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A Survey of Side-Channel Sensing in Wireless Networked Systems

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***Abstract*—In recent years, Side-Channel Sensing (SCS) became hotter and hotter in wireless network (a type of computer network that uses wireless data connection to connect network nodes) and mobile computing (a computer is transported during usage) systems. People found that sensors, RF radios, or even daily used lamps potentially can have more and stronger functionalities than their original purposes. Usually, the SCS can enable new application, save energy, perform novel communication or provide special data. Because of SCS, the fields such as Human-Computer Interaction, Indoor Localization and Device-to-Device Communication got further improved. In this paper, we perform a comprehensive survey on Side-Channel Sensing and analyze the concerns on energy, communication, and data. To do this, we firstly classify the recent studies by original purposes and extensional purposes. Later, we analyze the energy, communication, and data concerns on the technical layer. Eventually, we provide a summary on related works. Our survey covers more than 60 studies in recent three years from relative high ranked conferences.**

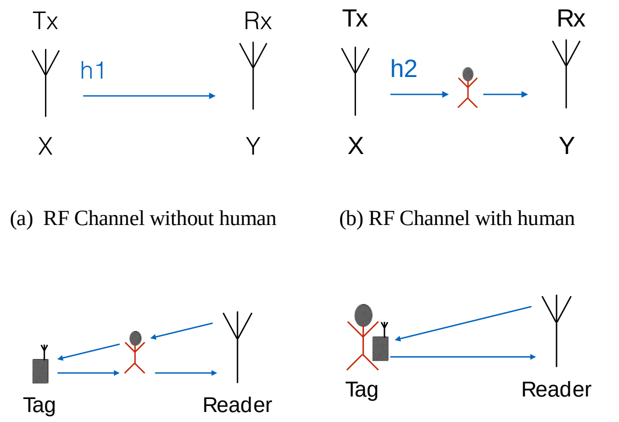
Keywords—Side-channel; Sensing; Wireless Network

I. INTRODUCTION

Devices or modules are always designed or manufactured for some original purposes (e.g., Wi-Fi access points provide wireless links between personal computers and the Internet, accelerometers embedded in mobile phones or other devices can measure the acceleration, lamps are used for illumination purposes since more than hundreds of years). These original purposes are the main design goal that many scientists and researchers put major efforts to improve the performance of specific devices. For example, people tried harder and harder to squeeze the spectral efficiency that the Wi-Fi protocol updated from IEEE 802.11 (1997) to IEEE 802.11ad (2012) or even further, the data rate was increased from 1 Mbit/s to 6.75 Gbit/s or even higher. The electric lamp goes from Incandescent lamp, Luminescent lamp, Electric Arc lamp, High-Intensity Discharge (HID) lamp to Light-Emitting Diodes (LEDs) that the power consumption reduced two orders of magnitude to emit the same lumens.

Recently, people are not satisfied with single functionality for a device and performed different experiments to excavate the potential in multiple directions and scenarios. Especially in the research area, the researcher put more efforts on SCS because they believe it's a kind of a waste if we don't utilize all the features the devices can provide.

In an old fashion to deal with the transmitted signal, we treated the transmitting loss and attenuation as noise. For example, an Amplitude Modulation (AM) signal could be easily affected if the received amplitude distorted. People have tried hard to design a filter or other modules to recover the original signal in order to decode the data. Recently, we treated the distortion as information modulated onto the transmitting signal instead of noise. Along with the improvement of signal processing technique and the computation speed, we are able to sample the signal at a higher sampling rate and precision. Extracting the modulated information becomes true. Generally, Side-Channel Sensing (SCS) uses high-performance equipment or algorithm to extract information which is modulated onto the original signal when it is transmitting. Then we process and analyse this information to obtain the interesting data.



(a) RF Channel without human (b) RF Channel with human

(c) Static Tag (d) Mobile Tag

Fig. 1. RF Channel.

Let us take Radio Frequency (RF) channel as an example, which is a widely used SCS. Fig.1a is a simplified model for RF channel, in which, the received signal $Y = h_1X$, where h_1 and X is the channel matrix and transmitted signal, respectively. The old fashion is to use a filter or other techniques to filter out the signal X from Y in order to eliminate the disturbance by the channel (h_1), this is how the communication system works. In Fig.1b, the channel h_1 is changed to h_2 since the activity of human between the transmitter and receiver. Some works are aiming to eliminate the impact of h_2 which is complicated than in Fig.1a since the channel matrix is dynamically changing along with the human movement, and this will seriously impact some system (such as CDMA because of the Doppler Shift). Here, however, instead of eliminating the impact, we enhance the channel matrix and extract information from it. Since the dynamically changing channel matrix is a function to human movement, hopefully, we can infer the human behavior by it in some ways. This process is so called Side-Channel Sensing.

The rest of the paper is organized as follows: category based on sensing purpose is introduced in Section II; the technical concerns related to energy, communication and data are discussed in Section III; finally, we conclude our survey in Section IV.

II. Category By Purpose

A. Side-Channel Source

The exploited SCS sources include the RF signal (mainly on ISM band), acoustic signal, light, accelerometer/gyroscope, camera, and others (bio-impedance, barometer, physical vibration, kinetic, magneto-inductive sensor, soft sensor, etc.).

a) RF Signal: Due to the high information bearing capacity, RF signal is the most important source for SCS [1]–[23]. Originally, the RF signal is used to communication between two or more wireless radios. Fig.1b depicts the common scene for RF based SCS, in which, the transmitter (Tx) sends an ISM signal to the receiver (Rx). The signal is modulated by arbitrary data to realize the original purpose that transmitting information from Tx to Rx. The data carried signal will be modulated again by the dynamical channel which is impacted by human movement or activities from other objects. By extracting information on the Rx side, we can obtain the information we want.

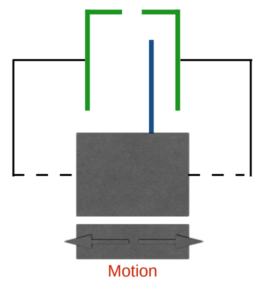


Fig. 2. Diagram of Accelerometer.

Another RF SCS known as backscatter or RFID is depicted in Fig.1c and Fig.1d. There is only one active radio known as a reader including the transmitter and receiver. The reader sends out an RF signal to the RFID tag. The tag reflects the RF signal back and modulates data onto the RF signal by the presence (indicates an “1”) or absence (indicates a “0”) of reflecting. In the first scenario (Fig.1c), the RFID tag is static, both of the forward channel and backward channel, which is from the reader to the tag and from the tag to the reader, respectively, go across the moving object so that the two channels will be changed by the activity. In the second scenario (Fig.1d), the RFID tag is carried by the mobile object that means the RFID tag is also moving along with the time. In both of these two scenarios, the readers send out carry-waves and receive the reflected signals, then perform signal processing and data analysis. The advantage of the backscatter/RFID SCS comparing with the RF SCS in Fig.1b is the reader has the knowledge of the carry-wave that means the reader can easily cancel that part in the received signal to increase Signal-to-Noise Ratio (SNR). However, the major disadvantage is the relatively short communication range due to the RFID tag which is a passive RFID tag and can not generate a signal but reflect the signal.

b) Acoustic Signal: Acoustic signal, basically, is the mechanical waves (caused by mechanical vibration) propagating in gasses, liquids, and solids. The acoustic signal is interesting for computer science research because of the “hearing” property of human. And the acoustic signal is an important carrier for human-to-human communication or human-to-computer interaction. The typical transmitter and receiver of the acoustic signal is the loudspeaker and microphone, respectively, on every cellphone or laptop. However, the acoustic signal is just the by-product of mechanical vibration, so people found other ways to recover the acoustic signal without microphone or utilize the vibration on loudspeaker to enable new applications [24]–[32].

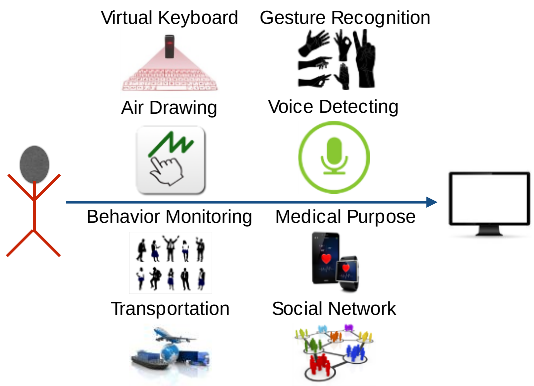


Fig. 3. HCI Scenarios.

c) Light: Light is an indispensable element for the human being. Since the invention of the electric lamp in late 19th century, which greatly promoted the development of humanity, an electric lamp is everywhere in today's society. However, the single purpose of illumination for light didn't utilize all the features. In recent decades, optical fiber communication provides us basic communication needs. However, the optical fiber communication is a dedicated system for high-speed network. The original purpose is not illumination but communication. It's not in the scope of this survey. Recently, Visible Light Communication (VLC) is a proposed technique to utilize the existing infrastructure to provide high-speed wireless links. Based on the development of VLC, people found the light can not only do illumination and communication but also can do some sensing task [33]–[37].

d) Accelerometer/Gyroscope: The accelerometer and gyroscope are two kinds of wildly used Micro-Electro-Mechanical systems (MEMS). Though the principle of these two sensors are different, both of them contain not only electronic parts but also mechanical parts. A diagram of accelerometer is shown in Fig.2. In which, the green component is a stationary plate and the dark blue is a moveable plate. When an acceleration is applied by the motion, the moveable plate moves that causes a change in the capacitance between the stationary plate. The change is recorded to measure the acceleration. MEMS accelerometers and gyroscopes are used in modern cars, autonomous, helicopters, planes and drones, or consumer electronics devices for a large number of purposes including airbag deployment, automatically sensing and balancing flying characteristics (such as roll, pitch and yaw), and orientation or motion detection. Thanks to the presence of mechanical components, the accelerometer and gyroscope can sense more things [38]–[49] than acceleration and orientation.

e) Camera: A camera is an optical device whose original purpose is recording images (the images may be individual photograph or organized in sequence to form videos or movies). Cameras also have other purposes such as security surveillance or military surveillance. However, these functions are just based on the property of recording and combined with image processing techniques. In the other hand, the camera can capture rich information including changes of light intensity and colors. These properties can provide possibilities for new applications [50]–[53].

f) Others: Besides the major SCS sources listed above, there are also other sources which can produce more information than origins, such as bio-impedance [54], barometer [55], [56], vibration motor [57], kinetic [58], magneto-inductive [59], social sensing [60], and soft sensor [61]. And we believe a bunch of devices or sensors are waiting for us to exploit their SCS.

In the following subsections, we will introduce the SCS applied for different purposes and applications.

B. Human-Computer Interaction

Human-Computer Interaction (HCI) studies on the computer technology, focusing on the interfaces between people and computers, Fig.3 depicts different HCI scenarios. Researchers devote on how humans interact with computers and let humans interact with computers in novel ways to be as smooth as human-to-human interaction. Devices such as keyboards, mice and monitors are typical interfaces between humans and computers. In recent years, speech recognition (e.g., Siri from Apple, Google now from Google) and gesture recognition enable new input methods for humans talking to computers. Along with the development of computer technology, more requirements such as non-invasive, non-contacted, non-line-of-sight and security-concerned are introduced in HCI. Also, portable and wearable devices become more and more popular, the requirements of low power consumption and portability are important. To meet these requirements, researchers devote on exploiting new features of existing infrastructures.

The papers [8], [39], and [14] propose to realize virtual keyboards by Wi-Fi signal, accelerometer, acoustic signal, respectively. They tried to capture different properties of normal typing actions and all of them are motivated by the hardness of input method for wearable devices and cumbersome of the traditional keyboard. In [26] and [38], the authors raised up the security and privacy issues for daily typing actions. They mentioned that the pervasive microphones embedded in smartphones and ubiquitous accelerometers embedded in smart bands or smart watches can easily snoop what the users have typed.

The papers [3], [7], [34], and [32] provide another Human-Computer Interaction experiences other than keyboard by RF signal, Wi-Fi signal, visible light sensing, and acoustic signal, respectively. Generally, they proposed different approaches to tracking the real-time movement of users' fingers or hands to depict what the users are drawing. The major challenge for RF SCS [3] and [7] are the multipath effect, both of them propose to solve it by Multiple-Input and Multiple-Output (MIMO) technique. The visible light approach [34] is limited on a plane and line-of-sight which works like the touch screen but has relatively high accuracy. [32] uses the mobile device to mimic an air mouse but using inaudible sound pulses instead of accelerometer and gyroscope on a mobile phone.

The paper [12] exploits the relationship between Wi-Fi signal and the human voice. It sounds impossible to detect voice by Wi-Fi signal. However, the RF signal could be converted by motions. In this paper, their approach recognizes the user's words by monitoring the signal reflected from their mouth that is similar to the leap reading. So they actually detect the motion of mouth when talking to infer the content instead of directly sensing the sound. [42] is another interesting paper which is talking about using gyroscope on the smartphone to eavesdrop speech near the phone. The basic concept of these two papers is the MEMS sensors contain the mechanical parts which would be affected by the sound, which actually is a mechanical wave.

Other than the arbitrary input method (keyboard and air drawing), gesture recognition is another kind of human-to-computer communication. Usually, the set of gestures is preset. The users perform different gestures as commands to remotely control computers or other electric devices. Gesture control is more useful in a smart home setting. Some gesture control approaches require training because the asymmetry among users. [33] leverages the existing LED infrastructure and photodiodes to capture the user's gestures and reconstruct the 3D model. [13] proposes to extract the Doppler Shifts in OFDM signal to infer the human gestures in order to control the appliance in a smart home. In [41], the authors designed an attachable circuit which can be connected to any mobile phone in order to recognize gestures by backscatter technique. [43] focuses on recognizing the specific gesture "smoking" by the embedded sensors on the wristbands. They utilized the 9-axis Inertial Measurement Unit (IMU) which actually is the fusion of accelerometer, gyroscope, and compass to construct the 3D model of wrist then recognize the "smoking" gesture. [40] uses the accelerometer to extract the features of a preset hot word to wake up the smartphone for the purpose of energy saving because accelerometer saves energy than a normal microphone.

The papers [15], [6], and [58] are working on the research of human behavior by backscatter, Wi-Fi signal, and kinetic. The human behavior recognition is a little bit different from the gesture recognition since the gestures are preset and the user will follow the instruction to perform the gestures, but the behavior is the habit or activity with some kinds of patterns. They extracted the features of these patterns by RF SCS or kinetic SCS. [16] recognizes a bunch of specific human behavior when the user is doing free-weight activities. They use Commercial Off-The-Shelf (COTS) RFID devices to figure out the patterns of different free-weight activities. [48] is another paper focusing on high mobility exercises detection. They used the accelerometer to monitor the muscle activation. The paper [47] uses the IMU (accelerometer, gyroscope, and compass combination) on smartphone to sense vehicle steering. Though the proposed approach is sensing the patterns based on vehicle activities, but it's still a reflection of human behavior. [59] uses a special sensor named magneto-inductive sensor to detect what electronic devices (e.g., the blender, mixer, food processor, microwave in the kitchen, the laptop, wireless mouse, lights, heater, TV, vacuum in the living room, the hairdryer, toothbrush, shaver in the bathroom, car, train, bus, plane in commute, etc.) the user is using due to the different electromagnetic radiation from electronic devices. [49] can also identify what the user is using but not limited on the electric device since the principle they use is different. What they did is utilizing the data from IMU sensors on the wrist band to figure out the hand movement, then infer what the object the user is using. [56] uses barometer on the smartphone to monitor the indoor activities such as door opening, climbing stairs, taking an elevator and walking in a building.

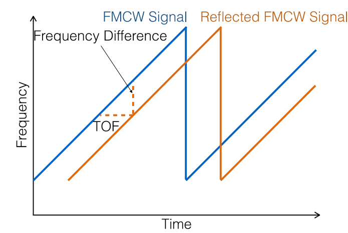


Fig. 4. FMCW Signal.

For medical purposes, [28] senses the non-speech body sounds to evaluate the health condition and detect illness. [29] proposes to measure the quality of sleep by capturing the body movement, cough and snore via the microphone of the smartphone and [23] states to sense the sleep-related physical and physiological variables by Doppler Shift of RF Signal. [27] is more professional to detect sleep apnea by smartphone through acoustic signal generating and receiving by smartphone. In a smart home setting, [21] proposes to utilize non-contacted RF signal to monitor the breath rate and even heart rate. The advantage of this work is this system can monitor multiple persons across a wall that the system fits the smart home setting very well to monitor the babies or elders.

The paper [54] and [46] are talking about the privacy issue for personal devices such as smartphones or wearables. [54] detects the bio-impedance on the skin to identify the users. Other than the privacy issue, the identification of individual can enable application of personality. [46] discards the pass word, PIN or patterns based schemes to unlock a personal device, they proposed to use not what the user inputs but how the user inputs to unlock the mobile phone. The way they mentioned is by detecting features of finger velocity, device acceleration, and stroke time to defend from attackers seeing what the user inputs.

Fig. 5. Indoor Localization Scenarios.

Transportation is an important part in daily life. [45] uses the data from the accelerometer to classify whether the user is stationary, walking or taking a bus, train, metro or tram. There is another unique paper [55] to use the barometer to detect if the user is idle, walking or in a vehicle. The benefit to use a barometer instead of an accelerometer is power saving due to the low sampling rate since it has to monitor 24/7. [44] points out that the walking direction inferred by accelerometer data is not that accurate because of other motion patterns during walking, such as up and down bounce of portable device, side-to-side sway, arms or legs swing, etc. This paper tries to break the assumption of known walking directions and research on the walking direction issue by analyzing the relationship between human motion and accelerometer/gyroscope data.

Social activities play an important role in psychology, economics, marketing, and management. The following two papers are talking about social activities. In [30], the authors proposed a novel way to detect whether a member is attending a meeting automatically by leveraging the microphone on the mobile phone carried by a member. For the online social network, it is very easy to build a model of communication topology for users. [31] devotes on face-to-face conversation network built-up. It uses the voice data recorded by smartphone to classify the users into different conversation groups or clusters. [61] proposes the concept of "soft sensor" which actually is the smartphone usage logs, application usage, messages, and phone calls. They utilized these data to infer the location information that the performance is not bad and with virtual no energy consumption since no physical sensor involved.

C. Localization

A localization or positioning system is a system to locate objects or people. Outdoor localization system is well solved by Global Positioning System (GPS) which can provide location information anywhere on the earth by line-of-sight signals from GPS satellites. However, the indoor localization (Fig.5 shows different scenarios) is still struggling to come to commercialize. We will discuss different localization approaches using RF signal, acoustic signal, accelerometer or other information. And we generally divide all these works into two categories, locating human or locating objects.

For human localization approaches, two kinds are available which are device-contacted and non-device-contacted. [37] designed a system to utilize the existing LED lamps as anchors and receive the light signals by light sensors. [35] proposes to combine Visible Light Communication (VLC) with the cameras on the smartphones to localize people. They leverage Binary Color Shift Keying (BCSK) and polarization-based VLC to deal with challenges such as low frame rate, uneven camera sampling rate, and rotation of smartphone. [22] states a novel way to keep away from a large antenna array on the receiver but still can get high localization accuracy from Wi-Fi signals. They proposed to twist the handheld device (e.g., a tablet) to mimic an antenna array.

The paper [5] proposes to use 2.4Ghz ISM band Wi-Fi signal to locate moving object through walls without carry any wireless device on the human. In [18], the author treated normal Wi-Fi Access Point (AP) as a backscatter sensor to receive the reflected signals from static objects and moving objects, then clustered them into different groups by declutterer. [11] uses the COTS RFID in a novel way to locate people behind the wall. Generally, they used a group of RFID tags to form an antenna array and used a central reader to gather the reflected signals. They can achieve a median accuracy of tens of centimeter. [20] and [19] use RF signals to locate people. The basic technique they applied is the Frequency Modulated Carrier Waves (FMCW), in which, the FMCW transmitter sends a bandwidth signal but makes the carrier frequency linearly change in order to convert the time-of-flight (TOF) of reflected FMCW signal into frequency difference (as shown in Fig.4). The FMCW Signal is useful in localization and tracking. Combined with MIMO technique, the approach in this paper could locate multiple persons and even static person.

The paper [60] presents not a basic people localization technique but a middleware between basic indoor localization systems and location based applications. It provides the ability to calibrate the users' location by the encounter and non-encounter events of users.

For the purpose of objects localization, [4] introduces the first fine-grained RFID localization system which could deal with the multipath effect and non-line-of-sight scenarios. [36] utilizes VLC to perform sensor nodes localization. They built a motor driven shade mounted on the ceiling to project location information in a concentrical manner. The sensor nodes on the floor can receive the location information by the photodiodes in order to figure out the position. [10] designed a 60GHz millimeter wave system to track a passive writing object such as a pen to enable the new applications such as wireless transcription and virtual trackpad at high accuracy. [1] proposes to locate objects on decimeter level by existing Wi-Fi deployments by combining the CSI information across subcarriers to estimate Angle of arrival (AoA) and Time of Arrival (ToF). [2] is a realistic work which designed a smart reader to simultaneously read the existing electronic toll collection transponders (e.g., E-ZPass) from multiple vehicles. They distinguished the collided signals by the observation of carrier frequency offset (CFO) of the transponders. The CFO is introduced by the variety of oscillators for active RFIDs. On top of the simultaneously reading, they can locate multiple cars by the Angle of arrival (AoA).

Different from other papers to track moving object or people, [17] proposes to locate static object or so-called image objects such as leather couches or metallic shapes. They leverage the multipath propagation that the transmitted 2.4GHz signals bouncing off from objects then arrive at the receivers by Multiple-Input and Single-Output (MISO) technique. [9] wants to use the 60GHz radio to image objects in the purposes such as autonomous drones, robots, and vehicles since the 60GHz are highly directional signals and the size of the antenna is small due to λ=S/F.

D. Communication

Communication is a broad concept. Here we mean computer-to-computer communication. If the word "sensing" means the computer system gets knowledge of the physical world, the "communication" means one computer system gets knowledge from the other computer system. We already have many mature communication systems to connect computers wired or wirelessly. The common communication media includes wired electrical signal, wireless electromagnetic wave, light wave, ultrasonic wave, and magnetic field. The dedicated system will choose one or more types listed above to perform communication. Here, we will discuss some special communication approaches through SCS whose original purposes are not for communication.

Near Field Communication (NFC) is used to perform physically proximate devices (typically within 10 centimeters) communication to enable applications such as money transactions, data exchange, and simplified setup for complex devices. However, the current NFC requires extra radio and antenna to do the RF signal transmitting and receiving. [24] proposes to realize the near field communication by acoustic signal which can achieve data rates of up to 2.4Kbps. Since the major portable devices have loudspeakers and microphones, this approach doesn't add extra module or cost for NFC. [57] designs another NFC system by using the vibration motor as transmitter and accelerometer as the receiver. The advantage of this approach is that it can prevent the remote snoop while the RF or acoustic approach could be stolen from the distance.

As we mentioned in Section II-A, the camera is mainly used for picture and video recording purposes. In recent years, the Two-dimensional (2D) barcodes (e.g., QR code, Data Matrix, and PDF417) are widely used for tag-camera communications. [52] and [51] enable a new link between screen and camera by dynamical 2D barcodes. [52] proposes to solve the imperfect frame synchronization issue introduced by frame rate diversity and variability due to different camera capabilities, lighting conditions, and other factors. [51] focuses on improving the transmission reliability and transmission rate. Another paper [53] follows the VLC trend but enable the light-to-camera link. Since the low frame rate of the camera (typical 30 frames/second) will lead an ultra low data rate, this paper addressed this issue by utilizing the Off-The-Shelf rolling shutter camera which samples one row by one row in a single frame. [50] raised up a security issue for screen-camera links. The authors studied on how to prevent users to videotape a movie played on a screen (e.g., in a cinema). They proposed a solution to cheating the video recorder, but keepping the high-quality for screen-eye channel. The basic idea is using the different principles between screen-eye and screen-camera to insert noise which can be captured by the camera but can not be observed by the human.

The paper [25] raised up a security concern for loudspeakers. Traditionally, if someone intends to prevent information leakage from loudspeakders, the way is using sound-proof isolators (e.g., concrete walls for a meeting room). However, potentially, the RF signal can capture the sound information by detecting the vibration of loudspeakers. This paper also provides countermeasures to reduce the attacker's audio quality when the attacker tries to recover the sound.

III. TECHNICAL CONCERNS FOR SCS

A specific sensor usually can provide fine-grained information or data. However, sometimes, granularity is not the only metric we should consider about. Especially for portable or wearable devices, we should make the tradeoff among energy, communication, and data.

A. Concerns on Energy

The tight energy budget is an essential problem for mobile, portable, or wearable devices since they usually have limited battery capacity or tiny energy harvesting rate. People devote decades on different techniques such as wireless charging, quick charging, etc. Due to this issue and the asymmetric development of the semiconductor technology and battery technology. On the other hand, people study on how to reduce the energy consumption not only on hardware, but on the operating system, application software, communication, and front-end as well. The backscatter/RFID tag is an excellent example to highly cut the energy cost for communication but still meet the requirements of the application. Since most studies are proving the possibilities to sense by Side-Channel, they didn't consider more about energy except the papers (such as [40] and [55]) which are motivated by the power consumption issues on commercial smartphones. Obviously, energy consumption is a hot topic before these SCS techniques come to mature.

B. Concerns on Communication

There are multiple concerns about communication on different aspects:

Capacity: RF spectrum is almost full for wireless data transmission. On one hand, people try to increase the spectrum utilization (e.g., the 2.4GHz Wi-Fi, Bluetooth, 2.4GHz ZigBee, etc. share a same band and have different technique to well use the band). So exploiting other media for communication is extremely urgent, such as Visible Light Communication [33]–[37], Near Field Communication by acoustic signal [24] and Vibration [57], and Camera based communication [50]– [53]. On the other hand, we can use the traditional RF band to do sensing tasks ([1]–[23]) since the wireless waveform can not only carry information from transmitter side but also embedded information through the channel.

Efficiency: To increase efficiency, it's a good solution to entrust a signal multiple functions. For example, in [1], [5], [7],

TABLE I. Classification of References

HCI	Virtual Keyboard	RF Signal	[8]
		Accelerometer	[38], [39]
		Acoustic Signal	[14], [26]
	Air Drawing	RF Signal	[3], [7]
		Visible Light Communication	[34]
		Acoustic Signal	[32]
	Voice Recognition	RF Signal	[12]
		Gyroscope	[42]
	Gesture Recognition	RF Signal	[13], [41]
		Visible Light Communication	[33]
		Accelerometer, Gyroscope, and Compass	[40], [43]
	Human Behavior Detection	RF Signal	[6], [15], [16]
		Accelerometer, Gyroscope, and Compass	[47]-[49]
		Kinetic	[58]
		Barometer	[56]
		Magneto-inductive Sensor	[59]
	Medical	RF Signal	[21], [23]
		Acoustic Signal	[27]-[29]
	Privacy for Personal Devices	Accelerometer	[46]
		Bio-Impedance	[54]
	Transportation Detection	Accelerometer	[44], [45]
		Barometer	[55]
	Social Activities	Acoustic Signal	[30], [31]
		Soft Sensor	[61]
Localization	Human Localization with Device-Contacted	RF Signal	[22]
		Visible Light Communication	[35], [37]
	Human Localization with Non-Device-Contacted	RF Signal	[5], [11], [18]-[20]
	Middleware between Localization System and Application	Social Encounter or Non-encounter	[60]
	Objects Localization	RF Signal	[1], [2], [4], [10]
		Visible Light Communication	[36]
	Objects Imaging	RF Signal	[9], [17]
Communication	Near Field Communication	Acoustic Signal	[24]
		Vibration Motor and Accelerometer	[57]
	Screen-Camera	Camera	[50]-[52]
	Light-Camera	Camera	[53]
	Security	Acoustic Signal and RF Signal	[25]

[8], [12], [17], [22], the authors proposed, potentially, the Wi-Fi signals can be used for communication and sensing. In [33]–[37], the light can be used to illumination, sensing even transmission at the same time.

Data Rate and Distance: These two are the most important metrics when we consider a communication system. However, for SCS communication, the purpose is not to improve the performance but on other aspects. For example,

[57] provides only 80 bits/s between two smartphones, and distance is almost zero (back to back). However, this system can provide secure transmission without remotely snooping. [37] also has low transmitting rate, but it's enough for a beacon node to send the location information to other devices.

Security: Security in a communication system is extremely important, especially for some sensitive applications. One example is the Wi-Fi or RF signal can penetrate through walls that could be intercepted. The VLC which requires line-of-sight is more secure than Wi-Fi. The other example is in [25], before reading this paper, we didn't notice the sound could be eavesdropped by wireless equipment even through the sound-proof walls.

C. Concerns on Data

In all the surveyed papers, RF signal counts a major part. That's because the RF signal can carry a big amount information not only on the dimension of amplitude, frequency, and phase but also on pattern and interval. On one hand, the RF SCS raises the spectrum utilization. On the other hand, we should consider the Shannon's channel capacity. The signal could be modified by the channel. Does that mean it didn't do well when the transmitter modulates the signal? It should have space to improve the modulation or coding method to reach higher performance.

However, rich information means rich computation and communication. We can find almost all the RF SCS studies [1]–[23] can not perform on portable devices such as mobile phone. In other words, the expected information is fused with other information (e.g., in RF SCS, the information from channel is fused with information from transmitter) that requires complicated signal process technique, data analysis technique, classification technique, etc. to filter out.

IV. Conclusion

In this survey, we investigated multiple works in the past three years. Firstly, we introduced the main ideas and techniques classified by the purposes of SCS. People put more effort on RF signal, HCI field, and indoor localization field since the RF signal is information-intensity, the HCI is important for the smart future, and the indoor localization is an urgent problem needs to be solved. Secondly, we discussed the energy, communication, and data concerns for SCS. These three components are integrated together for SCS, wearable and portable devices. All of them should be considered and balanced with each other. Finally, we summarized all the references in Table I.

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