FOCUSED ISSUE FEATURE

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Handheld Computers

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A smartphone is a mobile phone built on a mobile operating system with more advanced computing capability and connectivity than regular or conventional cell phones have [1]. Driven by increasing demands, they have become more popular in our daily life; there are already more than 1.08 billion smartphones around the world [2] and smartphone sales continues to grow. According to a press release by Gartner Inc., worldwide smartphone sales to end users reached 225 million units in the second quarter of 2013 and, for the first time, smartphones account for the majority of global cellphone shipments [3]. In particular, smartphones with Google's Android mobile operating system and Apple's iOS hold more than 93% of the market share [3].

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Smartphones have the following general features:

- They have good processors and data input/output interfaces. Many are now equipped with quad-core processors of over 1 GHz and sophisticated graphics processing units. They also have an operating system capable of running third-party general-purpose applications with a QWERTY keyboard on touchscreen and likely a relatively large high-resolution screen, making it possible to perform many of the computing tasks that were previously executed only on personal computers (PCs).
- They are often built with different kinds of sensors, such as commonly seen global positioning system (GPS), accelerometer, gyroscope, compass, cameras, light sensors, magnetometer, and so on. With the quickly advancing technology in hardware, there is no doubt that this collection of sensors will only become richer and provide more functions, data, and information. These built-in sensors open up the possibility of many new and interesting applications that make smartphones multiuse sensing platforms.
- They have the ability to connect to several different networks. For example, they commonly have built-in high-speed wireless communication capabilities such as third- or fourth-generation (3G/4G), long-term evolution (LTE) or Wi-Fi for Internet access and Bluetooth for short-distance or near-field communications (NFCs) for devices interconnection. With the possibility of connecting to the Internet and other devices, smartphones provide connectivity and communications anywhere and anytime.

In short, smartphones provide mobility combined with considerable computing and sensing power as well as a wide range of communication capabilities. As a result, many impressive, convenient, and useful applications have been or are being developed for smartphones in addition to just voice communications.

First, benefiting from smartphone hardware improvement, many traditional PC applications can be implemented on smartphones. Music and video entertainment, e-mail, Web browsing, and social networking such as Facebook and Skype are widely used with smartphones. Moreover, in comparison with PCs, smartphones provide a wider range of networking ability and are usually cheaper, have smaller sizes, and are easy to carry and use. They have become more popular with people around the world. In the places where computers and Internet access are too much of a luxury for common people, smartphones have become the popular replacements. Therefore, the increased popularity and general availability make smartphones a valuable platform for developing creative and useful applications.

Second, the rich built-in sensors as well as the portability of smartphones has given birth to many new impressive, convenient, and more applications that are difficult to implement or to be used easily in a PC. For example, with the help of the embedded GPS sensor, a smartphone can realize navigation by installing applications like Google Maps. In comparison with a dedicated navigation device, the smartphone navigation has the advantage of perpetual connection to the Internet, which makes it possible to implement sophisticated functions like real-time traffic detection and avoidance.

Smartphones can be considered powerful information, sensing, and computing platforms with accessibility and connectivity anywhere and anytime. With them arises many innovative and useful applications.

Smartphone-Centric Applications

Figure 1 shows a typical system architecture of a smartphone-centric wireless application. The accessibility, portability, and connectivity with a smartphone's easy-to-use input and output (I/O) interface present considerable sensing and computing power that allows a connection between the physical world we live in and the virtual world of information, making a smartphone the center or hub of a variety of applications.

In those applications, information around the smartphone are acquired by built-in or/and additional external sensors and sent to the smartphone via Bluetooth, Zigbee, and other wireless and wireline link technologies. Then the collected information or data are processed and analyzed by the smartphone. Also, depending on the application, they may be further sent to a cloud server via the Internet and updated and processed there. Finally, sensing results can be made available for browsing with a smartphone or other network terminals, and, if needed, control commands can also sent from the smartphones to other equipment in the physical world.

With the above architecture and ever increasingly advanced sensors [4], applications as shown in Figure 2 have been or can be developed across a wide variety of

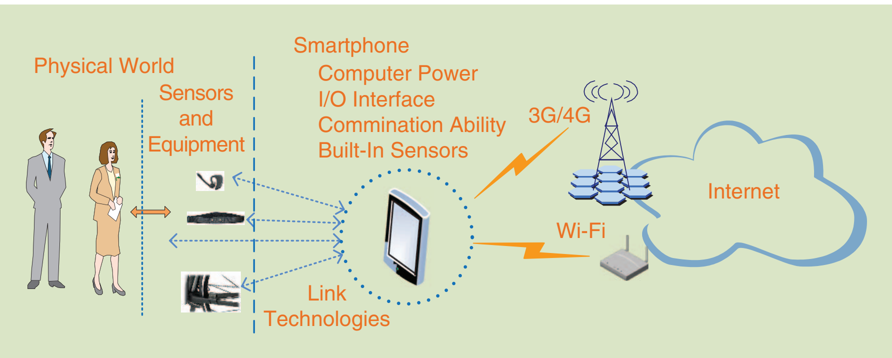

Figure 1. *A typical system architecture of smartphone-centric applications.*

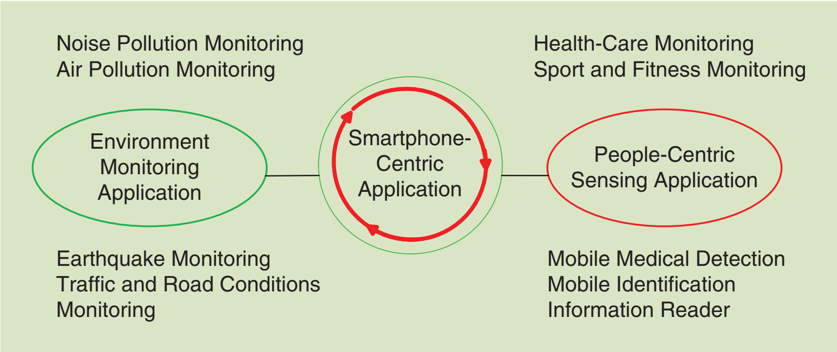

Figure 2. *Categories of smartphone-centric wireless applications.*

domains: they are divided into two general categories: participatory sensing-based environment monitoring applications and people-centric sensing applications.

Participatory Sensing-Based Environment Monitoring Applications

The ubiquity of smartphones and high density of people in metropolitan areas have paved the way for participatory sensing, which provides an exciting new paradigm for accomplishing large-scale sensing in urban areas [5]. The participatory sensing empowers participants to collect and share sensed data from their surrounding environments using their smartphones, which makes a promising technology for interesting applications. In a typical participatory sensing-based environment monitoring application, as shown in Figure 3, data are collected by sensors of participating smartphones and transmitted via smartphones' communications units to a central server for processing; then the central server analyzes the data and makes it available to authorized smartphones [5]. For example, price dispersion applications such as MobiShop [6] facilitates sharing of product pricing information among consumers. The products, prices, purchase available times and locations as well as the GPS coordinates of participating consumers (or users) are all uploaded to a central server. The server collates the information it gathers and maintains an updated repository of product prices at different stores. This database is interfaced to a global information system (GIS) street map populated with store locations. Once a user requests the price of a particular product, the server replies back with a list of the stores featuring this product along with their prices in the vicinity of the user.

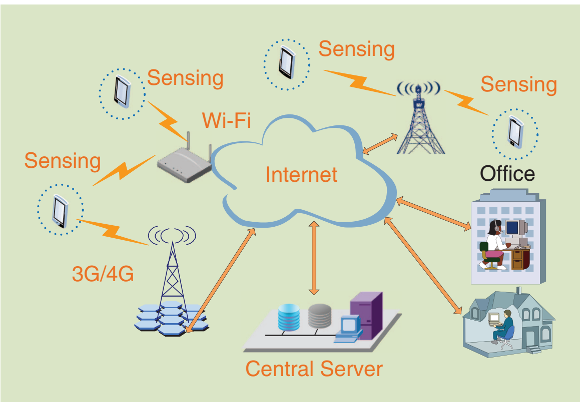

Figure 3. *The system architecture of a participatory sensing-based environment monitoring application.*

Noise Pollution Monitoring

Mobile phones and their built-in microphones can be exploited to measure the surrounding noise level and create noise maps. The noise map can then be used to visualize differences in noise levels of different areas. For an urban noise mapping system such as Earphone [7] and Laermometer [8], the basic idea is to crowd-source the collection of environmental data in urban spaces to people who carry smartphones equipped with sensors and location-providing GPS sensors [4]. Typically, a noise mapping system consists of a mobile phone and a central server. Noise levels are assessed on the mobile phones before being transmitted to the central server. The central server reconstructs the noise map based on the partial noise measurements and makes it accessible for the public or specialists [4].

Air Pollution Monitoring

Monitoring air pollution in an urban environment using smartphones has gained a lot of interest in recent years [4]. Unfortunately, built-in gas sensors are not available for smartphones. Therefore, external pollution sensors are required and connected to the smartphone for measuring air pollution and creating air pollution maps. As described in [5], Haze Watch developed a mobile air pollution sensor that can be attached to motor vehicles and used for measuring the concentration of carbon monoxides, ozone, sulphur dioxide, and nitrogen dioxide in the air. Using Bluetooth, the measured data will then be sent to an iPhone where both time and GPS coordinates are recorded and sent to a server that aggregates readings of all participants, builds a map, and makes it accessible to the public.

Instead of using Bluetooth or other wireless link technology, the external gas sensor presented in GasMobile [9] is directly connected to an HTC smartphone via cable with a USB mini-B port and a TS232-TTL interface.

In comparison to the measurements by meteorological stations that use more sophisticated testing equipment, smartphones may collect less accurate measurements. However, their inherent mobility allows observation of unpredictable events (e.g., accidental pollution), which cannot be detected by static stations. In addition, the smartphone system provides a larger spatial coverage. They can thus complement static high-fidelity data captured by traditional meteorological stations by providing finer-grained readings [5].

Earthquake Monitoring

The smartphone can be exploited to monitor earthquakes. The iShake [10] is a mobile client-back-end server architecture system that uses sensor-equipped mobile devices to measure earthquake groundshaking and process the data collected by a smartphone on a back-end server. The iShake system was created to take advantage of new seismic sensing capabilities offered by the GPS, accelerometer, and magnetometer on the smartphones. A client application for the iPhone was developed as the means of sensing ground motion activity. After a potential earthquake event is sensed, the data measured by the client application are streamed rapidly to the back-end servers, where raw data can be properly processed and aggregated with other client data. Then, summary data from the event can be immediately provided to emergency workers (as well to the general public) to aid in rescue missions [10].

As shown in [10], the iShake system allows anyone with an iPhone or iPod Touch device to participate in seismic sensing, which provides scientific communities and emergency responders with a dense array of ground motion data rapidly after an event. The system comes with an assurance of quantitative accuracy previously unattainable from crowd-sourced earthquake data.

Traffic and Road Conditions Monitoring

In order to reduce the time people spend in traffic, a system named VTrack [11] was developed for travel time estimation using GPS, Wi-Fi, and/or cellular triangulation sensor data from smartphones. In the VTrack system, users with smartphones run an application that reports position data to a central server periodically while driving. The server runs a travel-time estimation algorithm that uses these noisy position samples to identify the road segments on which a user is driving and estimates the travel time on these segments. The estimates are then used to identify hotspots and provide real-time route planning updates.

Smartphones can also be used to monitor road and traffic conditions. Nericell [12] is a system exploiting Windows Mobile OS-powered smartphones as a development platform. In Nericell, built-in microphones and GPS as well as external accelerometer sensors are used to detect and localize traffic conditions and road conditions such as potholes, bumps, or braking and honking. The information is then integrated to assess and mark road surface roughness, surrounding noises, and traffic conditions on maps that are available to the public [5].

People-Centric Sensing Applications

In addition to serving as a participatory sensing node for environment monitoring as described above, smartphones have also given rise to many people-centric sensing applications that focus on collecting sensor data about users through their smartphones. With the help of various built-in or external sensors, smartphones can provide numerous online or offline people-centric applications. For example, by tracking the user's eye movement with the front camera of a smartphone, an interfacing system named EyePhone [13] was developed, which is capable of driving mobile applications/functions by sensing the user's eyes movements.

Health-Care Monitoring

Smartphones can play an important role in health-care monitoring applications, particularly in safeguarding the lives of elderly, disabled, and chronically ill people. For example, the smartphone-based remote health surveillance and management is considered a promising technology for ubiquitous health care, which means health care anywhere and anytime. The pervasive sensing and computing ability provided by smartphones enables medical professionals to remotely perform real-time monitoring, early diagnosis, and treatment for potential diseases.

Figure 4 illustrates a ubiquitous personal health surveillance and management system (UPHSM); it was designed for remote health care and management. UPHSM can aid elderly persons and patients who need long-term attention to their illness, like chronic diseases, with ubiquitous surveillance and remote management of the recorded health data [14]. Smartphones act as an application-layer gateway (ALG) in the system for sensor gadgets. Sensor gadgets are attached to a patient's body and data collected by the sensors are sent, via ZigBee protocol, to a nearby smartphone that is attached and connected with an external ZigBee receiver. The smartphone then transmits the data to a remote server containing a health database through an Internet connection via either 2.5G/3.5G or Wi-Fi

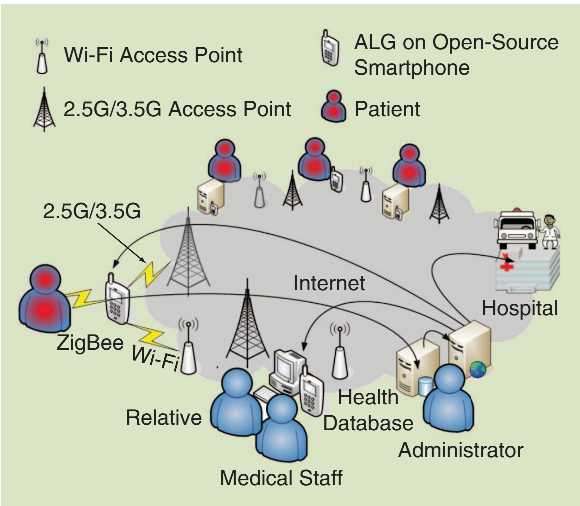

Figure 4. *The structure of the ubiquitous personal health surveillance and management system [14].*

wireless channel. The server stores the data, which can be viewed or obtained by remote authenticated users for later queries. For example, authorized medical staff can actively check in the database to see the specific patient's health condition. Moreover, a program can be made for a server to automatically and continually monitor and detect a specific patient's severe condition. If a patient's health condition is severe, a short message with the patient's concise health information including his/her GPS position will be immediately sent to the patient's relatives and hospitals for immediate attention. In such a way, ambulance corps and medical staff can treat a patient promptly and properly. At all times, the patients and their relatives, medical staff, and authorized administrators can remotely access, review, and manage the stored health-related data [14].

In [15], a real-time sleep apnea monitor is developed, which exploits a wireless smartphone to realize a cost-effective platform for electrocardiograph (ECG) acquisition, monitoring, and real-time screening and assessment of sleep apnea syndrome. In the monitor, one lead ECG sensor is used for recording heart activity; the measured ECG signal data are collected by a smartphone via Bluetooth from the sensor. As the data are collected, obstructive sleep apnea (OSA) assessment can be performed in real time on the smartphone, and the assessment results are sent over to a cloud server via Wi-Fi or cellular 3G networks for further actions and processing. In such a way, a smartphone provides a reliable, inexpensive, and fast approach to assessing OSA of the patients before, during, and after medical treatments.

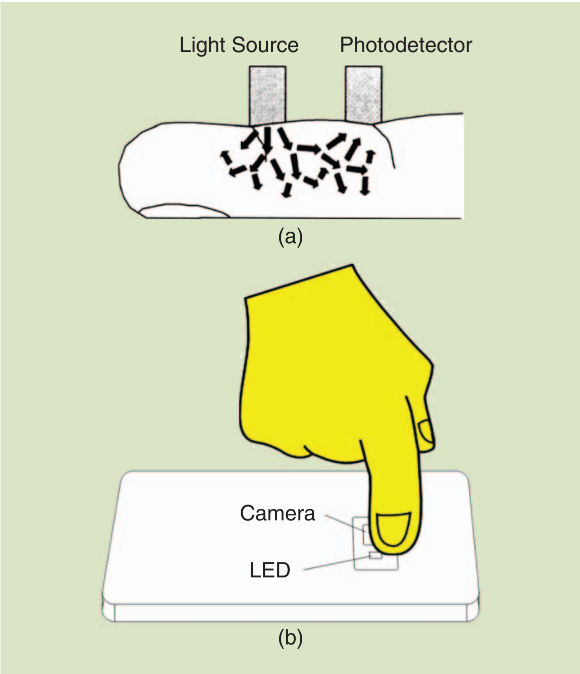

Figure 5. *The PPG acquistion scheme based on smartphones [19]. (a) The reflection mode for video acquisition. (b) The scheme to acquire video.*

In [16], the Health Guard system based on smartphones is presented for safeguarding the lives of the patients and the elderly, especially those who are staying alone without immediate assistance. Benefited from the powerful sensing, computing, and connectivity abilities provided by a smartphone, the system has incorporated important features, including location-based service, automatic falling detection with false alarm cancellation system and is built on cloud computing. The Health Guard system detects the stumbling or the crash sensed by the smartphone using the built-in accelerometer and triggers the automatic falling detection system. The smartphone will then judge whether the phone carrier or user is in a perilous position. Meanwhile, the predefined contact persons will be alerted by a message sent from the system. Assisted by the smartphone's internal GPS, useful information including location of the user and the route that can enable reaching the user in danger will be sent to the attending personnel.

Sports and Fitness Monitoring

Currently, a number of smartphone-based applications and devices for physical activities are available. For example, some smartphone applications utilize on-board GPS and an accelerometer for user motion detection. They are smart enough to track jogging/biking routes, workout data, and comprehensive workout history; to select and control music; to geo-tag photos along your routes; and to share information with friends and family via the Internet [17]. Smartphone systems can take advantage of the high accuracy of external mounted sensors to provide more functions such as a heart rate monitor or cadence meter for bikes, etc. [18].

In [17], a wearable digital fitness connector (DFC) is designed to capture, store, and stream data from health and fitness sensors and to send them to smartphones. The DFC can act as a pedometer and/or as a hub for the third-party fitness sensors. By using ANT+ wireless technology for sensing data collection and Bluetooth for smartphone connection, the DFC allows users to pick up from 80 ANT+ health and fitness sensors to track heart rate, speed, cadence, distance, pace, power, and other motion parameters.

Mobile Medical Device

The third emerging application is oriented toward mobile detection devices. In this scenario, smartphones may become a nexus of modular peripherals, where the peripherals that are plugged into a smartphone uses the computing power of the smartphone or even its power source to run the peripherals. Some representative applications are presented as follows.

In [19], an approach to detect the photoplethysmogram (PPG) signal from a fingertip using a smartphone's camera and built-in LED is proposed. The PPG is an optically obtained plethysmogram, which is often obtained by using a pulse oximeter that illuminates skin and measures changes in light absorption. As shown in Figure 5, a user's finger should be placed on the smartphone's camera in the way that the finger covers both the camera and the LED. The light emitted from the LED passes through the finger and the camera records the changes in the illumination. The volumetric change of blood in the finger changes the light absorption and, therefore, the detected change can be used to compute the PPG.

Because blood flow to the skin can be modulated by multiple physiological systems, the PPG can also be used to monitor breathing, hypovolemia, and other circulatory conditions [20]. Much research is also moving toward the development of apps that can extract possible vital signs from PPG [21]. For example, during a systolic pulse when the capillaries are rich in the blood, more light was absorbed by the blood, leading to a low-reflective index and darker frame intensities. Likewise, during a diastolic pulse, most of the light is reflected, leading to bright frames. The change in intensity of light passed through the finger creating an alternative pattern of waves. These changes in intensity with time were used to obtain the pulse of a person. [22] Accordingly, an easy-to-use, portable heart rate meter can be developed based on a smartphone by acquiring PPG [22]–[24].

To measure the saturation of oxygen in the blood, the PPG sensor has to light with two different wavelengths. It then acquires the measures of blood oxygenation by comparing the different absorption at two different wavelengths [25]. In [24], a smart wrist-worn device with two infrared LEDs is developed that enables the measurement of the blood oxygen level (SpO_2 values) and sends it to a smartphone by Bluetooth.

To measure blood pressure, [22] presents a new application of a smartphone with its built-in camera and microphone to replace the traditional stethoscope and cuff-based measurement technique. In addition to acquiring a PPG signal of a patient, the heartbeat sounds are recorded simultaneously by using another smartphone or an external microphone, as shown in Figure 6(a) and (b), respectively. By combining the preprocessed heartbeat and finger pulse signals, systolic and diastolic pressure values can be calculated.

Smartphones can also realize portable multifunction diagnostics by connecting various other types of peripherals. In [21], a portable ultrasonic system is introduced by a medical equipment company named Mobisante. As shown in Figure 7, it has a smartphone and an ultrasonic transducer that is plugged into the phone via a USB port. It provides a low-cost, portable, and easy-to-use ultrasonic device for point-of-care diagnostics.

An implementation of a smartphone-based portable ultrasonic pulsed-wave (PW) Doppler flowmeter for blood flow measurement is presented in [26]. As shown in Figure 8, it consists of three parts: a surface transducer that is attached to the skin for transmitting and receiving ultrasound signals for real-time measurement of blood flow velocity, an analog circuit that is used to obtain audio Doppler shift signals, and a smartphone that is employed to digitize and process the audio Doppler signals transmitted via its microphone jack. The measured results can be stored on a built-in memory card as well as displayed in real-time on the touch screen of the smartphone.

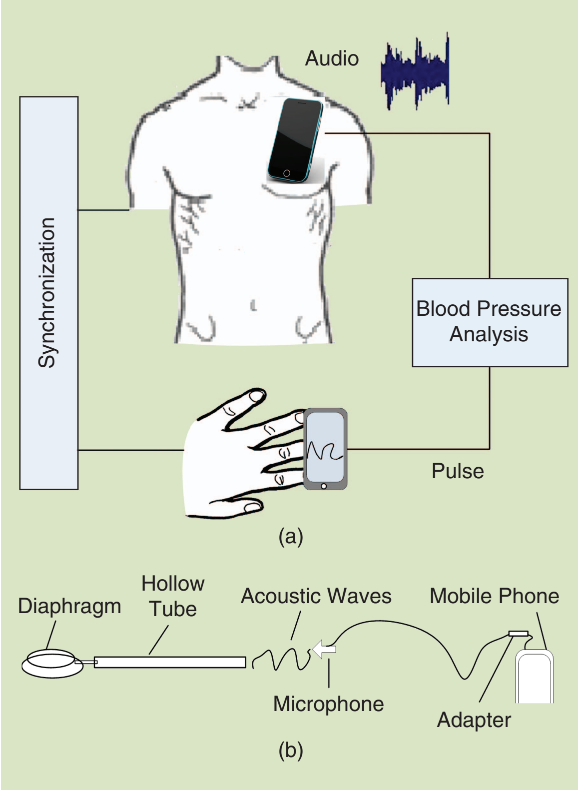

Figure 6. *Blood pressure estimation using a smartphone [22]. (a) Using two smartphones synchronized by Bluetooth. (b) Using an external microphone.*

Figure 7. *A portable ultrasonic system developed by Mobisante [21].*

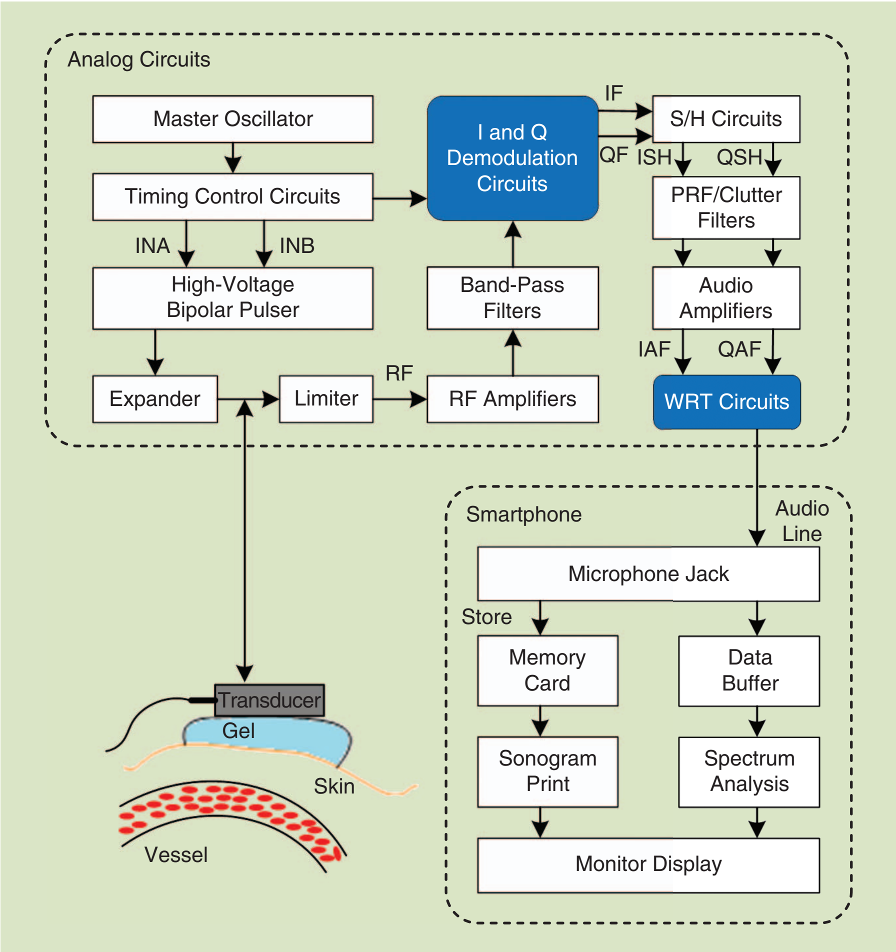

Figure 8. *A portable pulsed-wave Doppler flowmeter [27].*

Mobile Identification Reader

There are two widely explored technologies for mobile identification reading [28]: quick response (QR) codes and radio-frequency identification (RFID). They connect the physical and the virtual worlds through identification codes. Both technologies allow a reader to obtain an identification code that represents a unique identifier associated with a resource reference in a database. However, there have not been much progress in incorporating an RFID reader in a smartphone for NFCs. Even Apple's recently released iPhone 5s does not have the NFC support for RFID applications, most likely due to relatively high cost and complexity of an RFID reader. On the other hand, a QR code can be relatively easily scanned by a smartphone camera. As a result, because a modern smartphone is usually integrated with a sufficiently high-performance processor and a built-in high-resolution camera, a QR coder reader can simply be realized by installing an application software on the smartphone [28]. The scanned QR code can also be transmitted to/from other users and servers.

Another smartphone-centric identification application is to use it for debit or credit card transactions. A good example the smartphone-based card reader is the one developed by Square (https://squareup.com/); it allows a merchant to swipe a credit card on a smartphone. The card reader, named Square Reader, is a small plastic device that plugs into the audio jack of a supported smartphone. It can read the identification information from magnetic stripe of a debit or credit card and then send it to the Internet for payment processing.

Methods to Connect to Smartphones

It can be seen from the above overview that external peripherals are often needed in many smartphone-centric applications. To realize data transmission between these peripherals and smartphones, the most direct way is to plug the peripherals into a generic data interface of a smartphone. For example, Apple iPhones use a proprietary 30-pin connector interface to provide power and data communication, and Android phones generally use micro-USB connectors. However, there are drawbacks in using data interfaces. For instance, Apple's 30-pin connector is complex and expensive and takes up a lot of space. Apple's new eight-pin Lightning connector is significantly more compact, however, it is still a proprietary connector for Apple's devices, expensive, and incompatible with peripherals designed for the other smartphones. In addition, the phone needs to support the USB host mode that enables interaction with various peripherals or external sensors. However, most Android phones do not support the USB host mode. In order to circumvent the problem, recently, audio interfaces have been considered as an alternative universal data acquisition interface for sensing applications [29].

All smartphones have an audio interface (jack/plug), which typically provides two-way communications for audio signals between smartphones and external peripherals. Therefore, if properly designed, the audio interface can be used to transmit and receive data. Using a 3.5-mm phone jack/plug as an example, as shown in Figure 9, the jack/plug has four connectors: 1) left earphone connector (tip), 2) right earphone connector (ring), 3) common/ground connector (ring), and 4) microphone connector (sleeve). It provides three signal channels and therefore can be used for data exchange between smartphones and peripherals. They can even be used for extraction of power from a smartphone to the peripherals, which make battery-free and low-cost peripherals designs become possible. The typical application is HiJack, designed by the University of Michigan [29], which uses an audio channel for energy harvesting and another audio channel for data transmission from smartphones to peripherals. According to [2], Hijack can harvest up to 7.4 mW power from the audio interface of an iPhone, and such power can only support a simple digital system with strict design constraint on power consumption. To harvest more energy from the audio interface as well as maintain two-way communications between smartphones and external peripherals. We have designed a scheme in which smartphones use constant envelop modulation schemes, such as frequency-shift keying (FSK) and phase-shift keying (PSK), to modulate the information to be transferred to peripherals. As shown in Figure 10, compared with HiJack, the energy harvested from the audio interface of the electronic devices and the data rate can be doubled.

In addition to using the audio interfaces, a more convenient way for smartphones to communicate with peripherals is to use wireless technologies. Currently, most smartphones provide integrated Wi-Fi and Bluetooth connectivity. A Wi-Fi- or Bluetooth-enabled peripheral can then be easily connected to a smartphone. Unfortunately, a variety of other wireless link technologies, such as Sensium, ANT+, and ZigBee, while being employed for sensing applications [30], have not been supported by most smartphones due to various reasons. As a result, external communication adaptors are needed to make smartphones compatible with those wireless applications, which certainly increase the complexity and cost of the smartphone communications.

Nevertheless, smartphone wireless link technologies continue to evolve. Recently, NFC, Bluetooth low energy (Bluetooth LE, or BLE) and Wi-Fi Direct have emerged to provide new options for connections to smartphones. They are expected to be integrated into smartphones in the next few years, which will signally enhance smartphones' wireless communication abilities and make smartphone-centric RFID applications and low-power, high-speed transmission wireless applications become more convenient and effective.

Wireless technologies not only gradually replace the wired communication cable for smartphone-centric wireless applications, they also have been considered as promising for power charging. Wireless charging technologies such as Qi-standard (http://qistandard.org/) and Rezence (http://www.rezence.com/), allow for charging of devices by induction. More specifically, place a smartphone on a special table and it will pick up a charge from an embedded coil.

In addition to the near-field inductive coupling wireless power charging technology, recently, middle and long distance wireless power technologies attracted much attention. [31] With the wide use of wireless technologies, there are many RF signals in our surroundings that are sent by all kinds of radio transmitters such as mobile phones, Wi-Fi routers, TVs, radios, and mobile base stations. With such ubiquitous RF energy availability, even though these signals carry a small amount of energy, the possibility of using that to drive low power sensors or extend the battery life of devices is attractive. In [32], an ambient RF energy harvesting sensor node with onboard sensing and communication functionality was developed and tested. Some other research efforts have been devoted to wireless charging over distance by using retroreflective beamforming technologies. [33] Beamforming enables the wireless source to recognize the direction of devices for charging and spatially focused power delivery to devices, which will significantly improve the efficiency and distance for wireless charging.

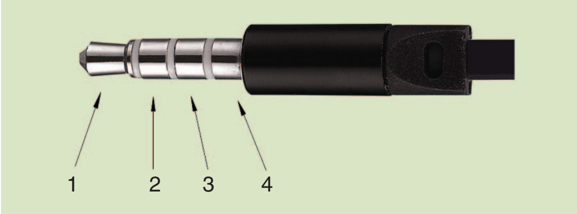

Figure 9. *Connectors of a 3.5-mm phone jack/plug.*

Future Trends and Conclusions

The accessibility, portability, connectivity, computing, and sensing power of smartphones have given rise to numerous smartphone-centric applications such as participatory sensing-based environment monitoring and various people-centric sensing like health-care application. In the future, smartphones will come with more built-in sensor components and communications tools to interact more than ever before with people and devices. Various built-in sensors for smartphones will continue to emerge and to pave the way for new smartphone-centric applications. On the other hand, for a particular application, sensors may not always be

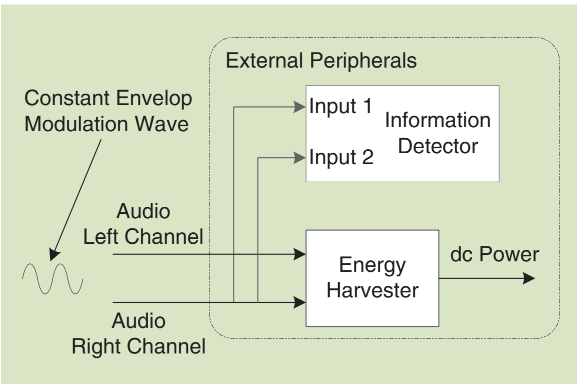

Figure 10. *Joint energy harvesting and communications for both audio channels.*

possible for physical integration with a smartphone. For instance, in the health monitoring application, they may need to be in the wearable form so they can be attached; the examples are a smart watch that needs to be attached to a body for vital signal detection or a sensor that needs to be built into a shoe for motion detection. For these sensors to communicate with smartphones, new wireless link technologies will continue to emerge and to be integrated into the future smartphones, providing reliable, efficient, and secure connectivity.

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