, New Zealand, May 1019, pp. 878–883.

[121] S. W. Luan, J. H. Teng, S. Y. Chan, and L. C. Hwang, "Development of an automatic reliability calculation system for advanced metering infrastructure," in *Proc. 8th IEEE Int. Conf. Ind. Inform. (INDIN)*, Osaka, Japan, Jul. 2010, pp. 342–347.

[122] V. C. Martins *et al.*, "Challenges and trends in the development of a magnetoresistive biochip portable platform," *J. Magn. Magn. Mater.*, vol. 322, nos. 9–12, pp. 1655–1663, 2010.

[123] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 6–28, Dec. 2004.

[124] B. Resch, M. Mittlboeck, and M. Lippautz, "Pervasive monitoring—An intelligent sensor pod approach for standardised measurement infrastructures," *Sensors*, vol. 10, no. 12, pp. 11440–11467, 2010.

[125] F. Lobo, A. Cabello, A. Lopez, D. Mora, and R. Mora, "Distribution network as communication system," in *Proc. Seminar SmartGrids Distrib. (CIRED)*, Frankfurt, Germany, Jun. 2008, pp. 1–4.

[126] A. Pascale, M. Nicoli, F. Deflorio, B. D. Chiara, and U. Spagnolini, "Wireless sensor networks for traffic management and road safety," *IET Intell. Transp. Syst.*, vol. 6, no. 1, pp. 67–77, Mar. 2012.

[127] R. Moghe, Y. Yang, F. Lambert, and D. Divan, "A scoping study of electric and magnetic field energy harvesting for wireless sensor networks in power system applications," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, San Jose, CA, USA, Sep. 2009, pp. 3550–3557.

[128] R. Moghe, F. C. Lambert, and D. Divan, "Smart 'stick-on' sensors for the smart grid," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 241–252, Mar. 2012.

[129] T. Hosseinimehr and A. Tabesh, "Magnetic field energy harvesting from AC lines for powering wireless sensor nodes in smart grids," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 4947–4954, Aug. 2016.

[130] S. Yuan, Y. Huang, J. Zhou, Q. Xu, C. Song, and P. Thompson, "Magnetic field energy harvesting under overhead power lines," *IEEE Trans. Power Electron.*, vol. 30, no. 11, pp. 6191–6202, Nov. 2015.

[131] Z. Wang, J. Hu, J. Han, G. Zhao, J. He, and S. X. Wang, "A novel high-performance energy harvester based on nonlinear resonance for scavenging power-frequency magnetic energy," *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6556–6564, Aug. 2017.

[132] S. C. Ergen and P. Varaiya, "PEDAMACS: Power efficient and delay aware medium access protocol for sensor networks," *IEEE Trans. Mobile Comput.*, vol. 5, no. 7, pp. 920–930, Jul. 2006.

[133] V. C. Gungor *et al.*, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 529–539, Nov. 2011.

[134] K. Dar, M. Bakhouya, J. Gaber, M. Wack, and P. Lorenz, "Wireless communication technologies for ITS applications," *IEEE Commun. Mag.*, vol. 48, no. 5, pp. 156–162, May 2010.

[135] S. Djahel, R. Doolan, G.-M. Muntean, and J. Murphy, "A communications-oriented perspective on traffic management systems for smart cities: Challenges and innovative approaches," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 125–151, Mar. 2015.

[136] A. Carta, N. Locci, C. Muscas, and S. Sulis, "A flexible GPS-based system for synchronized phasor measurement in electric distribution networks," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 11, pp. 2450–2456, Nov. 2008.

[137] A. Milenković, C. Otto, and E. Jovanov, "Wireless sensor networks for personal health monitoring: Issues and an implementation," *Comput. Commun.*, vol. 29, pp. 2521–2533, Aug. 2006.

[138] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi, "The flooding time synchronization protocol," in *Proc. 2nd Int. Conf. Embedded Netw. sensor Syst.*, 2004, pp. 39–49.

[139] X. Jiang, M. Van Ly, J. Taneja, P. Dutta, and D. Culler, "Experiences with a high-fidelity wireless building energy auditing network," in *Proc. 7th ACM Conf. Embedded Networked Sensor Syst.*, 2009, pp. 113–126.

[140] G. Geng, J. Wang, K.-L. Chen, and W. Xu, "Contactless current measurement for enclosed multiconductor systems based on sensor array," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 10, pp. 2627–2637, Oct. 2017.

[141] D. Lawrence, J. S. Donnal, and S. Leeb, "Current and voltage reconstruction from non-contact field measurements," *IEEE Sensors J.*, vol. 16, no. 15, pp. 6095–6103, Aug. 2016.

[142] S. Witsell, J. Hammer, S. Seshagiri, and Y. Ozturk, "A magnetoresistive sensor array for nonintrusive power consumption monitoring," in *Proc. 6th Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, San Diego, CA, USA, Dec. 2017, pp. 1226–1230.

[143] D. R. Muñoz, J. S. Moreno, S. C. Berga, and A. N. Antón, "Active power analog front-end based on a Wheatstone-type magnetoresistive sensor," *Sens. Actuators A, Phys.*, vol. 169, no. 1, pp. 83–88, 2011.

[144] E. G. Vidal *et al.*, "Electronic energy meter based on a tunnel magnetoresistive effect (TMR) current sensor," *Materials*, vol. 10, no. 10, p. 1134, 2017.

[145] M. Vopálenský, A. Platil, and P. Kašpar, "Wattmeter with AMR sensor," *Sens. Actuators A, Phys.*, vols. 123–124, pp. 303–307, Sep. 2005.

[146] A. Roldán *et al.*, "Analytical compact modeling of GMR based current sensors: Application to power measurement at the IC level," *Solid-State Electron.*, vol. 54, no. 12, pp. 1606–1612, 2010.

[147] L. Schor, P. Sommer, and R. Wattenhofer, "Towards a zero-configuration wireless sensor network architecture for smart buildings," in *Proc. 2st ACM Workshop Embedded Sens. Syst. Energy-Efficiency Buildings*, 2009, pp. 31–36.

[148] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE Trans. Ind. Informat.*, vol. 7, no. 3, pp. 381–388, Aug. 2011.

[149] S. R. Arias, D. R. Muñoz, J. S. Moreno, S. Cardoso, and P. Freitas, "A tunnel magnetoresistive effect wattmeters-based wireless sensors network," *Sens. Actuators A, Phys.*, vol. 264, pp. 224–233, Sep. 2017.

[150] P. Gao, S. Lin, and W. Xu, "A novel current sensor for home energy use monitoring," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 2021–2028, Jul. 2014.

[151] D. He, W. Lin, N. Liu, R. G. Harley, and T. G. Habetler, "Incorporating non-intrusive load monitoring into building level demand response," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1870–1877, Dec. 2013.

[152] S. Talari, M. Shafie-Khah, P. Siano, V. Loia, A. Tommasetti, and J. P. S. Catalão, "A review of smart cities based on the Internet of Things concept," *Energies*, vol. 10, no. 4, p. 421, 2017.

[153] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, "A survey on smart grid communication infrastructures: Motivations, requirements and challenges," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 5–20, 1st Quart., 2013.

[154] Y. Liu, G. Geng, S. Gao, and W. Xu, "Non-intrusive energy use monitoring for a group of electrical appliances," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3801–3810, Dec. 2018.

[155] C. Sun *et al.*, "Self-contained wireless Hall current sensor applied for two-wire zip-cords," *IEEE Trans. Magn.*, vol. 52, no. 7, Jul. 2016, Art. no. 8600204.

[156] A. H. Khawaja and Q. Huang, "Estimating sag and wind-induced motion of overhead power lines with current and magnetic-flux density measurements," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 5, pp. 897–909, May 2017.

[157] I. Kamwa, S. Samantaray, and G. Joos, "Optimal integration of disparate C37.118 PMUs in wide-area PSS with electromagnetic transients," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4760–4770, Nov. 2013.

[158] R. Morello, S. C. Mukhopadhyay, Z. Liu, D. Slomovitz, and S. R. Samantaray, "Advances on sensing technologies for smart cities and power grids: A review," *IEEE Sensors J.*, vol. 17, no. 23, pp. 7596–7610, Dec. 2017.

[159] A. H. Khawaja, Q. Huang, and Z. H. Khan, "Monitoring of overhead transmission lines: A review from the perspective of contactless technologies," *Sens. Imag.*, vol. 18, no. 1, pp. 18–24, Dec. 2017.

[160] B. Alphenaar, "Wireless sensor network for electric transmission line monitoring," Univ. Louisville, Louisville, KY, USA, Tech. Rep. DE-FC26-06NT42795, 2010.

[161] A. Grilo *et al.*, "A wireless sensors suite for smart grid applications," in *Proc. 1st Int. Workshop Inf. Technol. Energy Appl.*, Lisbon, Portugal, Sep. 2012, pp. 1–10.

[162] V. C. Gungor, B. Lu, and G. P. Hancke, "Opportunities and challenges of wireless sensor networks in smart grid," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3557–3564, Oct. 2010.

[163] V. C. Gungor and G. P. Hancke, "Industrial wireless sensor networks: Challenges, design principles, and technical approaches," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4258–4265, Oct. 2009.

[164] C. Eris, M. Saimler, V. C. Gungor, E. Fadel, and I. F. Akyildiz, "Lifetime analysis of wireless sensor nodes in different smart grid environments," *Wirel. Netw.*, vol. 20, no. 7, pp. 2053–2062, 2014.

[165] M. Tubaishat, Y. Shang, and H. Shi, "Adaptive traffic light control with wireless sensor networks," in *Proc. 4th IEEE Consum. Commun. Netw. Conf.*, Las Vegas, NV, USA, Jan. 2007, pp. 187–191.

[166] K. Kwong, R. Kavaler, R. Rajagopal, and P. Varaiya, "Arterial travel time estimation based on vehicle re-identification using wireless magnetic sensors," *Transp. Res. C, Emerg. Technol.*, vol. 17, no. 6, pp. 586–606, 2009.

[167] T. Thomas and E. C. V. Berkum, "Detection of incidents and events in urban networks," *IET Intell. Transp. Syst.*, vol. 3, no. 2, pp. 198–205, Jun. 2009.

[168] C. Roncoli, M. Papageorgiou, and I. Papamichail, "Traffic flow optimisation in presence of vehicle automation and communication systems—Part II: Optimal control for multi-lane motorways," *Transp. Res. C, Emerg. Technol.*, vol. 57, pp. 260–275, Sep. 2015.

[169] A. Bielsa, "Smart city project in santander to monitor parking free slots," Libelium, Zaragoza, Spain, Appl. Note, Feb. 2013. [Online]. Available: http://www.libelium.com/smart_santander_parking_smart_city/

[170] Z. Lei, F. Leung, C. Hau, K. Lui, W. Szeto, and P. W. Pong, "Green transport system: A technology demonstration of adaptive road lighting with giant magnetoresistive sensor network for energy efficiency and reducing light pollution," *Appl. Mech. Mater.*, vols. 284–287, pp. 2385–2390, Jan. 2013.