

Survey and Systematization of Secure Device Pairing

Mikhail Fomichev, Flor Álvarez, Daniel Steinmetzer, Paul Gardner-Stephen, and Matthias Hollick

Abstract—Secure Device Pairing (SDP) schemes have been developed to facilitate secure communications among smart devices, both personal mobile devices and Internet of Things (IoT) devices. Comparison and assessment of SDP schemes is troublesome, because each scheme makes different assumptions about out-of-band channels and adversary models, and are driven by their particular use-cases. A conceptual model that facilitates meaningful comparison among SDP schemes is missing. We provide such a model. In this article, we survey and analyze a wide range of SDP schemes that are described in the literature, including a number that have been adopted as standards. A system model and consistent terminology for SDP schemes are built on the foundation of this survey, which are then used to classify existing SDP schemes into a taxonomy that, for the first time, enables their meaningful comparison and analysis. The existing SDP schemes are analyzed using this model, revealing common systemic security weaknesses among the surveyed SDP schemes that should become priority areas for future SDP research, such as improving the integration of privacy requirements into the design of SDP schemes. Our results allow SDP scheme designers to create schemes that are more easily comparable with one another, and to assist the prevention of persisting the weaknesses common to the current generation of SDP schemes.

I. INTRODUCTION

In recent years, the advances in automation [1] and a rapid growth of the consumer electronics market [2] have resulted in a tremendous increase in the number of smart devices and personal gadgets. For example, it is estimated that the number of interconnected Internet of Things (IoT) devices used in a great variety of applications will reach 24 billion by 2020 [3]. Authenticating a plethora of devices in such a dynamic setting to provide secure communications is a challenge that has not yet been fully addressed [4]. This stems from the highly distributed and diverse nature of the IoT environment which makes it impractical to apply traditional approaches for establishing secure communications such as Public Key Infrastructure [5].

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Secure Device Pairing (SDP) was proposed as an approach to introduce security into the ubiquitous computing environment where devices pair in an ad-hoc manner [6]. Specifically, two parties that have never met each other and would like to bootstrap a secure communication channel need to perform key exchange and authentication procedures [7]. The latter is particularly difficult in the ad-hoc scenario, because two pairing devices do not have any prior security context or a common point of trust [8]. This aspect, in addition to wireless nature of ubiquitous computing makes device pairing vulnerable to man-in-the-middle (MITM) attacks [9]. Traditionally, the MITM threat was considered as one of the core challenges in SDP [10]. In order to overcome MITM attacks the use of auxiliary, so-called “out-of-band (OOB)” channels was proposed [8], [10]. Such channels aim to provide authenticity and even confidentiality to ensure that pairing is performed only between the intended devices, that is, no MITM has intermediated.

Since the initial idea was put forward [6], numerous pairing schemes utilizing various OOB channels have been proposed both in academia and “in the wild”. A great variety of suggested pairing schemes were studied and evaluated with respect to security [10], [11], usability [8], [12] and user interaction [13]. The prior work on SDP mainly considered two distinct use-cases: *a)* pairing among personal gadgets of a single user [14], and *b)* pairing devices of different users, for example, smartphones [15].

With the advent of the IoT, SDP has become one of the viable mechanisms to introduce security to this diverse and distributed environment [16]. The applicability of SDP to the IoT has already been demonstrated with different communication technologies, such as Wi-Fi and Bluetooth standardizing a number of various pairing schemes [17], [18]. Since Wi-Fi and Bluetooth serve as the backbone of centralized and ad-hoc device communications in the IoT, this clearly indicates the utmost importance of SDP in the IoT. Additionally, recent research has clearly demonstrated that SDP can be successfully applied to secure an important class of the IoT devices such as wearables [19]–[25], for example, smartwatches, fitness trackers, smartglasses, etc. Thus, we are convinced that the role of SDP as an ad-hoc security mechanism in the IoT is as important as its centralized counterpart, where a dedicated trusted server manages the key exchange and authentication procedures between the connected devices [5].

The complex IoT domain compounds the complexity of SDP, as well as increasing ambiguity, because of two reasons. First, the available hardware capabilities such as wireless radio interfaces, sensing functionality and computational power

vary significantly among different platforms [26]. Second, the interaction patterns among the devices as well as between human operators and devices have become more intricate. For instance, two devices can perform pairing without any human involvement at all [19], [27]–[29] or a user device can communicate with a third party device or infrastructure without explicit consent [30], [31]. These growing trends consider more heterogeneous settings and user-device interactions. Thus, adversary models and assumptions made for pairing here are different as compared to the “classic pairing” cases mentioned above.

The sound comparison of various pairing schemes is not straightforward. Several extensive surveys were conducted in order to analyze numerous pairing schemes from different viewpoints [8], [10]–[13]. Interestingly, all those studies come to a common conclusion: no universal pairing approach exists. Moreover, the comparative analysis cannot be accurately aligned and justified even over a single metric, for example, security or usability, since there is no common ground on what information should be provided about a pairing scheme to make an assessment. There are two reasons why such incompatibility occurs. First, available hardware interfaces have been traditionally considered as one of the main arguments for introducing yet another pairing scheme [20], [32]–[34]. From this starting point, the selection of OOB channels as well as justification for user interaction modes and use-case scenarios were made. Correspondingly, many proposed pairing solutions focused on specific issues in a restricted setting and were rather disconnected from the results of previous endeavors. Second, the study on user perception of SDP revealed that a choice of a particular pairing scheme is context and environment dependent [35]. Hence, employing different human-centric models widens the gap between properties deemed relevant for pairing which causes controversy [35].

Two other issues that introduce disparity to the field relate to a concept of OOB channel which is a cornerstone in SDP. The first problem is a lack of common understanding as to what constitutes an OOB channel. There were dozens of different alternatives proposed [8], [13] which is a direct consequence of the aforementioned design incentives behind many pairing schemes. Several attempts [10], [36] to categorize OOB channels applied mixed terminology and overlapping adversary capabilities which did not yield the desired clarification. The second issue is erroneous assumptions about the security of OOB channels which resulted in numerous attacks on various pairing schemes [37]–[40].

As it can be seen, the field of SDP is rather fragmented. The lack of coherent understanding of underlying key concepts has led to poor design decisions. That, in turn, resulted in a myriad of pairing solutions which only focus on specific goals, use different vocabulary and rely on unrealistic security assumptions. Hence, we are motivated to systematize knowledge in the field of SDP in order to identify the most difficult problems and facilitate further research on this crucial topic. We make the following specific contributions:

- A system model and consistent terminology that facilitates precise description and reasoning about SDP schemes, by considering the three components:
 - Physical (PHY) channels;
 - Human-computer interaction (HCI) channels; and
 - Application classes.
- Classification of the existing SDP schemes using this model.
- Identification and analysis of systemic security weaknesses commonly found in such schemes, revealing areas where future SDP research is required.
- Revelation of the rarity with which privacy is considered among current SDP schemes.
- Principles for designing robust SDP schemes.

The remainder of this article is organized as follows. In Section II we review existing surveys on SDP and highlight the contributions of our work. In Section III we present our consistent terminology and system model for SDP, and derive an SDP taxonomy based on this model. We survey PHY communication channels along with the representative pairing schemes which utilize those channels in Section IV. Section V follows, where we review the HCI channels applied to device pairing, as well as, the corresponding pairing schemes. In Section VI we discuss the application classes and classify the surveyed pairing schemes with respect to their application classes. We outline the open research challenges and provide the future perspective on the field of SDP in Section VII. We conclude by summarizing our findings in Section VIII.

II. RELATED WORK

In the literature several surveys have investigated different aspects of SDP. Kumar et al. [8] presented the first comparative study to quantify usability and security of various pairing schemes. Our work reveals that quantitative comparison of different SDP schemes is questionable due to the previously taken design decisions, and we qualitatively address the design aspects of SDP to enable meaningful comparison of different SDP schemes. Two other studies from Kobsa et al. [12] and Kainda et al. [11] focused more closely on usability and the role of user actions to achieve security in SDP. Our work has wider scope, because we consider the role of the user as one of the fundamental design aspects of SDP, in addition to physical communication media and particular use cases.

The work of Mirzadeh et al. [10] provided an extensive survey on security and performance of different cryptographic protocols used in various SDP schemes, in addition to presenting classification of OOB channels. In our work we devise a more fine-grained classification of communication channels in SDP by differentiating between PHY and HCI channels, and focus on security issues of those channels instead of cryptographic protocols. Since security weaknesses of various communication channels have resulted in numerous successful attacks on different SDP schemes, we consider our qualitative analysis of those channels as a novel contribution. In their survey Chong et al. [13] presented different modes of user interaction for SDP and analyzed a vast number of SDP schemes using this taxonomy. We refine their findings to classify HCI channels and, additionally, present a set of common security and usability properties to coherently analyze those channels and the SDP schemes relying on them, which has not been done before.

- A system model and consistent terminology that facilitates precise description and reasoning about SDP schemes, by considering the three components:

In our survey, we focus on SDP schemes proposed for two (or several) devices and consider multi-device SDP outside the scope of this article. In comparison to the prior work, our survey is innovative in three aspects. First, we devise a novel system model for SDP, which addresses security weaknesses of the existing generation of SDP schemes. Second, we propose a new approach to design SDP schemes, which enables their meaningful comparison. Third, we provide a deep insight into a current state of SDP from the point of PHY channels, HCI channels and application classes, as well as present an overview of SDP challenges and perspectives in light of the upcoming IoT.

In this section, we have reviewed the related work on SDP and highlighted the contributions of our survey. In the next section, we present our system model and taxonomy.

III. SYSTEM MODEL AND TAXONOMY

In this section we first give a high-level overview of a generalized pairing procedure together with widely-used notations. Second, we address ambiguity in current terminology by providing clear definitions to describe SDP. Third, we present a system model that illustrates the notion and properties of communication channels as well as facilitates a more unified approach towards the design of pairing schemes. Fourth, we discuss threats in SDP with respect to our system model. We conclude by explaining our taxonomy, which is used to systematize and evaluate proposed pairing schemes.

A. The Generalized Pairing Procedure

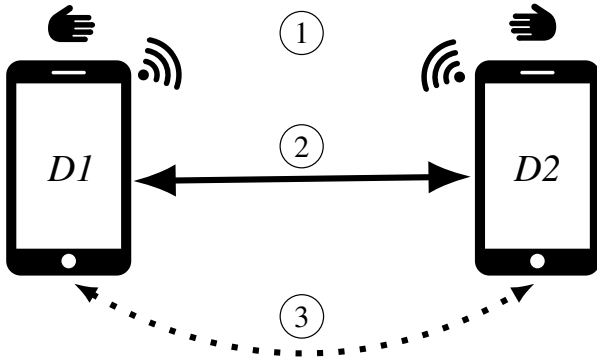


Fig. 1. Generalized pairing procedure

Traditionally, the pairing procedure has been considered as depicted in Figure 1. The scenario consists of two devices, $D1$ and $D2$, which do not share any prior knowledge and would like to pair. That is, two devices need to exchange some secret information, ensuring it came from the correct party, and is not obtained by any third party. In order to achieve pairing, three steps need to be followed: ① *discovery*, ② *secret exchange* and ③ *verification*. In the first step, $D1$ and $D2$ become aware of each other, which can happen either automatically, for example, Bluetooth discovery, or with user assistance, for example, physical contact. During the second step both devices exchange some cryptographic material, for example, public keys, or a password, which can later be used to

establish secure communication. In the final step, both parties verify the obtained secrets, to ensure that the process has not been compromised by an attacker.

To provide a better understanding of the interactions presented in Figure 1, we examine the commonly used notation for SDP. Three main terms are commonly used in the literature: (a) *in-band channel*, (b) *out-of-band channel* and (c) *user interaction*. By employing the generalized pairing procedure shown above, we demonstrate how those concepts apply using a well-known example [7]. Two devices discover each other, after having been brought together physically by a user (c). Then they exchange hashes of their public keys over an auxiliary channel (b), followed by a mutual transfer of the corresponding public keys over a wireless radio link (a). Of course, the given example illustrates just one possible case of how the pairing flow can be implemented. There are other variants, for example, where the discovery can happen without user interaction as in [19], or the secret key is first transmitted via the in-band channel, and subsequently verified via the OOB channel as in [41].

To gain a deeper understanding of the major pairing concepts, it is important to specify the characteristics of in-band and OOB channels that have been traditionally discussed by the research community. The pioneering work of Balfanz et al. [7] stated two related properties that an OOB channel should possess: *demonstrative identification* and *authenticity*, and also that *confidentiality* should not be assumed.

It is authenticity which is the defining characteristic of an OOB channel: it is the infeasibility of forging communications over an OOB channel, without being detected, that makes OOB communications so valuable in SDP. In practice, this implies that OOB channels must possess demonstrative identification, that is, it must be easy to demonstrate that the OOB communication is occurring between the intended parties, for example, by showing the display of a device to another user. Demonstrative identification, thus, implies that the devices must be brought sufficiently close to one another to allow their mutual positive identification by their users. While OOB channels should not be assumed to offer confidentiality, a number of the surveyed SDP schemes depended on the OOB channels being confidential.

The in-band channel, in contrast, has been generally regarded as a communication channel with relaxed security characteristics. That is, it refers to a wireless radio link which is easily accessible by a powerful attacker [42] and, thus, deemed as inherently *insecure*.

So far, we have discussed the core components of SDP along with their prime purposes and vital properties. Yet, there are no precise definitions of the OOB channel and user interaction which are common in the field. We consider this point to be the principle weakness of the existing terminology. Many researchers have described the OOB channel to be a side PHY channel, which is either human-perceptible and/or directly controlled by a user [8]. Nevertheless, there is a number of pairing schemes that intrinsically rely on user actions to accomplish pairing [11]. One example of the latter is Secure Simple Pairing [43] which is a de facto standard for connecting Bluetooth devices securely. Consequently, such

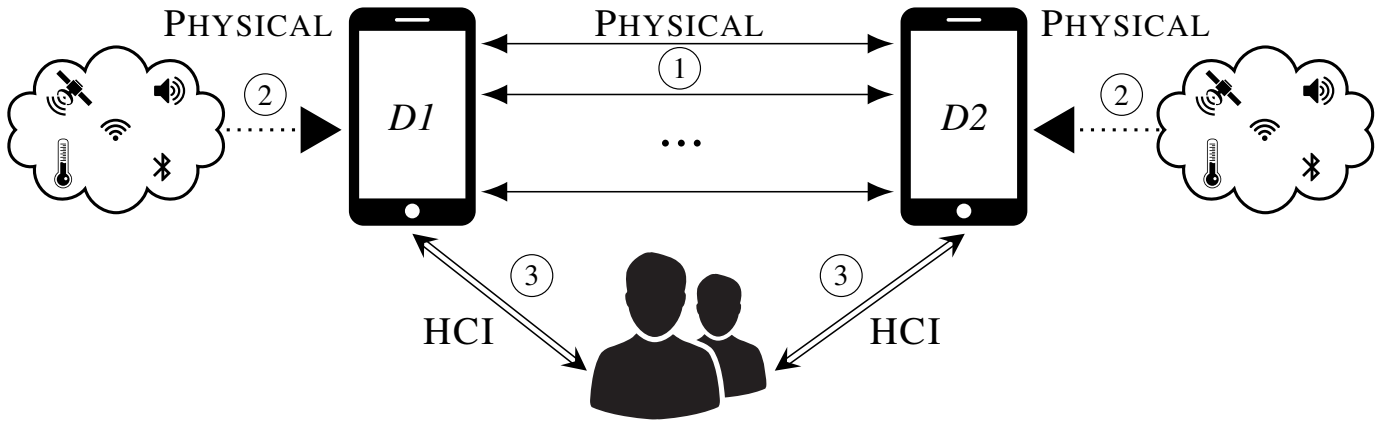


Fig. 2. System model for secure device pairing

disparity results in a situation where one part of the community only considers physical media as the OOB instance while neglecting the user-mediated channels, and vice versa. In addition, communication channels differ in fundamental ways, hence assumptions about media and attacker models vary significantly, and are not straightforward to align.

Another issue is that the boundary between the human-mediated OOB channels and user interaction is often blurred. That is, the latter is a more general term that can include the former. However, the essential purpose of the OOB channel is to provide some form of data authenticity. Specifically, a human operator can assist in initiating device pairing during the discovery step, for example, by co-locating devices, aligning them or enabling physical contact. Yet, we argue that only explicit actions which directly affect the security of the pairing scheme should be considered as the OOB channel.

B. Defining Secure Device Pairing Terminology

A specific challenge to the comparison and analysis of SDP schemes is the lack of accepted terminology covering such schemes. We therefore present the terminology that we use in the remainder of this article, both for clarity of explanation here, and as a suggestion for a common vocabulary to facilitate communications among practitioners in the future.

- *Pairing* refers to the establishment of a secure communication channel between two or more devices.
- An *application class* represents a particular pairing scenario that is determined by the degree of involvement and level of control that a user has over the pairing devices. An application class covers use-cases that share broadly similar security threats and objectives.
- An *SDP scheme* consists of the procedures, cryptographic protocols and the motivating application class required to securely pair devices.
- An *SDP method* or *SDP procedure* is the sequence of actions required to execute an SDP scheme. While considering method and procedure interchangeable, we avoid the synonym protocol, because of the strong association of this word with cryptographic protocols.
- A *party* is someone or something who controls of one or more devices that participate in an SDP procedure.

- A *security domain* is the set of devices, data, policies and intentions that a single party controls. That is, every device belongs to a security domain, but there may be more than one security domain involved in a given application class.
- A *channel* is a means by which communications occur in an SDP scheme, whether over a physical medium, or through an HCI.
- An *HCI channel* is a means of communication where a user acts as the channel by which the communications occurs by undertaking some form of interaction with the devices involved. This could take the form, for example, of a user reading information from the display of two devices, and entering confirmation that they match into one of those devices.
- A *PHY channel* is a communication channel that allows data transmission or acquisition over a physical medium. PHY channels can be described by their objective physical characteristics and where the information is not transferred by a user, that is, it is not an HCI channel.

C. System Model

To address the issues in SDP mentioned previously, we introduce our system model depicted in Figure 2. The objectives of our approach are threefold. First, it takes into account a set of diverse interactions that appear in the context of IoT. Second, it aims to resolve the ambiguities in the pairing concepts which are currently present in the field. Third, our model facilitates a more unified procedure for the pairing design.

Our system model contains three main components. Particularly, there are (a) *two devices* to be paired $D1$ and $D2$, (b) *a varying number of users* and (c) *the ambient environment* in which device pairing takes place. In addition, several types of distinctive interactions can happen between those elements. First, $D1$ and $D2$ can communicate with each other by means of various wireless technologies such as Wi-Fi, Bluetooth, etc. ①. Second, a device can obtain the information about the ambient environment such as temperature, location, etc. via its sensing capabilities ②. Third, the connection between a human operator and the respective device is established in a

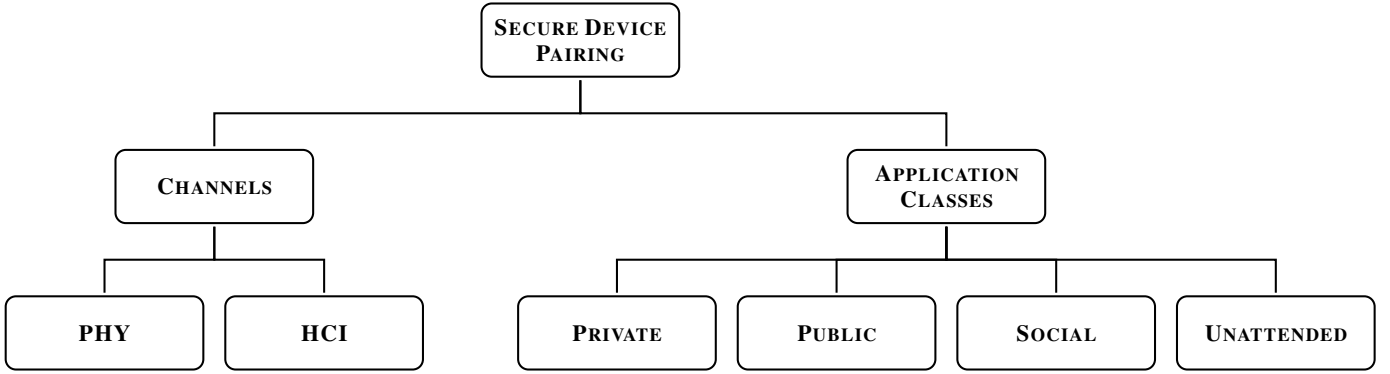


Fig. 3. Taxonomy of secure device pairing

form of HCI ③. We further consider the relationship between a user and a pairing device. Specifically, a human operator can either control both devices involved in SDP, a single one or none at all. Implied in the system model is the purpose for which the devices are being paired, that is, the use-case.

From the above, we can consider an SDP scheme as consisting of the automated communications between two devices over conventional PHY channels, plus the human-mediated communications between the devices over HCI channels. Pairing of devices always occurs for a purpose, that is, it happens within the context of an application class. We, therefore, use three key concepts as the foundation for our system model:

- PHY channels.
- HCI channels.
- Application classes.

Figure 3 illustrates the relationship between those concepts, that is, we consider the channels, both PHY and HCI to be orthogonal to the application classes.

The first two concepts specify two fundamentally different types of interactions that can be utilized by a pairing scheme. With this in mind, we further analyze PHY and HCI channels independently, to identify the most important features of each class, and expose the trade-offs involved. To account for both types of interactions, we understand “device” to mean any physical device that possesses one or more communication channels that can be used to connect to the outside world. SDP is achieved using some set of such channels. Figure 4 depicts an abstract visualization of such a device concept, including a comprehensive list of PHY and HCI channels. A rigorous discussion covering each channel category in detail is provided in Section IV, for PHY channels, and Section V for HCI channels.

As for the application classes, we identify four different cases which cater to classify all the pairing schemes proposed up-to-date. The categories are as follows: (a) *private*, (b) *public*, (c) *social* and (d) *unattended*. The private class corresponds to a “classic pairing” case, where a single user either owns or directly controls two devices that ought to be paired. The public class is related to a single user possessing one device, where the user performs the pairing with some third party infrastructure, for example, a payment terminal,

over which she has no control. The social class incorporates two users who would like to securely pair their corresponding devices. The unattended class deals with the case where two devices belonging to the same ownership domain, for example, owned by the same person or organization, pair with no user involvement.

For each application class, we present distinct interaction patterns, demonstrated by instantiating our system model (Section VI). Furthermore, we identify commonalities in the form of adversary capabilities, as well as security and usability implications that have to be taken into account for a particular application class. Consequently, it is possible to determine a set of common security and usability properties shared by a group of pairing schemes that have been designed with a specific application class in mind. Section VI explores the potential for such application classes to facilitate the design of better, more coherent SDP schemes.

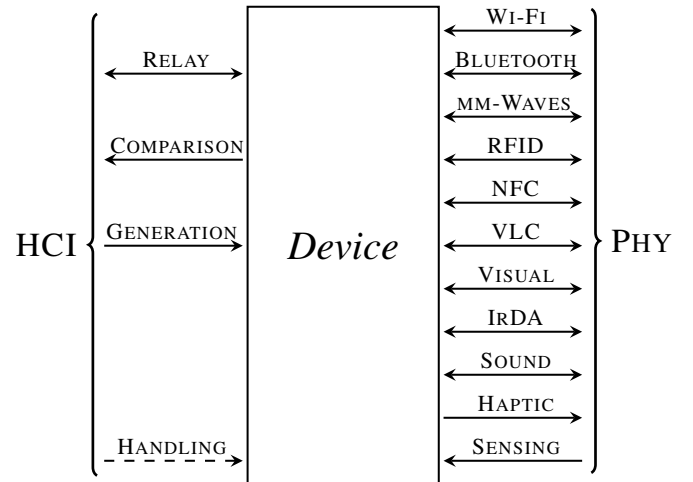


Fig. 4. Pairing device with PHY and HCI channels. This model is independent of application classes.

D. Worked Example

To demonstrate the relevance of our system model we consider the security of an important class of the IoT devices such as implantable medical devices (IMD). For example, the

case of Dick Cheney has raised further awareness of life-threatening repercussions stemming from the compromise of a pacemaker [44]. Unfortunately, the current state of security and privacy in existing IMD is still very immature [45].

To enable secure communications between the implant and a medical programmer or a base station, used for configuring or reading records from the implant, SDP can be applied. When designing a pairing scheme for such a use case it is important to understand that user interaction is restricted, that is, a user cannot be actively involved in the pairing process. Thus, an IMD and the maintenance equipment must pair autonomously, which implies the unattended application class. The actual implementation of such pairing schemes is, of course, an open question but it is already clear that pairing paradigms typical for the unattended application class, that is, a notion of physical proximity or the use of contextual information can be applied. Furthermore, communication channels used for SDP can be more reasonably selected. For example, since the user interaction is limited, using HCI channels as OOB does not seem feasible, thus, the use of PHY channels is justified. Given the critical nature of IMD, it is highly favorable to select either some short-range and restricted PHY channel such as 60 GHz, or employ some means of sensing as an OOB channel for SDP.

As it can be seen, starting a design process with the application class has laid the foundation for further design steps and established a common ground for SDP schemes targeting IMD. The selection of communication channels in SDP is also better justified, and corresponds to security countermeasures proposed to mitigate attacks on IMD, that is, the application of selective jamming [45] vs. the use of short-range and restricted PHY channel such as 60 GHz.

E. Overview of Threats

The formulation of a detailed adversary model is beyond the scope of this article. However, a general overview of relevant threats is still required to meaningfully compare different SDP schemes. We consider two pairing devices D1 and D2, as depicted in Figure 2, and assume that they are not compromised with malware and controlled directly by their respective owners. The goal of an adversary is always to undermine SDP.

We focus primarily on attacks against authenticity and confidentiality, as they are the most relevant to the SDP process. We consider two broadly representative classes of adversaries seeking to undermine SDP: first, those who want to attack via PHY communications channels, and second, those who wish to attack via HCI channels.

1) *Attacks on PHY Channels:* An adversary who exploits PHY channels can mount many different attacks. The majority of these attacks are considered particularly severe in SDP, as they undermine the basic assumptions of authenticity and confidentiality that SDP seeks to establish. PHY channels used for data transmission are especially vulnerable to attacks on confidentiality such as MITM and eavesdropping attacks, while PHY channels used for data acquisition, for example, environmental sensing, are susceptible to attacks that

undermine authenticity such as relay attacks. For example, the adversary can reproduce the relevant sensor readings, by manipulating the temperature or humidity to match that of a remote location.

Regarding availability and integrity properties, the adversary can jam or otherwise disturb the communication media which can result in denial-of-service (DoS) attacks. While DoS is a legitimate security issue, because it can prevent SDP, it cannot lead to a false sense of security, that is, where two users mistakenly believe that their devices have securely paired. Hence, DoS can deny availability, but not subvert authenticity or confidentiality. This stands in contrast to MITM, eavesdropping and relay attacks where the devices will behave as though they have paired securely, when, in fact, they have not.

More sophisticated attacks such as selective jamming, disturbing signal parts or bit-flipping can force retransmissions and increase adversary's chances of compromising SDP. Time-based attacks, for instance, replaying previously captured packages or delaying messages in transmission can also impair the SDP process. In our survey, we are primarily concerned with attacks on PHY channels that can subvert authenticity and confidentiality, that is, MITM, eavesdropping and relay attacks. More exotic attacks on various PHY channels are discussed in the respective sections where relevant.

2) *Attacks on HCI Channels:* There are two main classes of HCI adversaries: (a) an external attacker, that is, someone who is not a legitimate pairing party and (b) an internal attacker, that is, one of the pairing participants.

External adversaries aim to violate the authenticity and confidentiality of the HCI channel by observing user interaction, in order to be able to covertly participate in the communications between the pairing devices. For example, an external HCI adversary may monitor the HCI during a pairing event, in order to also derive the cryptographic material being exchanged during the pairing process.

Internal adversaries, on the other hand, already have such access, but seek to use the process of pairing in order to extract sensitive data from the other participant's device. This may take the form of social engineering. When the attacker's primary objective is to participate in the pairing, in order to undermine the privacy of the other party, we label them as honest-but-curious adversaries. For example, an honest-but-curious attacker may seek to obtain the telephone number of the other party, contrary to their wishes.

F. Taxonomy

We propose a taxonomy built upon the three key concepts that have been introduced and described above: PHY channels, HCI channels and application classes, which makes the following two contributions to the field of SDP. First, it provides systematization based on these three key concepts drawn from the design space of SDP. Second, it enables qualitative assessment and meaningful comparison of different pairing schemes. The structure of our taxonomy is given in Figure 3.

In order to investigate a device's channels we adopt the following framework. First, we identify the most important

characteristics that are relevant to a communication channel. For PHY channels, such parameters are measurable and objective, whereas the HCI channels are represented by more subjective metrics. Second, we focus on three sets of properties that are vital in the context of SDP, namely: security, usability and ease-of-adoption. Third, based on this structure we review the existing pairing schemes to reveal how these properties are addressed by a particular scheme and what are the trade-offs. With regard to application classes, we first provide a thorough description of each class followed by a discussion on its specific security and usability implications. Second, we map the proposed pairing schemes to the corresponding application classes to provide a more systematic overview of the current state in the field.

In this section, we have presented and motivated our system model, as well as provided the taxonomy which we use to survey existing SDP schemes. In the next section, we review PHY channels and the corresponding pairing schemes.

IV. PHYSICAL CHANNELS

The PHY channels listed in Figure 4 allow a device to communicate with other devices as well as interact with the ambient environment. We base our analysis on several aspects to conduct the meticulous investigation of PHY channels. Specifically, we consider *channel characteristics*, *known attacks* and *ease-of-adoption* to compare different types of communication channels. With regard to security, we identify a set of channel properties that have a direct security impact, namely they indicate the amount of effort necessary to intercept the pairing process. Furthermore, we discuss pairing schemes that utilize each surveyed channel to show how it is employed to achieve pairing. Finally, we summarize the most important findings, presented in Table I, and discuss key issues from our study of PHY channels.

A. Channel Characteristics

The physical nature of wireless communication channels is described by different properties. The most important ones are the *frequency range* of transmitted electromagnetic or mechanical waves and the achievable *data rates*. In fact, the data rate is defined by technical specifications of a communication protocol, such as the available bandwidth, coding and modulation schemes, rather than the underlying PHY channel. Hence, we consider this as the amount of transmitted information in a unit of time using common state of the art protocols. The frequency and bandwidth of a particular channel comes along with certain propagation characteristics, such as *coverage*, human *perceptibility*, *penetration*, and *line-of-sight* propagation. We put these properties into security perspective by refining the observations made by Balfanz et al. [7] on location-limited channels.

1) *Coverage*: Defines the maximum nominal distance at which a signal on a PHY channel can be successfully received, that is, differentiated from noise. Naturally, increasing the sensitivity of receivers leads to wider coverage, which makes it a questionable security property. However, the amount of effort and cost required to receive a signal far outside the nominal

range are high. For an adversary, a PHY channel with smaller coverage is harder to access and thus, attack.

2) *Perceptibility*: Specifies whether a user can perceive the fact of data transmission through major human senses such as sight, hearing and touch [46]. This property can have both advantageous and harmful repercussions. On the one hand, a benign user can be alerted if some unexpected interaction occurs. On the other hand, an attacker can easily observe such type of communication without any specialized equipment. Nevertheless, this trade-off can be leveraged by secure protocol design so that the benefits of human perceptibility greatly outweigh the risks.

3) *Penetration*: The propagation properties of a particular channel depend on the underlying physics. Both electromagnetic and mechanical waves are subject to diffraction, reflection, refraction, scattering and absorption [47], [48]. With these effects a signal can be partially or entirely blocked which hinders the communication. Penetration characterizes the ability of the signal to propagate through solid obstacles such as walls, doors, and furniture. Thus, a communication channel with high blockage, that is, low penetration, effectively limits the operation range of the channel, thus hampering the attacker's ability to access it.

4) *line-of-sight (LOS)*: Signals propagate throughout the environment and find multiple paths from the transmitter to the receiver over several reflections, diffractions, and refractions. As was stated above, channels are differently affected by these factors. Generally speaking, with higher frequency diffraction and refraction become less significant. With low multi-path components a channel becomes dependent on LOS which is a direct path between a transmitter and a receiver without obstruction. Correspondingly, non-line-of-sight communication does not require an obstruction-free path between a transmitter and a receiver. LOS enables predominantly directional communication which hinders the ability of the adversary to stealthily intercept the channel from outside the main transmission beam.

B. Known Attacks

To better understand the security implications of PHY channels in SDP we summarize the most prominent attacks that have been reported on various physical media. This list of attacks is by no means exhaustive but provides an overview of common possible attacks vectors. In the literature many attacks on widespread wireless radio channels can be found. We summarize those and additionally present security implications in other communication channels such as visible light, audio, etc. Overall, our study provides a deep insight into existing threats and outlines differences in vulnerabilities and security properties among different PHY channels.

C. Ease-of-adoption

In order to evaluate how feasible it is for a specific channel to be adopted in the context of SDP we compare it with a set of available interfaces on widespread hardware such as smartphones. We make this particular choice because of the ubiquitous nature of smartphones which are viably considered

as a gateway for the personal IoT environment [49] as well as the pairing mediator for the IoT devices [50]. In detail, we employ the hardware characteristics of the fifth generation of Nexus devices [51] as a reference to identify the common interfaces present on an average smartphone.

D. Survey of PHY Channels

In the following, we survey PHY channels suitable for SDP by focusing on the previously described properties.

1) *Wi-Fi Channel*: Wi-Fi is a wireless communication technology based on a set of IEEE 802.11 standards and is used to connect devices within a wireless local area network. The most common Wi-Fi standards such as 802.11 a/b/g/n/ac operate in 2.4 and 5 GHz frequency bands. Other frequency bands, for example, around 60 GHz are also standardized (IEEE 802.11ad) but less frequently used. Due to different propagation characteristics at high frequencies, we discuss IEEE 802.11ad separately in the mm-wave section (IV-D3).

Different modes of operation are available for Wi-Fi: infrastructure, direct, and ad-hoc. The infrastructure mode is established with a centralized access point (AP), which handles all network traffic from connected stations. The latter two modes are formed in a peer-to-peer fashion directly by the devices. While Wi-Fi direct is intended to be applied in use-cases where ad-hoc Wi-Fi was previously envisaged for use, its implementation is very different. The primary difference is that Wi-Fi direct internally uses the infrastructure mode, while ad-hoc Wi-Fi remains a separate mode. Because the specification of ad-hoc Wi-Fi has not been substantially updated since the 802.11b standard, more recent Wi-Fi security and performance improvements have not necessarily been incorporated into ad-hoc Wi-Fi implementations. This would be of limited concern, were it not for the continued use of ad-hoc Wi-Fi in certain applications, particularly those where multi-hop mesh networking is required [90], [91]. While some technologies now widely adapt Wi-Fi direct [92], [93], the pure ad-hoc mode is relatively rarely used despite the number of its advantages.

The data rates of Wi-Fi communication have increased significantly over the last decade and can exceed 1 Gbit/s [94]. Wi-Fi coverage varies from 30 to 250 meters [95], [96] for indoor and outdoor environments respectively. The 5 GHz band has a smaller communication range due to a shorter wavelength and higher attenuation as compared to 2.4 GHz [97]. Wi-Fi communication is human-imperceptible and enables omnidirectional transmission with signals propagating through most non-metal objects such as walls, doors and windows.

Since Wi-Fi channels are inherently broadcast and have wide coverage, they are susceptible to a number of threats [52]. Adversaries may, for example, obtain unauthorized access to intercept transmitted information, inject and modify data in the air with surgical precision, reroute traffic for analysis with MITM attacks [53], or efficiently jam the network to cause a DoS [55], [56]. Such attacks have been shown to be feasible with low effort [54]. Moreover, due to the widespread use of Wi-Fi, identity tracking might threaten user privacy [98].

As Wi-Fi chips are ubiquitous and integrated in a wide range of devices starting from powerful laptops to resource-constrained sensors, the technology became a de-facto standard for communication of mobile devices. In the following, we describe various pairing schemes which utilize the Wi-Fi channel to accomplish pairing.

Push Button Configuration (PBC) was introduced as a part of standardized Wi-Fi Protected Setup (WPS) [57] which incorporates two other pairing schemes known as “Pin Entry” and “Near Field Communication”. The pairing is initiated when a user presses a button on one device (enrollee) which starts searching for a PBC-enabled peer within its range to complete pairing. Once a button is pressed on the second device (registrar) an unauthenticated Diffie-Hellman (DH) key exchange is performed via the Wi-Fi channel.

Despite the fact that the PBC pairing scheme is implemented on real devices and provides protection against passive eavesdroppers, it is inherently vulnerable to active adversaries who can mount MITM attacks.

Capkun et al. [58] proposed *integrity codes (I-codes)* a security mechanism that enables authentication and integrity protection of messages exchanged over a wireless radio channel. In order to achieve the stated purpose, I-codes rely on three components: unidirectional message coding, on-off keying communication, and the ability of the receiver to determine if the transmitter is within its communication range. The authors showed that authentication through presence can be achieved if communicating devices are aware of each other’s reception distance and are synchronized with respect to the start of transmission.

Security properties of I-codes were discussed in the presence of a powerful attacker who has full control over a wireless channel except for her inability to disable the whole communication, for example, remove the energy of a signal. Based on I-codes a new version of the DH protocol was proposed which was claimed to be optimal in the sense of transmitted message length and the corresponding security level.

Gollakota et al. suggested *tamper-evident pairing (TEP)* [59], a scheme that utilizes on-off coding to prevent MITM attacks on the wireless channels. Specifically, the authors introduced a primitive called Tamper Evident Announcement (TEA) which completely prevents active attackers from either changing the content of a transmitted message or hiding the fact that the message was sent. To achieve the stated goal the TEA mechanism introduces silence periods. Particularly, the payload of the TEA message is appended by a sequence of short equal-sized packets called slots in which the transmitter chooses to either send data (on-slot) or remain idle (off-slot).

The TEP scheme uses a bit sequence produced by on-off slots to encode the hash of the TEA payload. In this case, an adversary might tamper with the off-slots by transmitting a signal, while she cannot remove energy from the on-slots. Hence, attackers that have no physical access to the pairing devices are prevented from tampering with the transmitted signal, they can neither suppress the communication nor create a capture effect [99].

TABLE I
SUMMARY OF PHY CHANNELS

PHY Channel	Channel Characteristics							Attacks	Common Interface	Pairing Scheme
	Description	Frequency Range	Typical Data Rates	Typical Coverage	Perceptibility	Penetration	Line-of-sight			
Wi-Fi (§IV-D1, pp. 8)	Wireless Radio Comm.	2.40 GHz–2.48 GHz, 5.03 GHz–5.83 GHz	1 Mbit/s–1 Gbit/s	30 m–250 m	○	High	○	Eavesdropping [52] MITM [52], [53] Jamming [54], [55] DoS [55], [56]	●	Push Button Configuration [57] Integrity codes [58] Tamper-evident pairing [59]
Bluetooth (§IV-D2, pp. 8)	Wireless Radio Comm.	2.40 GHz–2.48 GHz	1 Mbit/s–24 Mbit/s	1 m–100 m	○	High	○	Eavesdropping [60] MITM [37], [60] DoS [60]	●	Just Works [43]
mm-Waves (§IV-D3, pp. 10)	Wireless Radio Comm.	57 GHz–64 GHz	6.75 Gbit/s	10 m	○	Low	●	Eavesdropping [61]	○	Push Button Configuration [57]
RFID (§IV-D4, pp. 10)	Wireless Radio Comm.	120 kHz–150 kHz, 13.56 MHz, 850 MHz–960 MHz, 2.45 MHz, 5.8 GHz, 3.1 GHz–10.6 GHz,	4 kbit/s–1.5 Mbit/s	10 m (passive) 100 m (active)	○	Medium	○	Eavesdropping [62] Unauthorized access [63], [64] Relay [63], [65] DoS [62]	○	Noisy tags [66] Adopted-Pet [67]
NFC (§IV-D5, pp. 11)	Wireless Radio Comm.	13.56 MHz	424 kbit/s	10 cm	○	Medium	○	Eavesdropping [68] Unauthorized access [64] Relay [69]	●	Near Field Communication [17] Out-of-band [70]
VLC (§IV-D6, pp. 11)	Wireless Visible Comm.	400 THz–800 THz	11 kbit/s–96 Mbit/s	10 m	●	Low	●	Eavesdropping [71]	○	KeyLED [72] Enlighten Me! [73] Flashing displays [74]
Visual (§IV-D7, pp. 12)	Wireless Visual Comm.	400 THz–800 THz	12 Mbit/s, 324 kbit/s	10 m, 20 cm	●	Low	●	Eavesdropping [75] Replay [76]	●	SBVLC [75]
IrDA (§IV-D8, pp. 12)	Wireless Infrared Comm.	334 THz–353 THz	2.4 kbit/s–1 Gbit/s	1 m	○	Low	●	Replay [77] Eavesdropping [71]	○	Talking to Strangers [7]
Audio (§IV-D9, pp. 13)	Wireless Acoustic Comm.	20 Hz–20 kHz	20 bit/s, 4.7 kbit/s	~20 m, ~4 m	●	Medium	○	Eavesdropping [39] Relay [78]	●	Loud and Clear [41] HAPADEP [33] Zero-Power pairing [79]
Ultrasound (§IV-D10, pp. 13)	Wireless Acoustic Comm.	20 kHz–20 MHz	230 bit/s, 2 kbit/s	11 m, 2 m	○	Low	○	Eavesdropping [80] Relay [80], [81]	●	Ultrasonic ranging [82]
Haptic (§IV-D11, pp. 14)	Wireless Haptic Comm.	40 Hz–800 Hz	200 bit/s	physical contact	●	Low	○	Eavesdropping [39]	●	Vibrate-to-unlock [83] Shot [38] Vibreaker [84]
Sensing (§IV-D12, pp. 15)	Onboard Sensors	n/a	n/a	n/a	●	n/a	●	Relay [78], [85] Context-manipulation [78] Reproducible readings [38] GPS: Spoofing, jamming [86]	●	Amigo [27] Good Neighbor [87] Wanda [88] Ambient Audio pairing [28] Zero-interaction pairing [19] MagPairing [89] Touch-And-Guard [21]

● = fulfills property; ● = partly fulfills property; ○ = does not fulfill property

2) *Bluetooth Channel*: Bluetooth is a wireless communication technology which operates in the 2.4 GHz frequency band and is used to connect several devices in an ad-hoc manner, thus forming a personal area network [100]. Typical data rates for Bluetooth are 1–3 Mbit/s but can reach 24 Mbit/s [101]. Bluetooth coverage varies from 1 to 100 meters depending on the utilized antennas [60] and can be used in both indoor and outdoor environments. Physical characteristics of Bluetooth communication are similar to those of 2.4 GHz Wi-Fi, therefore it cannot be sensed by humans, achieves relatively high penetration of solid objects and does not require LOS for data transmission.

Bluetooth communication is vulnerable to similar security

issues as Wi-Fi, despite the fact that a Bluetooth channel is more difficult to access due to its shorter range. In addition, attacks to extend over the nominal communication range, obtain unauthorized data access, or fuzz protocol implementations to reveal vulnerabilities have been shown to be feasible [60] with low hardware requirements. Moreover MITM attacks [37], as well as DOS [60] are as practical as in Wi-Fi.

Currently, low-power Bluetooth chips are pervasive and can be found in billions of devices. Further, we review a prominent pairing scheme that relies on the Bluetooth channel.

Secure Simple Pairing [43] proposed by the Bluetooth SIG is a de facto standard for pairing multiple personal devices. With a recent security enhancement [18] there are now

four schemes available for Bluetooth pairing: “Just Works”, “Numeric comparison”, “Passkey Entry” and “Out-of-band”. However, only the first scheme solely relies on the Bluetooth channel to achieve pairing, whereas others utilize HCI or other PHY channels, for example, Near Field Communication (NFC), to ensure authenticity.

The *Just Works* scheme is used to perform pairing with constrained devices, for example, a headset, which lack convenient input/output capabilities such as a keyboard or a display. In essence, Just Works is based on an unauthenticated DH key exchange which provides protection against passive eavesdroppers but is inherently vulnerable to active MITM attackers [43].

3) *mm-Waves Channel*: mm-Wave wireless communications operate in a wide frequency band from 30 to 300 GHz. The lower part of the mm-Wave spectrum (30–50 GHz) is considered to be used in cellular and indoor environments with the coverage of up to 200 meters [102], although high-speed outdoor point-to-point links can work over longer distances [103]. At higher frequencies, an unlicensed spectrum around 60 GHz is being standardized (IEEE 802.11ad [104]) and deemed to be actively used for a great variety of indoor applications [105].

With mm-Waves very high data rates are possible due the wide channel bandwidths available. For example, IEEE 802.11ad achieves transmission speed of up to 6.75 Gbit/s within the coverage area of up to 10 meters [106]. Due to high attenuation and absorption rates mm-Waves at 60 GHz do not propagate through solid objects, for example, walls, and the LOS requirement is imposed on the mm-Wave communication [107]. Being a part of the microwave spectrum mm-Waves cannot be perceived by humans.

The plausible properties of mm-Waves such as the short range, LOS transmission and no wall penetration were claimed to provide highly secure operation [103]. However, as was recently shown [61] eavesdropping is possible on a 60 GHz channel through reflections caused by small-scale objects located within a transmission beam. At the moment, 60 GHz chips can only be found in a few commercial products, for example, [108], but the number of supported devices will undoubtedly increase in the medium term. Next, we describe a pairing scheme which uses the mm-Wave channel.

Despite being a relatively new technology, 60 GHz communication has already adopted pairing schemes from the standardized WPS such as PBC [109]. Nevertheless, the PBC pairing is susceptible to MITM attacks as stated above. However, due to the short-range transmission with LOS, an adversary would have to be co-present, that is, in the same room, and interfere within a transmission beam in order to mount such an attack. These actions are much harder to perform stealthily without a benign user noticing them, which was not the case for the legacy Wi-Fi PBC.

4) *Radio-frequency Identification (RFID) Channel*: RFID is a wireless communication technology which is used for automatic identification in both indoor and outdoor environments. That is, an RFID system consists of tags (active or passive) which store the identification information and readers that query the tags in order to extract and verify

that information [110]. More ubiquitous passive tags have to harvest energy from nearby RFID reader’s interrogating radio waves, whereas active tags have on-board power supply, for example, a battery.

RFID operates in several frequency bands [110]: Low Frequency (120–150 kHz), High Frequency (13.56 MHz), Ultra-High Frequency (860–960 MHz), Microwave (2.45 and 5.8 GHz), Ultra-Wide Band (3.1–10.6 GHz). Typical data rates vary from several to hundreds of kbit/s and depend on the utilized spectra [111]. The coverage that was reported for the RFID technology ranges from 10 to 100 meters for passive and active tags correspondingly [110], [112]. Regardless of the underlying frequency, RFID communication cannot be sensed by humans. However, the capability of RFID transmission to pass through solid objects depends on the used spectrum as well as the employed antenna and is higher for active RFID. For sending and receiving data with RFID LOS is not required.

There are several security concerns regarding RFID communication. First, its wireless nature poses threats similar to Wi-Fi and Bluetooth which are especially prominent for active tags operating over longer distances [62]. Second, passive tags are very constrained devices and can promiscuously respond to any reader request [113] despite being short-range. It was shown that RFID channels are vulnerable to eavesdropping, unauthorized access, relay and DoS attacks [62]–[65]. The relay attacks on contactless smart cards are especially severe, as they can easily circumvent security of payment and access control systems [65], [114], and defending against such relay attacks is an active research area [113], [115], [116].

RFID tags are presently ubiquitous and can be found in many applications such as logistics, tracking and access control [117]. Nevertheless, most consumer devices, for example, smartphones, are not supplied with built-in RFID chips and use the NFC technology instead. Several representative pairing schemes which employ the RFID channel are described below.

Castelluccia and Avoine [66] presented a pairing scheme called *Nosy Tags* for secure key establishment over a wireless RFID channel between a passive tag and a reader. In essence, the pairing scheme relies on noise injection into a public communication channel, which makes the actual signal meaningless for an eavesdropping adversary, but allows the reader to efficiently restore the original message. This idea is implemented by introducing an extra RFID tag (a nosy tag) which belongs to the reader and shares a secret key with it.

The proposed pairing scheme works as follows. When the reader queries a passive tag within its proximity the nosy tag generates a sequence of random bits, which prevents the eavesdropper from differentiating between the original message sent by the queried tag and the one injected by the nosy tag. On the reader’s side the generated noise can be subtracted to recover the actual signal.

The authors provided three variants of their pairing scheme based on the nosy tags and analyzed its security against passive attackers. Nevertheless, the pairing scheme can still be circumvented by active adversaries.

Amariuca et al. [67] suggested *Adopted-Pet*, an automatic time-based scheme for pairing a passive RFID tag with a

reader without any human interaction or additional PHY channels, for example, NFC. The main idea is as follows. A tag can reassure that a particular reader is trusted only if it spends a sufficient amount of uninterrupted time within the proximity of this reader. Specifically, a tag has to be interrogated only by a single reader (uninterrupted property) for a time period during which the tag gradually transmits pieces of its secret password which are accumulated by the reader in order to eventually restore the secret.

The authors implemented their pairing scheme using a linear-feedback shift register and argued that it is robust against adversaries who can spend numerous interrupted time intervals in the proximity of a victim tag.

5) *NFC Channel*: NFC is a wireless communication technology which is used to establish point-to-point communication between two devices brought to close proximity. NFC is an offshoot of RFID technology, thus NFC devices can similarly be active or passive [118]. NFC operates in 13.56 MHz frequency band and supports data rates of up to 424 kbit/s [69]. NFC has very limited coverage of up to 10 cm [69]. Similarly to RFID, NFC communication cannot be perceived by humans, is able to penetrate solid object to a certain degree, and does not require LOS for data transmission.

Initially, security assumptions about NFC were based on its very short range and, hence, severe difficulty for an attacker to access it. However, recently it was shown that eavesdropping on NFC channels is possible at a distance of up to 240 cm [68]. In addition, unauthorized readings [64] pose a real threat which can lead to practical relay attacks on the NFC communications [69]. With the advent of mobile NFC payments, the relay attacks on such systems have become a severe security threat [119]–[121], which has not yet been fully addressed [122], [123].

NFC chips are widely deployed, and can be found in numerous smartphones and other devices. We present two pairing schemes which utilize the NFC channel.

Near Field Communication [17] is a pairing scheme from the standardized WPS mentioned previously. Specifically, the NFC channel can be used to transmit a hardware generated password from one device that initiates pairing (enrollee) to another device (registrar) with which the pairing should be performed. Another pairing setting available with WPS NFC is to exchange hashes of public keys between the enrollee and registrar once they are brought to close proximity, that is, physical contact.

The security assumptions of WPS NFC are based on the limited communication range provided by the NFC technology, which is much more difficult for an adversary to eavesdrop.

Out-of-band [70] is a pairing scheme provided by standardized Bluetooth Secure Simple Pairing. It works as follows. Once two devices have discovered each other via the Bluetooth channel, the NFC channel is used to exchange authentication information, for example, Hash C, Randomizer R or TK-value, between the devices in order to accomplish pairing.

The security arguments for the Out-of-band scheme rely on the restricted nature of the NFC communication which cannot be easily accessed by an attacker.

6) *Visible Light Communication (VLC) Channel*: VLC is a wireless communication technology which carries information by modulating light in the visible spectrum that is used for illumination [124]. VLC operates in the 400–800 THz frequency band and is widely considered to be used for indoor short range communications [124]. The data rates that can be achieved by the existing standard (IEEE 802.15.7 [125]) vary from 11.67 kbit/s to 96 Mbit/s [126], although recent research demonstrated throughput of up to 20 Gbit/s [127]. Typically, VLC has coverage of up to 10 meters [128] and it is perceived by humans via the sight sense. VLC transmission requires LOS and cannot penetrate non-transparent solid objects such as walls and doors.

Therefore, VLC communication is concealed, to some extent, from an adversary who is not co-present. However, recently it was shown that VLC can be efficiently eavesdropped by the attacker located outside of the room where communication happens [71]. Additionally, in [129] it was discussed that the integrity of a VLC channel can be affected by an adversary using a directional light source, for example, a laser.

At present, there are no commercial devices, for example, smartphones, that support a standardized VLC technology (IEEE 802.15.7). However, fully functional prototypes [130] have been recently demonstrated, which makes it feasible that the VLC-enabled devices will appear on the market soon. In the following, we review representative pairing schemes that rely on the VLC channel.

Roman and Lopez [72] studied the applicability of visible light as OOB in the context of wireless sensor networks (WSN) where two previously unknown devices want to exchange sensitive information. The authors developed a scheme called *KeyLED* with which two constrained sensors can pair. Particularly, two devices located in close proximity utilize a LED-photosensor pair to set up a short distance communication channel (few cm) and transmit their public keys using on-off keying.

The security of the proposed pairing scheme was discussed with respect to eavesdropping, injection and DOS attacks. It was claimed that even though such threats are feasible, mounting them in practice is difficult and a benign user who initiates communication between two sensors can be easily alerted in case of the attack.

The similar line of work by Gauger et al. [73] investigated an ad-hoc key assignment for devices in WSN. The suggested *Enlighten Me!* scheme was considered for two application scenarios: *a*) initial key assignment as a part of the WSN configuration *b*) dynamic key re-assignment of already deployed sensors.

The proposed pairing scheme works as follows. There is a master device (key sender), which provides a set of sensors (key receiver) residing within its wireless range with secret keys using an auxiliary light channel. During the key assignment procedure, the discovery of a receiving device, secret transmission and verification is achieved with a light source-sensor channel using Manchester coding.

The authors implemented two types of key senders: a sensor node lamp with a powerful LED and a smartphone with a

varying brightness level on a display. For both prototypes they argued that eavesdropping the transmitted key is difficult to achieve in practice, because the realized VLC channel can be effectively concealed from an outside observer.

Kovačević et al. [74] proposed *Flashing displays*, two multichannel deployment schemes for secure initialization of wireless sensors using only a multi-touch screen of a smartphone or a tablet as a light source. Particularly, both schemes utilize two channels: wireless radio and VLC, where the former is considered as insecure and the latter is used as OOB.

The first scheme relies on a visible light channel that is established between a display of a smartphone and a light sensor of a constrained device once it is put on top of the screen. In this setting, several constrained devices can simultaneously receive secret keys which have to be verified later on over a wireless radio channel.

The second scheme was introduced in order to address a powerful adversary who can still eavesdrop on the VLC channel via electromagnetic emissions of a flashing display. Specifically, the developed mechanism incorporated both the VLC channel, for synchronization purposes, together with customized integrity codes [58]. The authors showed that such a pairing scheme is secure against an attacker who can read the content of the flashing screen at any moment in time.

7) *Visual Channel*: A visual channel enables wireless communication in the visible light spectrum (400–800 THz) by utilizing currently abundant LCD-camera hardware. Such real-time transmission was shown feasible at 12 Mbit/s within a distance of 10 meters using large displays and high-speed digital cameras [131]. Another line of research [132]–[134] investigated visual communication that can be established with the LCD-camera found on commodity hardware such as smartphones. The results indicate that data transmission at 324 kbit/s is possible in the vicinity of 20 cm.

Such visual channels, whose properties include short range of communications and interference-free operation, were claimed to provide secure transmission [131], [135]. However, the fact that an LCD-camera channel can be observed and easily interpreted by humans comes with a drawback. Specifically, eavesdropping either in a form of shoulder surfing or ubiquitous CCTV was shown to be a real threat [75], especially taking into account the continuous increase of display sizes [136], [137] and recent advances in CCTV [138]. Another security issue that was raised is related to the “liveness” of the captured video stream, which can lead to replay attacks [76].

At present, camera-display peripherals are ubiquitous on numerous devices such as smartphones. Further, we describe a pairing scheme based on the visual channel.

Zhang et al. [75] investigated secure bar-code communication for smartphones. They proposed *SBVLC*, a novel approach for secure ad-hoc interactions which can be established via a short-range LCD-camera channel on mobile devices.

The authors suggested a pairing scheme based on SBVLC that works as follows. To pair, two parties utilize a full duplex LCD-camera channel which is realized as a sequence of QR-codes displayed on the screen of one device and

captured by the camera of another device. Specifically, once two smartphones are brought to physical proximity, that is, within a few inches, they start to simultaneously exchange key material using the described visual channel. Afterwards, one of the devices randomly picks a universal hash function which is used to build a shared secret key from the material accumulated by both parties.

The security of the proposed approach was formally analyzed against the eavesdropping adversary by employing 2D and 3D geometric models. In addition, it was shown that proactive rotation of the devices during pairing can enhance security, since the attacker is forced to capture frames simultaneously from both displays to undermine the pairing scheme. Moreover, the authors showed that the established key has enough entropy, that is, cannot be recovered, if the adversary misses at least one frame during the key exchange, which further improves security.

8) *Infrared Data Association (IRDA) Channel*: IRDA is a set of wireless communication technologies that uses the infrared radio spectrum 334–353 THz [139] for point-to-point data transmission. Since IRDA is susceptible to interference from ambient light sources [140] it is mostly considered for indoor applications. With the IRDA communication high data rates of up to 1 Gbit/s [141] are possible. IRDA has coverage of up to 1 meter, is human-imperceptible and requires direct LOS.

IRDA was claimed [141] to provide secure data transmission due to its short range, directional operation (a 30° beamwidth) and the fact that infrared communication cannot traverse through solid objects such as walls and doors. However, such claims cause controversy because with toolkits like *TV-B-Gone* [77] a variant of replay attacks can be mounted over relatively long distances [142]. In addition, the eavesdropping attack through reflections recently demonstrated on VLC [71] can be feasibly applied to the infrared channel since the two media have very similar physical properties.

Presently, many IRDA-enabled devices can be found in consumer electronics and household appliances, although such technology is obsolete on modern smartphones. Nevertheless, there is a growing number of personal devices supplied with IR-blasters [143] which indicates the restored interest to the infrared communication. One such pairing scheme which makes use of the infrared channel is described next.

Balfanz et al. [7] suggested a pairing scheme known as *Talking To Strangers*. The core idea behind was to combine demonstrative identification from the user perspective, for example, two physical devices with which a user interacts, with location-limited channels that aim to provide data authenticity. The latter concept denotes exactly the OOB channel.

The basic pairing scheme proposed by the authors works as follows. First, two devices exchange commitments to their public keys, that is, hashes, over an IRDA communication channel which serves as the OOB channel. Second, they transfer their corresponding public keys over a wireless radio channel. The wireless communications is verified against the initial commitment that was transmitted over the infrared channel. In addition, several other schemes were developed

upon the basic pairing approach which dealt with constrained devices and group pairing.

The authors discussed security implications of the proposed pairing and pointed out that an adversary would have to actively intercept the OOB channel in order to undermine the pairing scheme.

9) *Audio Channel*: Audio is a mechanical pressure wave caused by periodic vibrations within an audible frequency range of 20 Hz–20 kHz [144]. An audio channel in this case would be represented by a speaker-microphone pair, where the former generates a sound and the latter records it.

The line of research [145]–[148] investigated the throughput and coverage of the audio channel utilizing different modulation schemes. The results indicate that with inexpensive speakers and microphones found on commodity hardware, such as laptops, data rates can go from 20 bit/s to 4.7 kbit/s over distances from 19.7 to 3.89 meters respectively. Naturally, the audio channel can be perceived by humans via the hearing sense. The audio signal can, to a certain extent, pass through solid objects, for example, walls, although the penetration capability very much depends on the used frequency and environment which determine pass loss factors [149]. For transmission the audio channel does not require LOS, however, the signal reception is largely affected by several aspects: *a)* intensity of a sound source *b)* ambient noise *c)* acoustic environment *d)* directionality and sensitivity of a microphone [150].

With respect to security, eavesdropping was shown to be easily achievable using off-the-shelf equipment even for specifically designed short-range sound waves [39]. Moreover, relay attacks are possible since audio streaming tools are highly available on mobile devices such as smartphones [78].

Currently, microphones and speakers are pervasive on many existing platforms ranging from simple sensors to powerful laptops. We describe several pairing schemes which utilize the audio channel.

Goodrich et al. [41] suggested an approach to human-assisted authentication of previously unknown devices using the audio channel. The developed *Loud and Clear* (LC) pairing scheme requires two devices to be equipped with speakers, or when one device does not have a speaker, it should be supplied with a display.

The LC pairing consists of two phases and works as follows. First, both devices exchange their public keys over a wireless radio channel such as Wi-Fi or Bluetooth. Second, the audio channel is used to transmit the hashes of public keys encoded as MadLib sentences which can be verified by the user. Specifically, in case of both devices having speakers the user has to confirm the equality of the generated audio sequences. Whereas, for the speaker-display setting the user needs to ensure that a sentence played by the first device is similar to the one displayed on the screen of the second device.

The authors analyzed the security of the LC pairing scheme and concluded that MITM attacks can be easily detected if the user is diligent when comparing verification audio sequences.

Soriente et al. [33] proposed a pairing scheme called *HAPADEP* which relies on the audio channel to transmit both

data and verification information between previously unknown devices.

The HAPADEP pairing scheme consists of two steps and works as follows. First, both devices exchange their public keys over the audio channel using the fast codec which allows higher transmission speed, but makes the signal meaningless for a user. During the second phase two devices encode the hash of the exchanged cryptographic material using the slow codec and play back the sound, for example, a melody or a MadLib sentence, that can be recognized and verified by the user. That is, if both audio sequences heard by the user match then the pairing is considered to be successful.

The authors provided the implementation of the HAPADEP pairing and conducted a usability study, which revealed that the scheme was generally accepted by the users. Moreover, they discussed the resilience of the proposed pairing to MITM, impersonation and DoS attacks. The HAPADEP scheme was cryptographically extended in the unified pairing framework [151] to provide perfect forward secrecy (PFS), which further increases security against MITM attackers.

Halperin et al. [79] investigated security and privacy implications in IMD. Specifically, they revealed that communication between the implant and the medical programmer, used for the collection of sensitive data and IMD reprogramming, happened without encryption or authentication. This opened the door for attacks such as eavesdropping, replay and DoS. To mitigate the aforementioned threats, the authors proposed zero-power pairing, which can be applied to batteryless constrained devices such as passive RFID tags.

The suggested pairing scheme works as follows. The programmer initiating pairing sends a RF signal to power the passive component of the IMD, which, in turn, generates a session key and broadcasts it as a modulated sound wave that is recorded by the programmer's microphone.

The authors reasoned about the security of the proposed pairing scheme based on two points. First, since the microphone is placed within a few centimeters of a patient's chest it can easily receive the audio signal. However, it is very difficult to obtain the same signal from farther distance without dedicated hardware equipment. Second, by utilizing the audio channel for the key exchange, the user is provided with audible and tactile feedback, which brings her attention to the fact of pairing.

10) *Ultrasound Channel*: Ultrasound refers to acoustic waves that lie within a frequency range above audible sound (20 kHz–20 MHz) [152]. In this spectrum, frequencies higher than 250 kHz are strongly absorbed by the air and, thus, mostly used for medical imaging rather than data transmission [153]. As in case of audio, the ultrasound channel is formed by an ultrasonic speaker-microphone pair, which are based on the piezoelectric effect to produce high frequency waves [48].

Similar to audio, the throughput and transmission range of the ultrasound channel were evaluated in prior work [145]–[148], [154]. Specifically, data rates can vary from 230 bit/s to 2 kbit/s at corresponding distances of 11 and 2 meters. Contrary to audio, the ultrasound communication cannot be sensed by humans. When propagating through air, the ultrasound signal is subject to high reflection and absorption rates

caused by solid objects, for example, walls, which makes the ultrasound communication limited to a single room [80]. For data transmission with ultrasound LOS is not required.

As for security implications, it was shown that a co-present adversary can eavesdrop and manipulate the ultrasound channel, although attacker capabilities largely depend on her position relative to communicating parties [80]. Moreover, relay attacks can be mounted on the ultrasound channel when it is used for a distance estimation as a part of the authentication procedure [80], [81].

At the moment, few end-user devices are supplied with dedicated ultrasonic chips. However, the lower part of the ultrasound spectrum can be generated and recorded by non-specialized hardware present on existing smartphones [155] and laptops [154]. A pairing scheme that employs the ultrasound channel is presented below.

Mayrhofer et al. [82] studied how secure spontaneous interactions can be established with spatial references. They developed a pairing scheme that utilizes the ultrasound channel for initial device discovery and then implicitly for authenticity verification.

The proposed pairing scheme works as follows. First, two devices become aware of each other and learn their corresponding distances and relative positions by employing the ultrasound sensing. Second, both devices perform an unauthenticated DH key exchange over a wireless radio channel. Third, devices authenticate each other by sending a nonce encrypted with a shared key over a wireless radio channel and transmitting the plain nonce over the ultrasound channel using the interlock protocol [156]. Specifically, the nonce value is split into pieces and each part is transmitted as a delayed ultrasound pulse to another device, which results in a longer distance than the previously obtained spacial reference. Thus, the receiving device can subtract the initially learnt distance from the received measurement to acquire a part of the nonce and gradually learn the full nonce.

The authors discussed the security of the pairing scheme with respect to eavesdropping, relay and MITM attacks. It was claimed that the suggested pairing can mitigate and detect those adversaries even if they have access to both radio and ultrasound channels (assuming a benign user is attentive).

11) Haptic Channel: A haptic channel is formed by low frequency waves within a range of 40–800 Hz that cause tactile sensations [157]. For data transmission such a channel can be represented by a vibrator-accelerometer pair, where the former generates a set of pulses captured by the latter. Recently, it was demonstrated that with advanced modulation and coding schemes, data rates of up to 200 bit/s can be achieved over the haptic channel using off-the-shelf hardware [158]. Obviously, haptic communication requires direct physical contact between the sender and the receiver. By its nature haptic transmission does not propagate well in the air and cannot pass through solid objects, for example, walls. Furthermore, haptic communication is human-perceptible and it does not require LOS.

Despite the restricted nature of the haptic channel it was shown that eavesdropping is possible through acoustic side channels [39].

The haptic channel realized with a vibration motor and an accelerometer can presently be found on numerous end-user devices such as smartphones. Several pairing schemes that use the haptic channel are presented below.

Saxena et al. [83] proposed a pairing scheme called *Vibrate-to-Unlock* which is used to establish a shared secret between an RFID tag and a smartphone that belong to the same user.

The suggested pairing scheme works as follows. Initially, a smartphone selects a secret PIN (14-bits) and transmits it as an on-off coded sequence of vibrations. An RFID tag that is brought to contact with the vibrating phone records the data with its accelerometer, decodes the PIN and stores it. After the enrolling step, two devices share a common secret. Later on, when an RFID tag is powered once in the vicinity of the reader it can only be unlocked if a user authenticates herself by proving the possession of the pre-shared PIN with her phone, that is, similarly as described above.

The authors claimed that their scheme has a corresponding security level of the 4-digit PIN prompted at the ATM with 3 attempts. Moreover, they argued that the suggested pairing can mitigate such attacks as user tracking, impersonation and ghost-and-leech.

Studer et al. [38] investigated security implications of the Bump exchange protocol [159] and revealed that it is vulnerable to MITM attacks. Hence, the authors presented a new scheme known as *Shot* to pair two smartphones in a user-friendly manner.

The Shot scheme uses a server which is considered as an insecure channel between two devices to be paired and works as follows. The first device (endorser) hashes its public key and transmits the truncated version of the hash (80-bits) to another device (verifier) as a sequence of vibrations. This message serves as a pre-authenticator and is used by the verifier to bootstrap communication with the server, that is, as a session identifier. By utilizing the server two devices exchange their identities and public keys. With such information at hand, the verifier can compute the hash of the endorser's public key and compare it with the previously sent pre-authenticator. Once checked the verifier informs the endorser about the success or failure of the pairing via a binary vibration.

The authors analyzed the security of Shot pairing and claimed that it can withstand all types of active attacks on the insecure channel given an adversary cannot inject messages into the haptic channel.

Anand and Saxena [84] investigated how the previously proposed Vibrate-to-Unlock scheme [83] can be secured against acoustic side channels [39]. Their approach was to actively inject noise in order to cloak the acoustic leakage emanating from the vibrations. The enhanced pairing scheme called *Vibreaker* utilized a built-in speaker of a smartphone to generate a masking signal, which makes the acoustic side channel indistinguishable for an eavesdropping adversary. Specifically, the authors explored white noise and vibration noise, for example, pre-recorded representation of audio leakage, as feasible candidates for masking. In this case, the pairing procedure (Vibrate-to-Unlock) is complemented by an extra step when a transmitter injects the masking signal during the PIN transmission through vibrations. The results indicated that

both types of noise can efficiently conceal the acoustic side channel even if the attacker applies filtering techniques.

12) *Sensing Channel*: A sensing channel is used to obtain information about the ambient environment as well as determine a device's location, position and orientation. Recently, the use of built-in sensors was proposed for authentication purposes where proximity detection was applied in order to mitigate relay attacks [31], [63], [160], [161]. There are several types of sensor modalities that were discussed in prior research:

- Radio (Wi-Fi, Bluetooth).
- Audio.
- Motion and position (accelerometer, gyroscope, magnetometer).
- Location (GPS).
- Physical (temperature, pressure, luminosity, humidity, etc.).

Radio and audio are used to obtain information about wireless radio and acoustic channels described above. That is, with Wi-Fi and Bluetooth antennas signals from APs and peer devices can be received, while ambient audio can be captured with a microphone. In case of radio and audio the sensing range cannot be delimited precisely, because it very much depends on the receiving antenna or a microphone, transmitting power and the channel quality.

Motion and position is measured by a set of sensors that allow a device to detect movement as well as determine its relative position and orientation [162]. Readings from an accelerometer, a gyroscope and a magnetometer are easily affected by user actions and the ambient environment which makes the measurements obtained by similar sensors within some distance highly uncorrelated [89].

Location sensing is represented by the GPS system, which provides the worldwide outdoor positioning within the accuracy of several meters [163]. The GPS technology utilizes several frequency bands such as 1575.42 MHz and 1227.60 MHz for transmission. The data rates available with GPS can go up to 50 bit/s. The GPS communication requires direct LOS since the signals cannot easily pass through non-transparent solid objects such as walls and doors.

Physical sensing is used to capture information about the surrounding environment such as temperature, pressure, luminosity, etc. Typically, physical characteristics do not vary too much within close proximity, but significantly differ for various locations, for example, indoor vs. outdoor or neighboring rooms, etc.

Previously, it was claimed [160] that tampering with the ambient environment is a hard task in which an adversary is unlikely to succeed. However, a more recent study [78] revealed that it is feasible to manipulate readings of different sensors such as radio, audio and physical in a controlled way using off-the-shelf hardware. With regard to motion and position modalities, it was demonstrated that accelerometer readings can be reproduced with sufficient precision [38]. This vulnerability stems from the limited accuracy of built-in sensors and can be further increased in case the attacker manages to observe specific user actions, for example, shaking or bumping. As for outdoor location services, such as GPS, it

was shown to be susceptible to attacks such as spoofing and jamming [86].

Currently, many devices are supplied with sensing capabilities with smartphones having several different ones, although various physical sensors are still not widely deployed. In the following, we review a number of pairing schemes which utilize the sensing channel.

Varshavsky et al. [27] proposed a pairing scheme named *Amigo* to authenticate co-located devices without explicit user involvement. Specifically, they suggested utilizing a common radio profile which is location and time specific as the indicator of physical proximity.

The pairing scheme works as follows. First, two devices, brought to close proximity, perform an unauthenticated DH key exchange over a wireless radio channel (Wi-Fi). Second, both devices start monitoring the ambient radio environment for a short period of time and construct a signature containing identifiers and signal strength of the packets received during the snapshot. Finally, two devices exchange their signatures over a secure channel using a commitment scheme in order to verify if the received and local measurements match.

The authors analyzed the security of their pairing scheme and reported that *Amigo* is resilient to attacks such as eavesdropping, MITM and impersonation.

Cai et al. [87] investigated how to establish secure communication between previously unknown devices without any shared secrets and OOB channels. They proposed a pairing scheme called *Good Neighbor* which uses received signal strength (RSS) between multiple antennas of the same device (receiver) to differentiate if another device (sender) is nearby or not. Specifically, if the sender is in close proximity of the receiver, the RSS values measured by two receiver's antennas would be substantially different, which is not the case when the (malicious) sender is far away irrespective of its transmitting power.

The suggested pairing scheme relies on the correlation between the RSS and physical proximity and works as follows. First, the sending device initiates pairing by requesting a public key of the receiving device once brought close to its first antenna. Second, the sender generates a session key which is encrypted with the receiver's public key and starts to repeatedly transmit the session key to the receiver. Meanwhile, the sender needs to be moved to the second antenna of the receiver. Finally, the receiver calculates the ratio of the RSS values obtained from two antennas and checks if the number of consecutive measurements are above a pre-defined threshold.

The authors evaluated their pairing scheme with respect to a powerful adversary who can eavesdrop on the wireless channel, arbitrarily adjust the transmitting power of her devices and gain knowledge about the location of receiver's antennas. The results indicated that the proposed pairing can successfully mitigate such an attacker.

Pierson et al. [88] proposed *Wanda* a pairing scheme built upon *Good Neighbor* pairing [87] to securely introduce mobile devices. Conceptually, the "Wand" was realized as a portable hardware device supplied with two antennas located half wavelength apart. Similarly to *Good Neighbor* the scheme uses signal strength to determine if the Wand and a target

device are nearby (detect primitive). However, Wanda expands upon Good Neighbor by utilizing wireless signal reciprocity to securely transmit data between the Wand and the target device via the in-band channel (impart primitive).

The proposed pairing scheme works as follows. First, a user enables the target device, for example, pressing a button, which starts broadcasting beacon packets and points the Wand to it. Using the RSS ratio of the received beacons from two antennas the Wand determines if the target device is in close proximity. Second, to send a message the Wand encodes it as a binary string and transfers one bit at a time. Particularly, a packet transmitted using the closest antenna is considered as “1”, and “0” if it is sent from the farthest antenna. To decode the message the target device calculates the average RSS from all received packets and checks if the RSS of a specific packet is above or below the average, that is, either “1” or “0”. Finally, the Wand sends the hash of the transmitted message, which can be verified by the target device.

The authors evaluated the security of the Wanda scheme against eavesdropping and malicious packet injection. Their findings showed that the proposed pairing can withstand both types of attacks.

Schürmann and Sigg [28] studied how a secure communication channel can be established between two devices in an ad-hoc manner by utilizing ambient audio. Specifically, they proposed a mechanism that uses audio fingerprints obtained by two devices from the shared ambient environment to derive a common secret key without exchanging any information about the captured audio context.

The suggested pairing scheme works as follows. First, two devices synchronize their clocks by running an NTP-based protocol. Second, two devices start simultaneously recording the ambient audio with their local microphones. The obtained audio fingerprints are very similar but not identical due to noise and sampling effects. Finally, error correction codes (Reed-Solomon) are applied to obtain identical codewords which are mapped to the unique secret key.

The authors analyzed the security of the proposed pairing scheme with respect to an adversary who is not in the same context but can eavesdrop, as well as, mount MITM, DOS and audio amplification attacks. The experimental results confirmed that such threats can be successfully mitigated.

Miettinen et al. [19] proposed context-based zero-interaction pairing for IOT devices which can happen without any user involvement. Specifically, the notion of sustained co-presence was employed, meaning that two devices would sense the same context over a substantial period of time if they are in close proximity.

The proposed pairing scheme works as follows. First, two devices derive a shared secret key using an unauthenticated DH key exchange. Second, both devices continuously monitor ambient audio and luminosity in order to obtain contextual fingerprints over time. Using these readings two devices can iteratively evolve the initial secret key and obtain a new secret key each time two fingerprints are sufficiently similar. Finally, after a number of successful key evolution steps two devices can authenticate each other and use the evolved secret key for secure communication.

The authors discussed the security of the suggested pairing scheme with regard to an adversary being inside and outside the same context, as well as, examining context replay attacks. Their findings implied that the proposed pairing can withstand both types of adversaries and mitigate the replay attacks.

Jin et al. [89] proposed a pairing scheme called *MagPairing* which requires minimum user interaction and, thus, yields good usability. Particularly, they exploited magnetometer readings of two smartphones brought to close proximity in order to establish pairing.

The suggested pairing scheme works as follows. First, two devices are tapped which triggers an authenticated DH key exchange during which both devices measure magnetic fields with their sensors. Second, two devices securely exchange their magnetometer readings via the interlock protocol [156]. Finally, both devices can authenticate each other by comparing if the received and local measurements match.

For security analysis, the authors considered attacks such as eavesdropping, MITM, replay and reflection. The results revealed that *MagPairing* is immune to the mentioned threats even if a powerful active adversary is within a few centimeters from the pairing devices.

Wang et al. [21] suggested a pairing scheme known as *Touch-And-Guard (TAG)* for associating a wearable and another nearby device by utilizing resonant properties of a human hand. Specifically, a shared secret is obtained from a hand touch using vibration motors and accelerometers.

The proposed pairing scheme works as follows. First, a user initiates pairing by touching a target device, for example, a payment terminal, with the hand on which a wristband is worn. Second, the target device generates vibrations which excite both the device itself and the hand. At this point, both the wearable and the target device record vibrations with their accelerometers. Finally, both devices process their accelerometer data separately without exchanging it, in order to extract reciprocal information to eventually generate a shared secret.

The security of the TAG scheme was empirically evaluated against an eavesdropper acting via acoustic side channels. It was shown that the proposed pairing can withstand such attackers even if they are located in proximity. However, the authors pointed out that the TAG scheme can still be susceptible to advanced visual eavesdroppers who utilize high-speed cameras.

E. Discussion

The results of our survey on PHY channels reveal interesting details. First, the literature makes it clear that there are no known confidential channels, despite considerable efforts having been invested in pursuit of this goal. Second, at the time of writing, the most promising communication channels, in terms of security, were not present in the majority of devices. Third, the use of sensors to obtain a shared context has recently been proposed as a new approach for SDP, however it is not without challenges. We expand on these points in the following.

1) *There are no Confidential Channels:* Confidentiality cannot be guaranteed by any of the PHY channels surveyed,

even though this appears to be an explicit or implicit assumption in a number of pairing schemes. As shown in Table I, all PHY channels that we studied are vulnerable to eavesdropping attacks, and those attacks have been successfully mounted in the past. Hence, none of these channels provides a secure transmission medium on its own.

The problem here is two-fold. First, the probability of “off-the-shelf” eavesdropping, that is, performed without specialized equipment, has increased tremendously since numerous smart devices nowadays are equipped with various peripherals, for example, cameras, microphones, etc., and the sensing capabilities of commodity hardware continue to grow [164]. Second, as indicated by Halevi and Saxena [39] side channels pose a real threat because they can completely circumvent the security of the pairing scheme. Specifically, they showed that three pairing schemes (Zero-power pairing [79], Vibrate-to-unlock [83] and BEDA [32]), which assumed confidentiality of the OOB channel were successfully broken by exploiting acoustic side channels.

The importance of side channels as a vital security issue has been recognized by the research community and addressed in recent communication systems [158] and pairing schemes [21], [84]. Nevertheless, new sources of sensitive information leakage are being continuously discovered [165], which raises a fundamental question whether it is feasible to identify and tackle all hidden channels in modern systems. Therefore, we argue that confidentiality of the PHY channel is very hard to achieve and guarantee in practice. Correspondingly, this property should be treated with a great deal of attention when a PHY channel is considered as a candidate for the OOB channel.

Regardless of this state of affairs where it is questionable that confidential channels are possible in practice, pairing schemes continue to be proposed that rely on secrecy of data transmission, for example, [166].

2) *Most Potentially Secure Channels Missing From Current Commodity Hardware*: The physical characteristics of various PHY channels provide different security properties. We have identified an important trade-off between security and ease of adoption. That is, a number of newer communication channels, such as mm-Waves and VLC can offer improved security, however they are not yet ubiquitous.

In particular, mm-Waves and VLC possess valuable security characteristics. Their short-range of communications, together with LOS requirements and low penetration rates, make them ideal for deployment and use as OOB channels in the IOT domain. Research is, however, still ongoing to improve on both mm-Waves [107] and VLC [128] communications. A further advantage is that both technologies can be efficiently implemented on constrained devices. For example, the antennas required for mm-Wave transmission are very small, and the VLC building blocks such as diodes and photosensors are inexpensive. Hence, these technologies are worth considering for SDP.

The challenge lies in the maturing of these newer channels, such that they become widely available on commodity hardware. This requires the action on both researchers and vendors.

3) *Using Environment Sensing*: A different approach to pairing is to utilize the sensing channel to obtain the shared context, which can be used either as an indicator of physical proximity, or as an entropy source to derive a shared secret key. The use of sensing information enables scalable pairing, which is crucial in a distributed and diverse environment such as the IOT. It also reduces or eliminates the user effort, which results in more usable and less error-prone pairing.

For example, the use of physical environment sensing [161] and GPS data [167], as it widely explored in schemes such as zero-interaction authentication (ZIA), can provide a suitable base to increase security in device pairing as well. The key insights provided by ZIA both those that are security-enhancing, such as fusing multiple sensing modalities [31], as well as those that are adversarial, such as context-manipulation threats [78], should also be taken into account in SDP.

Channel state information (CSI) in radio communications provides a different use for sensing. Reciprocal radio channels, meaning that the same antenna is used for transmitting and receiving, lead to correlated channel observations at both sides of a communication link. This correlation of channel observations allows the transmitter and receiver to obtain a common fingerprint of the radio environment, that can in turn be used to mitigate various types of attacks, including MITM and relay attacks.

Pairing schemes such as Amigo [27], Good Neighbor [87], and Wanda [88] and also [166], [168]–[174] rely on such information to ensure that both pairing devices communicate over the same channel. However, the robustness of such channel fingerprinting schemes against spoofing is still an open question under investigation. For example, Zafer et al. [175] have demonstrated an active CSI spoofing attack. Hence, pairing schemes leveraging the radio channel must account for manipulated and forged channel states.

Environment and channel sensing can provide an additional layer of verification. However, it still suffers from similar security limitations as PHY channels. Therefore, the sensing channel cannot, by itself, guarantee that no one is intermediating communications between the pairing devices, for example, through an MITM attack.

In this section, we have investigated and discussed PHY channels along with the SDP schemes utilizing them. In the next section, we review HCI channels and the corresponding pairing schemes.

V. HUMAN-COMPUTER INTERACTION CHANNELS

Modern information and communication technologies have become an indispensable part of the human society. The way people live, work and interact with each other and the environment has changed significantly with the advent of smart devices, social networking and cloud-based services. Various research and technologies have utilized HCI to provide security in a wide range of applications such e-commerce, home automation, and social networking [176]–[178]. With the upcoming IOT the importance of developing socially compatible security tools based on HCI is becoming more evident [179], [180]. However, relying on human interactions to achieve

security often introduces vulnerabilities to the system. Bruce Schneier [181] emphasized the relevance of the human factor in the system as follows: “... security is only as good as it’s weakest link, and people are the weakest link in the chain.” Hence, the security of the system where a user is involved depends not only on the technical aspects of the system, but also on how people understand and use it, in addition to the system’s capability to mitigate threats and issues introduced by users themselves [176], [182], [183]. From the pairing perspective, a user also plays an important role with regard to security. Traditionally, the security of pairing schemes has involved an aspect of human supervision, which can take the form of perception, for example, image comparison [184], decision making, for instance, pressing a button [32], and other interactive techniques, for example, drawing a pattern [185].

We start our discussion by identifying three points which are the base for rigorous HCI investigation. In particular, we specify several types of HCI *channels* which have been used in SDP and denote two sets of properties, namely *security properties* and *usability properties* being studied. Afterwards, we review existing pairing schemes that rely on various HCI channels to exhibit the trade-offs between security and usability. Finally, we discuss the most significant insights and implications that were identified in our survey on HCI channels.

A. HCI Channels in Device Pairing

Recently, numerous devices with rich input/output capabilities and considerable processing power have become widely available, which has significantly improved the quality of HCI [177]. Correspondingly, many pairing schemes proposed up-to-date rely on some form of user involvement. Chong et al. [13] surveyed existing pairing schemes by considering user actions required to establish a secure channel between two devices. We refine their findings to obtain fine-grained categories of user interaction that have been used in SDP.

Specifically, we define three HCI channels that fully satisfy our definition given in Section III-B: *Data relay*, *Data comparison* and *Data generation*. In addition, we consider *Device handling*, which while not a conventional HCI channel, represents a more passive form of user interaction that is often (implicitly) present in device pairing:

1) *Data Relay*: A channel where a user is prompted to transfer data generated by one pairing device onto another pairing device.

2) *Data Comparison*: A channel where a user is required to compare and analyze data produced by two pairing devices, for example, to verify the correctness or consistency of the information.

3) *Data Generation*: A channel where a user provides common input to both pairing devices simultaneously, for example, shaking, drawing, or first imposes (secret) input on one device and then provides it again on a second device.

4) *Device Handling*: A form of user interaction where a human actor is required to bring pairing devices in proximity, make physical contact, align them, or take similar action.

B. Security Properties

The security properties of the pairing schemes based on HCI channels are quite different from the ones purely relying on PHY channels. First, users are the unavoidable source of errors [183], [186] and their behavior, as well as, attitude towards security sensitive tasks can vary significantly [182]. Second, user interaction is subject to observation by both an internal participant, who is curious, and an external adversary, who is malicious. To compile the list of representative security properties we combined issues that have been raised in the pairing community with respect to human factors [187], [188] and complemented them with the implications found in the authentication domain [189]:

1) *Inattentive User*: Defines if a pairing scheme has certain tolerance to mistakes and errors introduced by the user. In particular, a pairing mechanism that does not verify user input for errors or provide corresponding feedback can be circumvented by the attacker who can impersonate a legitimate device.

2) *Rushing Behavior*: Specifies if a pairing scheme accounts for rushing users who are willing to skip certain steps of the pairing procedure or accept specific conditions without verification, in order to speed up pairing.

3) *Consent Tampering*: Determines if a pairing scheme is resilient to consent tampering by a dishonest user. That is, if the user can accept pairing even if the data exchanged between two devices mismatch, or conversely, reject pairing, even though both devices successfully establish a connection.

4) *User Observation*: Defines if a pairing scheme is resistant to an adversary who can observe user actions during the pairing process. In other words, the attacker does not benefit from learning user interactions, including (secret) data exchanged on the HCI channel, and cannot compromise pairing with such information at hand.

5) *Forward Secrecy*: Determines how resilient a pairing scheme from a cryptographic perspective to an eavesdropper who can leverage user observation and the compromise of the long-term keys. That is, if the underlying cryptographic protocol used in the pairing scheme mitigates brute-force offline attacks aided by (secret) data observed on the HCI channel, and restricts an adversary to a one-off (online) guessing game. We evaluate this property under the assumption that DH keys used by the underlying cryptographic protocols are ephemeral.

6) *Honest-but-curious*: Specifies if a pairing scheme is susceptible to an honest-but-curious adversary who legitimately participates in the pairing process but tries to learn or infer more information about another pairing party.

C. Usability Properties

As mentioned previously, usability of pairing schemes has been a subject in several studies and a number of works investigated how usability can be enhanced in case of device pairing [190]–[192]. However, many works applied mostly quantitative metrics to evaluate usability such as completion time and error rate [8] which are implementation dependent. In addition, subjective characteristics such as personal preferences vary with context, as has been previously demonstrated

[35]. Thus, there is a lack of a common baseline approach which would allow usability evaluation of pairing schemes more qualitatively and coherently. We aim to remedy that situation by presenting a set of usability properties, which we derived by studying the usability implications in general human-device interaction [26], as well as, authentication techniques [189] and projecting the findings onto the pairing domain:

1) *Effortless Initialization*: Defines minimal user effort during the discovery phase of the pairing process. For example, a user is not required to provide any additional information, such as a number of participants, or pre-configure devices prior to pairing.

2) *No Secret Relay*: Does not prompt users to transfer any (secret) information from one pairing device to another or if it is required the length of the relayed data should be minimal.

3) *Automatic Secret Generation*: Specifies that the data used for authentication, for example, cryptographic keys, is generated by pairing devices without requiring any user input or assistance, such as shaking, drawing, etc.

4) *Automatic Consistency Check*: Determines user effort necessary for verifying that information exchanged between pairing devices is similar.

5) *Environmental Insensitivity*: Defines applicability of the pairing schemes with respect to the ambient environment. For example, a pairing scheme may lead to high error rates or even fail if the environment is too noisy, crowded or has poor illumination.

6) *Explicit User Feedback*: Specifies if a pairing scheme provides meaningful feedback to the user during and upon the completion of the pairing process. For example, two pairing devices can indicate success by making an appropriate sound, and provide explanatory, actionable, feedback if pairing fails.

7) *Familiarity*: Determines if the user actions imposed by the pairing scheme correspond to the daily user experience [35], [176]. That is, if a pairing scheme relies on well-established interaction patterns, for example, smartphone usage, and requires no extra training for an average user in order to be adopted.

D. Survey of HCI Channels

In this section we review representative pairing schemes which rely on HCI by focusing on the properties given above.

1) *MANA*: Gehrmann et. al. [193] presented several *MAN*ual Authentication (*MANA*) schemes for authenticating DH public keys. They assumed that devices have at least one input and/or output interface, for example, a display and/or a keypad. From the user perspective, a human operator plays a crucial role in pairing. Three variants of the *MANA* scheme were proposed which work as follows:

- *MANA I*: One device has a display and a simple input interface, for example, a button, while another device has a keypad and a simple output interface, for instance, an LCD panel. The first device computes a random key and a checksum value and displays this data. The user reads the checksum value and the random key from the screen of the first device and inputs this information into the second

device. Then, the second device computes the checksum value using the provided random key and compares the two checksums. The outcome of the comparison is indicated as an accept or reject message to the user. Finally, the user enters the result back into the first device.

- *MANA II*: Both devices have a display but neither of them a keypad, although they are supplied with a simple input interface, for example, a button. Similar to *MANA I*, the first device computes the random key and the checksum and displays two values. In addition, the first device sends the random key to the second device over an insecure channel, for example, wireless radio. Afterwards, the second device computes the checksum value and outputs it together with the key. By comparing values displayed by both devices a user has to either accept the connection if they are equal or reject it otherwise.
- *MANA III*: Both devices are assumed to have a keypad. The user enters a short random bit-string \mathbf{R} into both devices. Then, each device generates a random message authentication code (MAC) key and calculates a MAC value over \mathbf{R} concatenated with a device identifier and the DH-public keys. Afterwards, both devices exchange their corresponding MAC values via a wireless radio channel. Only upon receiving the MAC value from the pairing peer each device reveals its MAC key. Finally, both devices verify the received MAC values and indicate the result to the user who is required to compare and confirm it. A simpler variant exists in case one of the devices has only a display, that is, no means of input.

The authors argued that *MANA*-schemes are robust against MITM attacks, given user diligence in verifying calculated hash values.

2) *Access point authentication*: Roth et. al. [194] suggested a pairing scheme to protect the connection between an AP and a client device against evil twin attacks.

The proposed pairing scheme uses short authentication strings (*SAS*) for key establishment and consists of two phases. In the setup phase, both devices exchange their public keys and a nonce value over an insecure wireless channel. During the authentication phase, a user is required to compare a certain number of color sequences (minimum two) in order to verify that pairing was performed with the intended AP. In detail, each sequence is comprised of two colors and represents a *SAS*. Both devices display the sequence of colors, that is, one color at a time, and the user has to verify their equality by pressing a button and proceeding to the next sequence. The number of sequences shown depends on the desired level of security and eventually the user is prompted to either accept or reject pairing.

The authors discussed the security of the proposed pairing scheme and concluded that it can withstand evil twin attacks.

3) *Shake Them Up!*: Castelluccia et al. [195] proposed a pairing scheme for CPU-constrained devices, for example, sensors, that do not have enough computational power to perform public key cryptography.

The proposed pairing scheme utilizes the anonymous broadcast channel and works as follows. In order to derive a shared secret key, two devices are held together and shaken,

TABLE II
SUMMARY OF HCI CHANNELS

Pairing Scheme	HCI Channel				Security Properties						Usability Properties					
	Data Relay	Data Comparison	Data Generation	Device Handling	Inattentive User	Rushing Behavior	Consent Tampering	User Observation	Forward Secrecy	Honest-but-curious	Effortless Initialization	No Secret Relay	Auto. Secret Generation	Environment Consistency Check	Explicit User Feedback	Familiarity
MANA I [193]	●	—	—	—	○	○	○	○	○	○	○	○	○	○	○	○
MANA II [193]	—	●	—	—	○	○	○	○	○	○	○	○	○	○	○	○
MANA III [193]	—	○	●	—	○	○	○	○	○	○	○	○	○	○	○	○
Access point authentication [194]	—	●	—	—	○	○	○	○	○	○	○	○	○	○	○	○
Shake Them Up! [195]	—	—	—	●	○	○	○	○	○	○	○	○	○	○	○	○
Shake Well Before Use ShaVE [196]	—	—	●	●	●	●	●	○	●	●	●	○	○	●	●	○
Shake Well Before Use ShaCK [196]	—	—	●	●	●	○	●	○	●	●	●	○	○	●	●	○
SAPHE [197]	—	—	●	—	○	○	○	○	○	○	○	○	○	○	○	○
Authentication using ultrasound [198]	—	●	—	●	○	○	○	○	○	○	○	○	○	○	○	○
Beep - Blink [34]	—	●	—	—	○	○	○	○	○	○	○	○	○	○	○	○
Blink - Blink [34]	—	●	—	—	○	○	○	○	○	○	○	○	○	○	○	○
RhythmLink [199]	—	—	●	—	○	○	○	○	○	○	○	○	○	○	○	○
Seeing-Is-Believing [200]	●	—	—	●	○	○	○	○	○	○	○	○	○	○	○	○
Visible Laser Light [201]	—	—	—	●	○	○	○	○	○	○	○	○	○	○	○	○
VIC (mutual authentication) [202]	—	●	—	●	○	○	○	○	○	○	○	○	○	○	○	○
BEDA (B2B) [32]	—	—	●	—	○	○	○	○	○	○	○	○	○	○	○	○
BEDA (D2B, SV2B, LV2B) [32]	●	—	—	—	○	○	○	○	○	○	○	○	○	○	○	○
Playful Security [188]	●	—	—	—	○	○	○	○	○	○	○	○	○	○	○	○
Safeslinger [203]	—	●	○	—	○	○	○	○	○	○	○	○	○	○	○	○
Synchronized Drawing [185]	—	—	●	●	○	○	○	○	○	○	○	○	○	○	○	○
Proximity Authentication [204]	—	—	●	●	○	○	○	○	○	○	○	○	○	○	○	○
Checksum Gestures [20]	●	—	—	○	○	○	○	○	○	○	○	○	○	○	○	○

● = fulfills property; ○ = partly fulfills property; ○ = does not fulfill property; — = n/a

either by a single user, or by two users in close proximity. Meanwhile, both devices broadcast empty packets over an insecure wireless channel. The anonymous broadcast implies that each device sends a packet by setting its own identifier or the identifier of the pairing peer as the source of the message. In this case, an adversary can read the transmitted packets but cannot distinguish the source. In contrast, each pairing device knows if it has sent a particular message or not, which is interpreted by the device as a secret bit 1 or 0, and the shared key can be obtained by observing a pre-defined number of packets. The shaking is done to thwart signal strength analysis by an attacker to identify the actual sender.

The authors analyzed the security of their pairing scheme against an adversary who can read all packets but cannot distinguish the source of the packet and reported that it is resilient against MITM and DOS attacks. However, Rasmussen et. al. [205] showed the vulnerability of this scheme by using radio fingerprinting to identify the sender.

4) *Shake Well Before Use*: Mayrhofer et al. [196] suggested a pairing approach which utilizes accelerometer data generated from distinct movement patterns. Specifically, they proposed two schemes to securely pair devices where a user is required to hold them together and them shake simultaneously.

The first scheme (ShaVE) uses the DH key exchange to derive a shared key over an insecure wireless channel followed by the exchange of accelerometer readings via the interlock protocol [156] to verify authenticity of pairing devices.

The second scheme (ShaCK) relies on the data captured by the accelerometer to derive a shared secret key. In detail, two devices hash their synchronized feature vectors obtained from

the sensor readings and accumulate them until the entropy is sufficient to produce the shared secret key.

The authors discussed the security of the proposed pairing with regard to an active adversary and concluded that both schemes can withstand MITM attacks. However, they conceded that the ShaCK variant does not provide forward secrecy and is vulnerable to offline guessing attacks.

5) *SAPHE*: Groza and Mayrhofer [197] proposed a pairing scheme based on shaking, which improved upon the previous works, for example, ShaCK [196], by devising a more lightweight approach to securely exchange low entropy vectors obtained from accelerometer data.

The suggested pairing scheme employs a hashed heuristic tree and works as follows. First, the commitments between two devices are exchanged in the form of hashes of randomly generated values. Second, accelerometer data produced by shaking two devices together is recorded and used to obtain a unique secret key on each device. The unique secret keys are extracted by comparing the accelerometer readings to the threshold values obtained from the initial commitments by means of the Euclidian distance. The key extraction algorithm relies on a hashed heuristic tree, which is essentially a search tree, where the accelerometer readings are first sorted in a descending order with respect to the distance from the threshold values, and then bit-by-bit hashing is applied to retrieve the unique secret key. Third, both devices exchange challenges which are nonces encrypted with the individual secret keys, and each device proves the possession of the peer's key by verifying the challenge.

The authors analyzed the security of the proposed pairing

scheme and claimed that their approach provides better resilience to MITM attackers, who try to guess the low entropy vectors obtained from accelerometer data. However, the authors conceded that further research is required to evaluate resilience of the SAPHE scheme against the adversaries who can observe user interaction.

6) *Authentication using Ultrasound*: Kindberg et. al. [198] presented a pairing scheme which utilized ultrasound to physically validate two devices and establish a secure channel between them.

The proposed pairing scheme consists of two phases and works as follows. In the locate phase, a user selects a target device to communicate with, and makes sure that her personal device (client) is in LoS with the target. Then the client sends a message to locate the target, which replies with its designated identifier, for example, network address, over RF and ultrasound channels. The client receives those messages, matches the identifier and is able to calculate the approximate distance to the target device, which is displayed to a user for verification. During the associate phase, the user points the client device to the target and initiates pairing. The target device replies with the RF message containing its public key together with a random number and simultaneously emits the ultrasound message with the same random number. Upon receipt, the client checks if random numbers from RF and ultrasound messages match and asks the user to confirm the relative position of the target device. Finally, the client encrypts a session key with the target's public key and sends it along with a random number back to the target.

The authors argued that the proposed pairing scheme is robust against various spoofing and replay attacks given the adversary is unable to counterfeit ultrasound messages.

7) *Synchronized Audio-Visual Patterns*: Prasad and Saxena [34] presented two pairing schemes suitable for devices with only basic interfaces such as a pair of LEDs and/or speakers. Specifically, both schemes rely on SASs transmitted by two devices in the form of synchronized audiovisual patterns, for example, blinking LEDs, which have to be compared by a user for equality.

In the first scheme (blink-blink) two devices encode their SASs as sequences of blinking LEDs and the user is required to compare these sequences and determine if they are synchronous on both devices, for example, green or red LEDs.

In the second scheme (beep-blink) one device transmits its SAS as a sequence of blinking LEDs, while another device encodes the SAS as a series of beeping sounds and silence periods. The user has to verify if these two patterns match, such as the LED light corresponds to the sound.

The authors analyzed the security of the proposed pairing with regard to a MITM adversary and concluded that both schemes can withstand such attacks, yet security depends on user diligence when comparing two audiovisual sequences.

8) *RhythmLink*: Lin et. al. [199] proposed a pairing scheme based on rhythm tapping.

Initially, a user inputs a song rhythm several times on her personal device, for example, a smartphone, to provide some training data and eventually obtain a tapped password, referred

to as a tapword. Afterwards, this generated tapword is stored on the user device and used further for pairing.

To pair with a target device, the user inputs the same tapped rhythm into it. Therefore, the target device can compute a tapword and compare it with the pattern stored on the user device by means of the Euclidean distance. The protocol uses elliptic curve cryptography to calculate the Euclidean distance between the tapwords, without either device revealing its tapword. To generate a session key, password authenticated key exchange is used in order to avoid MITM attacks. A device encrypts its model information with this session key and sends the encrypted data to the other device, which decrypts this information and computes the Euclidean distance. Afterwards both distances are compared. If the distances match, the devices accept pairing.

9) *Seeing-Is-Believing (SiB)*: McCune et. al. [200] proposed a pairing scheme, based on taking a snapshot of a two-dimensional barcode displayed on the screen of one device by the camera of another device. The two-dimensional barcodes are generated by the devices automatically without any human effort. A user is required to configure the camera and take the snapshot of the 2-D barcode.

To perform pairing, one device sends its public key to another device over an insecure channel, for example, WiFi, and displays a two-dimensional barcode. This barcode represents a visual encoding of the public key sent over the insecure channel. The second device, supplied with the camera, takes a snapshot of the barcode and runs a barcode recognition algorithm in order to process the image and extract the public key. Afterwards, this device compares the data obtained from the barcode with the data received over the insecure channel. If they match, the second device can trust the first device. The barcode-scanning procedure has to be executed by both devices for bidirectional authentication.

The security assumption made by this pairing scheme is that mounting active attacks is difficult without being detected. The authors further analyzed the security of their pairing scheme against passive attacks and proposed to additionally use the DH session key exchange protocol to protect against brute-force attacks.

10) *Visible Laser Light*: Mayrhofer et. al. [201] described a pairing scheme based on visible laser light for personal mobile devices equipped with a laser diode. These personal devices interact with another remote device, which is able to detect the laser light.

The proposed pairing scheme works as follows. First, a user presses a button and turns on the laser on the personal device. This causes the device to begin continuously transmitting messages. When the remote device detects these messages, it generates a response and broadcasts it over a wireless radio channel. Second, both devices start a key agreement protocol, and the target turns on a LED to identify itself. Third, if the LED is activated on the target device expected by the user, she presses a second button triggering an autonomous phase. During the autonomous phase the derived secret key is verified by sending a series of cryptographic challenges via the wireless radio channel, and requiring that the responses to the challenges to be transmitted via the laser.

The authors evaluated their pairing scheme in the face of an active adversary attempting to mount a MITM attack. They reported that the attack would only succeed if the adversary can compromise the integrity and confidentiality of the laser and wireless radio channels at the same time.

11) *Visual authentication based on Integrity Checking (VIC)*: Saxena et. al. [202] improved the SiB pairing scheme by providing mutual authentication between devices to be paired using only a unidirectional visual channel, that is, requiring that only one of the two devices has a camera, instead of both.

The proposed pairing scheme employs short authenticated integrity checksums for key agreement and works as follows. First, each pairing device exchanges its public data, a public key and a random bit string, over an insecure channel. Second, each device calculates a checksum, in practice a cryptographic hash-function, over this public data, that is, both public keys and random bit strings. Third, one of the devices sends its results to the other device using the visual channel for comparison, that is, the second device uses its camera to read the 2-D barcode displayed by the first device. Fourth, the second device compares the hash transmitted over a display-camera channel by the first device with the locally computed value. If the two values match, the second device accepts the connection, and displays a confirmation message to the user. Finally, the first device prompts the user to indicate if the second device accepted the connection or not.

The authors discussed the security of their pairing scheme and indicated that it is resilient to MITM attacks, only if the hash function used in the scheme is collision-resistant.

12) *BEDA*: Soriente et. al. [32] investigated how to pair devices with very limited interface capabilities such as a single button. They proposed a pairing scheme which first performs a DH key agreement and then executes the pairing procedure to authenticate the DH public keys.

The suggested pairing scheme consists of two phases and works as follows. In the first phase, a short 21-bit secret is distributed between the devices with user assistance. Depending on the available hardware interfaces this initial secret can either be obtained via the user input provided to both devices (Button-to-Button) or by relaying the data generated by one device to another device (Display-, Short Vibration-, Long Vibration-to-Button). In the second phase, the authenticity of the exchanged public key is incrementally verified in a 21-round procedure by using the initial secret.

The security of the proposed pairing depends on the confidentiality of the channel. The authors discussed that their pairing scheme is secure against MITM attacks only if the data exchanged between the devices cannot be eavesdropped. The BEDA scheme was cryptographically extended in the unified pairing framework [151] to provide PFS, which further increases security against MITM attackers.

13) *Playful Security (Alice says)*: Gallego et. al. [188] proposed a pairing scheme based on the memory game Simon. The suggested scheme uses SASs computed by each device individually, and a user is required to transmit these strings from one device to the another device.

The proposed pairing scheme works as follows. One device displays several audiovisual patterns and the user relays these patterns to another device supplied with the input interface. The first pattern consists of a single color and tone that encodes the first two bits of the SAS. For the next round two bits will be concatenated to the first pattern. This data forms a new pattern that needs to be similarly transmitted by the user. This iterative process continues until a sufficient number of bits have been successfully exchanged between two devices. If an error occurs in a round, a new pattern will be concatenated with the previous patterns that were exchanged successfully. To avoid synchronization issues the first device is equipped with two buttons. If an error occurs, the user selects previous button to repeat the exchange of the SASs between the devices.

The authors argued that the proposed pairing scheme is robust to human errors and, therefore, can mitigate MITM attacks caused by such errors.

14) *Safeslinger*: Farb et. al. [203] presented a pairing scheme for data exchange with smartphones. That is, users upon a physical encounter can initiate the exchange of their public keys, as well as, selected contact information and communicate securely afterwards. The SafeSlinger scheme is built upon two cryptographic mechanisms, namely multi-value commitments and group DH key agreement. The pairing scheme requires active user interaction, which includes entering the number of participating devices, selecting the data to be exchanged, and finally, comparing a 3-word phrase which has to be commonly chosen by all users.

The authors analyzed the security of their pairing scheme and argued that SafeSlinger mitigates attacks such as MITM, group-in-the-middle, impersonation and sybil attacks, by involving the user in the security chain and accounting for user misbehavior.

15) *Synchronized Drawing*: Sethi et. al. [185] presented a pairing scheme based on physical proximity and commitment-based cryptographic primitives.

The proposed pairing scheme consists of four phases and works as follows. In the first phase, two devices attempt to establish a shared secret using DH or a similar protocol over an insecure channel. In the second phase, fuzzy secrets are extracted from user input produced by simultaneously drawing the same pattern with two fingers of the same hand, for example, a thumb and index finger, on two touchscreens or surfaces of two devices to be paired. In the third phase, each device sends an unencrypted commitment message to another device, which contains a hash of: (a) the device's identifier, (b) the fuzzy secret derived from the drawing, (c) a random number, and (d) the DH-shared key. In the fourth phase, each device encrypts its random number and fuzzy secret obtained in the third phase using the shared secret calculated in the first phase.

By carefully ensuring that both devices complete the third phase before entering the fourth phase, authors argued that MITM attacks can be prevented.

16) *Proximity Authentication*: Li et. al. [204] presented a pairing scheme which uses proximity to perform mutual authentication between two devices without using NFC chips.

The suggested pairing scheme works as follows. First, a user draws a zigzag pattern simultaneously on both devices to be paired, using two fingers of the same hand. Second, each device individually derives a set of common features obtained from the drawing. Third, the private set intersection approach [206] is applied to the feature vectors of both devices in order to generate a shared secret key.

The authors discussed security implications of their pairing scheme and claimed that it is secure against dictionary and MITM attacks.

17) *Checksum Gestures*: Ahmed et. al. [20] proposed a pairing scheme based on SASs, where a continuous gesture is required for encoding authentication information.

The suggested pairing scheme works as follows. First, the user and target devices execute a key exchange protocol based on SASs to obtain a checksum string (at least 20 bits) stored on both devices. Second, the user device transforms this checksum string into a motion pattern, which is displayed to the user, who is required to reproduce this motion pattern as a continuous gesture on the target device. Third, the input gesture is captured and processed by the target device, which then compares the obtained data with the motion pattern derived locally from the shared checksum string. If both match, the unidirectional communication channel is authenticated between the user and target devices. The security of the proposed pairing scheme is based on the feasibility of gesture recognition technologies, particularly in maintaining sufficiently low false-positive and false-negative error rates.

The authors analyzed the security of their pairing scheme based on the probability of interpreting a false input of an attacker as a correct gesture and reported that the probability of success of a relay attack is under 5.5%.

E. Discussion

The results of our HCI study are summarized in Table II, from which we identify and discuss four key points which have important security and usability implications for SDP. First, we identify an important trade-off that exists between passive and active HCI channels. Second, the significance of usability properties, including the provision of explicit user feedback and insensitivity of HCI input to environmental conditions is considered. Third, security issues resulting from various forms of intentional and unintentional, as well as, benevolent and malicious user misbehavior are explored. Finally, the vital problem of observation threats for HCI channels is presented, that is, the situation where an attacker can observe and exploit human interaction.

1) *Trade-offs Between Passive and Active HCI Channels*: The *handling* channel yields the best results in terms of usability because it requires the minimum amount of user effort. However, such pairing schemes do not give a user fine-grained control over the pairing process and provide less assurance that pairing was established with the intended device. In contrast, *data relay*, *comparison* and *generation* require more user involvement but provide better control and assurance of pairing. Yet, these types of interaction are susceptible to user misbehavior and errors, which makes it necessary for

users to adequately understand the impact of their actions. For example, if the generation channel is involved it is not sufficient to only incorporate common user experience. It is additionally required that the user is alerted if the generated secret lacks sufficient entropy for its intended use, so that the user can take appropriate action.

Hence, we identify an important trade-off between different HCI channels. While passive user interaction can be viably used for pairing in situations where no sensitive information, such as financial or personal data, is involved. Active user participation should be used for more critical applications, for example, bank transactions, where user awareness can be leveraged to increase security in device pairing.

2) *Usability Properties*: Two usability properties which are crucial to augment both usability and security in pairing are providing explicit user feedback, and ensuring insensitivity to environmental conditions.

First, the importance of *explicit user feedback* was outlined previously [35], [73], yet only a few pairing schemes provide it in a meaningful way. However, the user feedback can not only mitigate input errors, and present the evidence of pairing devices, for example, that pairing with the intended device was successful, but also assist a human operator with security advice. For instance, if the user generates data to produce a secret, the pairing mechanism can notify the user if the provided input has sufficient entropy for the intended application, or not.

Second, *environment insensitivity* is also vital for maximizing user experience. That is, a pairing scheme should work for the intended use-case, irrespective of the ambient conditions that might be reasonably expected to occur. Section VI examines a range of specific use-cases exploring this topic further. The key point is that these two factors interact, for example, a pairing scheme that requires audio comparison and confirmation from the user should not be expected to be used in public scenarios.

3) *Security Issues*: The prior work emphasized the security issues in pairing stemming from unintentional or deliberate user misbehavior [8], [187], [207]. Interestingly, only two pairing schemes (Playful Security [188] and Safeslinger [203]) accounted for such properties as *inattentive user*, *rushing behavior* and *consent tampering* by design. Table II clearly indicates that human interaction by itself does not bring any security benefit if it does not consider threats posed by the user behavior, for example, MANA [193]. Additionally, in our analysis we introduced an *honest-but-curious* participant who tries to obtain more information about the pairing party. The motivation for this stems from a number of application classes that we considered. Since social and public pairing are in scope (Section VI), it cannot be assumed that all pairing parties are benign and collaborative. For example, social engineering can be used to infer extra information about another user or if the sensing channel is involved another device or participant can leverage this sensor data to violate privacy. Moreover, *human observation* has not been well addressed in the pairing literature. However, as we show under observation threats, the situation is dire and this point must be taken into account if the pairing scheme relies on human interaction.

4) *Observation Threats*: Regarding observation threats, we focus on security implications in authentication techniques as the adversary similarly tries to circumvent security by examining user interaction. The examples of malicious observation include, but are not limited to, shoulder surfing, audio or video analysis of the keyboard utilization and voice recognition. Specifically, Halevi and Saxena [208] showed that keyboard acoustic emanations can be used to successfully retrieve (even random) passwords prompted with different typing styles. Similarly, Davis et al. [209] proposed a method to extract audio data from the high-speed video analysis in order to perform acoustic eavesdropping without having a microphone. More sophisticated attacks [210] exploited reflection from the objects to reconstruct any confidential data displayed on the screen of a device. Yue et al. [211] applied computer vision techniques to show that it is possible, with 95% probability, to reconstruct user input on the touchscreen of a mobile device using a low resolution video of user interaction. Recent attacks against voice verification [212] demonstrated that voice impersonation is achievable with the success rate of 90% using only a limited number of victim’s voice samples. In short, observational threats are increasingly easy to achieve, and therefore this risk should be taken into account when designing SDP schemes.

In this section, we have investigated and discussed HCI channels along with the SDP schemes utilizing them. In the next section, we review the application classes and classify the surveyed SDP schemes accordingly.

VI. APPLICATION CLASSES

In this section, we explore and analyze the four application classes introduced in Section III. First, we describe each application class with respect to typical interactions, as well as its security and usability insights. Second, we categorize the pairing schemes covered in Sections IV and V with regard to their application classes and discuss the most interesting results of this classification. Finally, we highlight important open issues in SDP that have been identified in our study of application classes.

A. Overview of Application Classes

An application class covers a set of similar SDP use-cases, each of which involves a similar degree of involvement and level of user control over the pairing process. We recall the four application classes introduced earlier: *a)* private, *b)* public, *c)* social, and *d)* unattended. The private class corresponds to a “classic pairing” case, where a single user either owns or directly controls two devices that ought to be paired. The public class is related to a single user possessing one device, where the user performs the pairing with some third party infrastructure, for example, a payment terminal, over which she has no control. The social class incorporates two users who would like to securely pair their corresponding devices. The unattended class deals with the case where two devices belonging to the same ownership domain, for example, owned by the same person or organization, pair with no user involvement. Figure 5 depicts the four application

classes, instantiated from our system model, to provide a better understanding of the typical interactions for each application class.

The ownership of the devices being paired plays a critical role in SDP, necessitating its explicit consideration when describing application classes. We recall that a *security domain* is the set of devices, data, policies and intentions that a single party controls. That is, a security domain refers to the limit of enforcement of security policy by a particular owner or controller of one or more devices. These security domains are especially significant when more than one exists, as it allows for security requirements of pairing devices to be differentially achieved or undermined, either by the pairing process, or subsequent actions of one of the pairing parties.

For example, consider Figures 5a and 5c. In Figure 5a, a single user controls all devices, and so a single security domain exists. Therefore, following a successful pairing procedure, there are only two possibilities: either, the policy requirements of the single security domain are met, or not. In contrast, for Figure 5c, there are two users each controlling a separate device, D1 and D2 respectively. In this case, if the security policy requirements of each user differ, it may be possible that the security policy of one user is satisfied, but not for the other. Similarly, one of the users may later reveal information that, without violating their own security policy, may violate that of the other. That is, the presence of the second security policy allows for a more complex set of outcomes, as compared to if there were only a single security domain.

In the following, we expand on the four application classes under consideration.

1) *Private*: Figure 5a depicts the well-known private class, which applies when a single user either owns or controls both devices. A good example of this scenario is pairing smart devices that belong to the same person. In such a setting, a rich set of HCI interactions are possible since a user can freely communicate with and handle her portable devices in many ways. The physical interactions between the devices, as well as, with the ambient environment are user-enabled, and only limited by the availability of hardware interfaces on the devices.

From a security perspective, private pairing is often performed in a rather restricted environment, for example, home premises or a workplace, where such threats as external observation and communication interception are reduced. The private class consists of a single security domain, that is, all devices are subject to the same security policy requirements, because they are controlled by a single party. In this context, the focus of the user tends towards usability, due to the combination of reduced perceived threats and the relative frequency of pairing that may occur, especially given the increasing numbers of devices that people own. Hence, usability must be preserved and emphasized, even in the face of numerous devices to be paired with one another. Despite the lower perception of risk, it remains important to maintain security.

2) *Public*: The public class, shown in Figure 5b, corresponds to the case where a single user possesses one device but has no control over another device to be paired with. For example, the user wants to pair her personal device, for

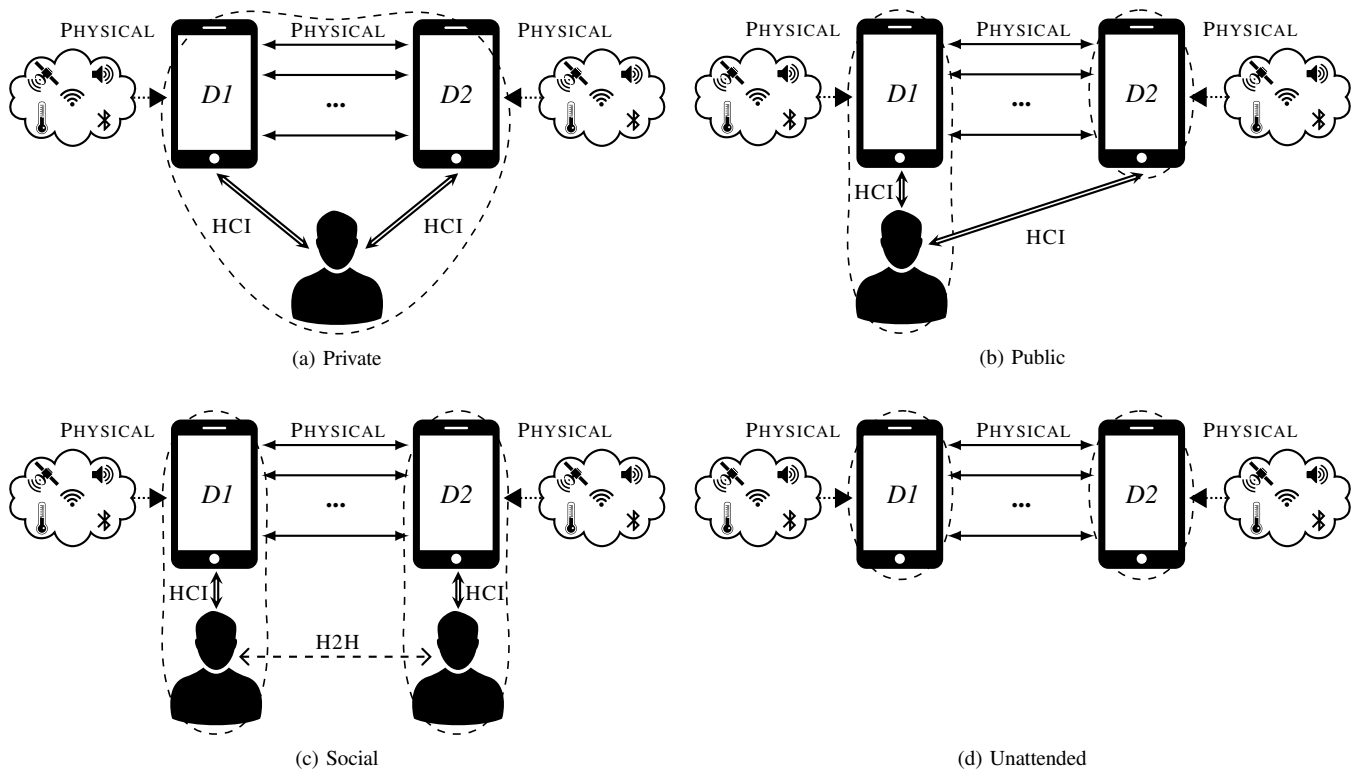


Fig. 5. The four application classes. Each application class consists of two devices to be paired, each from a distinct security domain, except for the private application class (a). The boundaries of security domains are indicated by a dashed line.

instance, a smartphone, with a third party infrastructure such as a public AP, a printer or a payment terminal.

In terms of HCI interactions, a human operator has fewer options as compared to the private class, because the public infrastructure typically has only a few common user interfaces and cannot be moved, shaken or handled in a convenient way. Similarly, physical interfaces used for communication between the devices, as well as, with the ambient environment are restricted and typically cannot be invoked by the user.

From a security perspective, the public class implies a more hostile environment, that is, public places, as compared to the private class. Thus, user actions during the pairing procedure are subject to external observation, which can come in the form of shoulder surfing or ubiquitous CCTV. Additionally, an attacker can stealthily install rogue devices in the public premises to interfere or hijack the pairing process.

The public class incorporates two distinct security domains, namely the user with her device and the infrastructure, which opens a door to a number of threats outlined in the following discussion. In comparison with the private class, users are likely to have an increased perception of security risks in such public scenarios. Therefore, users may reasonably accept some shift in the balance away from usability in order to improve security. However, care must be taken not to reduce usability to the point where users' tolerance is exhausted.

3) *Social*: The social class, illustrated in Figure 5c, represents a case where two different users would like perform pairing between their personal devices [15]. Pairing two smartphones that belong to different people is a good example of such a scenario. It is obvious from the given example that

the social class implies two distinct security domains, that is, two users with their devices. The presence of multiple security domains can result in complicated security outcomes, as previously described.

The reality of users' concerns regarding these complications can be observed, for example, through users' reluctance to hand their personal devices over to others. Explicit human-to-human (H2H) interaction can be used to resolve this concern, that is, to allow users to pair their devices, without losing physical possession of them at any point during the pairing process. Since users are interfacing with their devices individually, numerous HCI and physical interactions can be enabled similarly to the private class.

With regard to security, social pairing is vulnerable to external observation. On the one hand, the typical environment for the social class may present lower inherent risk as compared to the public class, for example, by occurring in a private house instead of in public places. On the other hand, the social pairing may still occur in a public place. Also, social pairing procedures typically involve user interaction, which is particularly at risk of observation attacks. Thus, while the social class can suffer from a similar level of risk to the public class, users' perception of the risk may be lower, potentially reducing their tolerance for security measures that harm usability. Therefore, considerable attention should be given to optimizing user experience for social pairing procedures, while still ensuring adequate security.

4) *Unattended*: Figure 5d depicts the unattended class, which applies when two devices perform pairing without any user involvement. For example, two IoT devices, for instance,

sensors, located nearby can pair and similarly wearables, as well as, IMDs can be paired. In the case of wearables and IMDs, a user is present, but acts only as a carrier of the devices, and does not consciously participate in the pairing process.

Since no user is involved, unattended pairing relies solely on various physical interactions, especially those used for data acquisition, that is, sensing. The key approach employed in unattended pairing is to utilize various sensor capabilities to measure the ambient environment over time. Thus, if two devices continuously sense sufficiently similar contexts, they interpret this as evidence of their physical proximity. When two devices believe that they are in physical proximity, they may then attempt to pair [19], [28]. The ambient environment does not only refer to physical characteristics such as wireless radio, audio, luminosity, humidity, etc. It can also correspond to measuring the human body, for example, a heartbeat rate [30] or muscle contraction [22], as well as, capturing user specific actions, for example, a gait [25], [213], an approach trajectory [214] or a head movement pattern [23].

In terms of security, the unattended class significantly differs from other application classes since the pairing devices communicate in a standalone fashion without explicit user control. This poses major security challenges, such as physical access to the devices by an adversary, in addition to her ability to efficiently monitor [122], disturb or even manipulate [78] the pairing environment without being noticed. Moreover, it is not straightforward to unambiguously define a number of security domains in the unattended class. For example, the proposed pairing schemes [19], [28] assumed that devices originated from the same ownership, for example, either a user or the infrastructure, and, thus, security domain. An open question is the pairing of IOT devices which belong to different security domains.

The unattended pairing is by definition an autonomous process, removing all user interaction. It can be viewed as pushing the usability-security trade-off completely in the direction of usability. It is, therefore, not surprising that the security properties of unattended pairing schemes are often weaker as compared to the other application classes. Thus, more research is required to devise more secure unattended pairing schemes.

B. Classification of Pairing Schemes

To categorize different pairing schemes with respect to their application classes, we used the following approach. First, we considered pairing schemes that were surveyed in the physical and HCI sections. Second, for each pairing scheme we sought a particular use-case discussed by the authors, or looked at the specific setting in which the implemented pairing scheme was tested and evaluated. Using this information, we explicitly assigned each pairing scheme to one or more of the application classes. Finally, we considered for each pairing scheme, whether it could be extended to other application classes, either by an implicit reference in the paper, or by considering the physical and HCI interactions necessary for a specific pairing scheme, and comparing them with interactions

possible in each application class. Then pairing schemes that rely on biometry and have been used in the field of IMDs, for example, [30], are outside of the scope of this article, and thus, are not included in these results, and are mentioned here only for completeness. The results of our classification are presented in Table III, and are discussed below.

In line with the prior research we see that most of the proposed pairing schemes are aimed at the private application class. The public class is the second most targeted application scenario, followed by the social and unattended classes respectively. It was also observed that many pairing schemes could be extended to other application classes, especially schemes that implement security mechanisms on the physical layer [58], [59] or utilize contextual sensing [19], [28]. An interesting trade-off exists between those two groups of pairing schemes. While the former can offer provable security guarantees, it requires low-level changes of the communication stack which hinders the wide-spread adoption. In contrast, the latter group can be more easily deployed, but lacks clear security guarantees [78].

Another observation is related to pairing schemes deployed in commercial products, for example, [17], [43], [57], [70]. Often these schemes are claimed to be applicable to multiple of the application classes, irrespective of whether they are suitable on the basis of their security properties. For example, the PBC scheme [57] is available in both the infrastructure mode, as well as for Wi-Fi direct [215]. However, PBC is known to be vulnerable to MITM attacks, and the exposure is much greater in public and social contexts as compared to the private application class. Similar arguments apply to Just Works [43] which is the Bluetooth pairing scheme. Two other pairing schemes provided by the standardized bodies, namely Near Field Communication [17] and Out-of-band [70] rely on the NFC technology to transmit sensitive data, for example, a device generated password, in plain text. Despite being difficult, eavesdropping the NFC channel is not impossible and the chance of successful attack is much higher in public and social scenarios.

C. Discussion

Based on the investigation of the application classes, we discuss three open issues that have not been resolved by the prior research in SDP. First, how the presence of multiple security domains introduces complications. Second, what privacy issues arise in the respective application classes. Finally, whether pairing of devices should be valid indefinitely, or only for a finite time.

1) *Multiple Security Domains*: Issues arise when pairing devices belong to different security domains. The goals of two pairing parties, and the assets they protect can vary. This leads to security, privacy and usability implications that can affect the adoption of a given pairing scheme. For example, in the public application class the infrastructure side can provide acceptable user experience, and a certain level of security, but ignore users' privacy. Since privacy awareness is growing [216], many users may be reluctant to adopt a pairing scheme with such a drawback. The opposite situation is also feasible,

TABLE III
APPLICATION CLASSES - CLASSIFICATION OF PAIRING SCHEMES

Pairing Scheme	Application classes			
	Private	Public	Social	Unattended
Push Button Configuration [57]	●	●	●	○
Integrity codes [58]	○	●	○	○
Tamper-evident pairing [59]	●	○	○	○
Just Works [43]	●	●	●	○
Noisy tags [66]	○	●	○	○
Adopted-Pet [67]	●	○	○	●
Near Field Communication [17]	●	●	●	○
Out-of-band [70]	●	●	●	○
KeyLED [72]	●	○	○	○
Enlighten Me! [73]	○	●	○	○
Flashing displays [74]	●	○	○	○
Talking to Strangers [7]	○	●	○	○
Loud and Clear [41]	●	○	○	○
HAPADEP [33]	●	○	○	○
Zero-Power pairing [79]	○	○	○	●
Ultrasonic ranging [82]	○	○	○	○
SBVLC [75]	●	●	●	○
Vibrate-to-unlock [83]	●	○	○	○
Shot [38]	○	○	●	○
Vibreaker [84]	●	○	○	○
Amigo [27]	○	●	○	○
Good Neighbor [87]	●	○	○	○
Wanda [88]	●	●	○	○
Ambient Audio pairing [28]	○	○	○	●
Zero-interaction pairing [19]	○	○	○	●
MagPairing [89]	○	○	●	○
Touch-and-Guard [21]	●	●	○	○
MANA [193]	●	○	○	○
Access point authentication [194]	○	○	○	○
Shake Them Up! [195]	●	○	○	○
Shake Well Before Use [196]	●	○	○	○
SAPHE [197]	●	○	○	○
Authentication using ultrasound [198]	○	○	○	○
Synchronized Audio-Visual Patterns [34]	●	●	●	○
RhythmLink [199]	●	●	○	○
Seeing-Is-Believing [200]	○	○	○	○
Visible Laser Light [201]	○	○	○	○
VIC (mutual authentication) [202]	○	○	○	○
BEDA [33]	●	○	○	○
Playful Security [188]	○	○	○	○
Safeslinger [203]	○	○	○	○
Synchronized Drawing [185]	●	○	○	○
Proximity Authentication [204]	●	●	○	○
Checksum Gestures [20]	○	●	○	○

● = explicitly applies; ○ = can be applied; ○ = does not apply

when the infrastructure side aims to enhance security and privacy, but this occurs at the expense of usability. In this case, users may become confused, as they seek to understand how pairing works. Such confusion could result in high error rates, that can negatively affect both security and privacy, as well as jeopardize the acceptance of the pairing scheme. Similarly, in the social application class two users may have completely different attitudes towards security and privacy. Therefore, it should not be assumed that both participants are always attentive, collaborative and security-motivated. A pairing scheme that is designed to operate in the presence of several security domains should take into account the possible inconsistencies existing between them, and the impacts that this can have on user behavior and resulting security.

2) *Privacy Issues*: Each application class differs from the others in terms of the privacy risks and their potential impact. The key privacy issues regarding each application class are summarized below.

The private class is the least problematic, since only a single user is involved, who directly controls both devices. Therefore, all private information remains within the sphere of control of the user involved. Nonetheless, there exists the potential risk of observation attacks exfiltrating private information.

The public class introduces the risk of user tracking. Consider, for example, a distributed service that allows paying for the petrol in some area. Initially, a user pairs with the terminal on a petrol station. Behind the scenes, the user is being enrolled in the service, so that she can easily pay at other stations without the need to pair again. This example is both simple and realistic, and would allow the service to track the users, significantly impacting their privacy.

The social class is exposed to the risk of honest-but-curious participants. Such a threat can come in different forms, for example, peeking at another person's screen or observing her actions, or making a deliberate mistake to get physical access to the peer pairing device or retrieve extra data. None of the surveyed pairing schemes considered this type of attack. This is, therefore, a topic that justifies attention.

The unattended class is also prone to privacy leakage. The surveyed unattended pairing schemes rely on contextual sensing, which was shown to be plagued with privacy issues [217]. Since IOT devices at home or wearables can disclose a great deal of private information about the user and/or their environment, unattended pairing schemes must account for privacy protection during pairing. This presents, perhaps, the most critical privacy issue uncovered during this survey. That is, devices which can pair autonomously and may have access to the considerable amount of private data currently rely on the pairing mechanisms that do not take privacy into account, and the current state of the art does not yet offer any solution.

3) *Pairing Validity*: Historically the norm for device pairing has been to establish a "once and forever" pairing. However, there are good reasons why this is not always the most sensible approach, when instead the alternative may be more appropriate, that is, a temporary or transient pairing. In the private class, once-and-forever makes sense, where, for example, a user wishes to pair her smartphone with her car's entertainment system. In such cases, there exists an expectation of a long-term relationship between the devices, and that the devices will continue to belong to a single, common security domain. In contrast, many pairing scenarios in the public class are more sensibly handled by creating transient relationships between devices, for example, when paying for a parking ticket, printing or some other short-lived, transient activity. In such situations the devices belong to separate security domains, and the owner of one device has no control over the behavior of the other, or its handling of any potentially private data. It, therefore, makes no sense for the pairing relationship to endure indefinitely. Indeed, there may be additional advantages to transient pairing, for example, by preventing the user tracking. An open question is how one should implement short-term pairing in the public application class.

One approach would be to un-pair the devices after the necessary operation has been completed. However, it should be seamless and require no human effort, otherwise the usability will be jeopardized. Recently, a similar problem was addressed with respect to de-authentication [218], exposing the non-triviality of designing such schemes in a secure way.

Regarding the social class, both transient and long-term pairing may be applicable, depending on the social context and the amount of trust two people put into each other. For encounters of naturally limited scope or duration, for example, the exchange of contact details at a conference, pairing two devices permanently may be excessive. Furthermore, the level of trust between people can degrade which is another argument against pairing once-and-forever. Short-term pairing can also provide users with better security and privacy assurances, as the pairing is established only on an as-needed basis. This is in stark contrast to long-term pairing, which can be abused by another person or her device, for example, if the other person's device were to be compromised. However, if two users communicate regularly, for example, colleagues, having to repeatedly pair the same devices may be inconvenient.

Finally, considering the unattended class, the once-and-forever paradigm does not take into account the highly dynamic nature of IOT environments. In such environments it is already common to pair devices only if they are physically co-located. It may, therefore, make sense to un-pair devices whenever they conclude that they are no longer in close proximity. Yet, it remains unclear how to handle such un-pairing events, including how to determine when confidence of physical proximity reduces such that un-pairing is justified.

In this section, we have discussed the application classes and provided the classification of existing SDP schemes. In the next section, we outline open research challenges and future perspectives in the field of SDP.

VII. FUTURE CHALLENGES AND PERSPECTIVE

In order to design and build viable pairing schemes a wide range of challenges and open issues need to be resolved. We discuss several prominent challenges and provide a broad outlook for future research. We begin by explaining the need for creating adaptable SDP schemes, that are independent of specific PHY and HCI channels. The importance of including human interaction in the security chain is then discussed in terms of its potential to improve both security and usability. Following this, we explain why it is critical that the design process of a pairing scheme begins with the target use-case or application class, so that, again, security and usability can be maximized for each application. Fourth, we emphasize that SDP schemes currently lack ease of comparability, which hampers evidence-driven improvement of the state of the art for such pairing schemes. Finally, we highlight the problem that user privacy is rarely considered by the current cohort of SDP schemes.

A. Adaptable Secure Device Pairing

As has been shown through the course of this work it is impossible to find a universal pairing solution. The selection

of both PHY and HCI channels highly depends on a number of factors, including: application classes, the environment and (social) context, potential attacks, the data to be exchanged and availability of the channel. Thus, we argue that future research should be conducted towards a more general framework for pairing, which would take the aforementioned factors into account, and develop dynamic and customized pairing schemes built upon various PHY and HCI channels. In this case, the best security-usability trade-off can be obtained for a given situation. Such a framework should offer a higher level of abstraction, which would account for adding new factors, for example, in a form of "rules", that influence pairing, as well as, PHY and HCI channels seamlessly. Finally, we stress that the current design flow in pairing which starts with the hardware capabilities should be fundamentally rethought.

B. Including Human Interaction in the Security Chain

So far, the role of human interaction in SDP has not been fully acknowledged as fundamentally important. Yet, human interaction is unavoidable in device pairing, for example, when a user wants to have more control and assurance of the pairing process. In our study, we have shown that human interaction can be used to improve security if properly utilized. However, users' incentives for pairing, and the common HCI practices in pairing have not been well-studied. Surprisingly, few pairing schemes we reviewed accounted for mitigating user misbehavior, or actually leveraging human involvement to achieve better security. Thus, we advocate for making the HCI component an indispensable part of the pairing design and outline several points that are subject to future investigation. First, having a continuous and transparent feedback loop between a user and a pairing mechanism is crucial. As we stated before, feedback to the user can mitigate many aspects of user misbehavior. Also, the prior research relied heavily on human-perceptible PHY channels, but the full potential of this property has not been yet realized. For example, with the feedback loop, both security and usability benefits can be obtained, such as leveraging user perception to locate the source of the attack to improve security, or making a human-device link more interactive to improve usability. Second, more research on basic user experience and its applicability to pairing should be carried out to facilitate the creation of more usable and error-resilient pairing schemes. Finally, we highlighted several issues with regard to HCI observation attacks, however more sophisticated analysis is required to evaluate security of HCI channels.

C. Application Class Driven Design

Many of the pairing schemes surveyed were designed without a particular application class or use-case in mind. However, our findings have shown that each application class has unique and often highly-divergent security and usability requirements. Similarly, the sensitivity of the data being exchanged varies considerably among use-cases [35], ranging from negligible, for example, exchanging contact information at a conference, to critical, such as performing internet banking transactions. Therefore, it makes sense to begin the design process of a

SDP scheme with the target data, use-case, application class in mind. Only in this way can the resulting design be optimized to the particular needs and opportunities afforded by the target use-case. This optimization of the security-usability trade-off is critical to ensure the best possible outcome.

D. Improving Comparability of SDP Schemes

A sound comparative analysis of different SDP schemes was previously impractical, given the current design approach that starts from hardware capabilities, instead of the target application class or use-case. While the contributions of this paper have facilitated comparison of SDP schemes, complications remain, for example, due to the lack of distinction between PHY and HCI channels in most of the SDP schemes surveyed. By shifting the focus to the target use-cases and application classes, it becomes possible to identify a set of implementation-independent security and usability metrics. Those metrics could then be used to provide qualitative or quantitative comparison between different pairing schemes within an application class. Building a more generalized attacker model within an application class would assist in defining such security metrics. Derivation of specific threat-models for each of the application classes would be a particularly valuable contribution, as it would allow more objective assessment and comparison of the security properties of proposed pairing schemes.

E. Considering User Privacy

Prior research has not adequately addressed privacy issues in SDP. Increasing numbers of user devices store sensitive information and have sophisticated sensing capabilities with which many aspects of users' daily life can be directly measured or inferred [219]. Privacy concerns relating to this exist, and attacks that can obtain private data are feasible in the public, social and unattended application classes. Several channels by which users' privacy can be readily violated were revealed in the process of this survey. While not necessarily new information, it is a clear reminder of the attention required to devise systems that are privacy-preserving. That is why SDP schemes should be designed with user privacy and the specific target use-cases as the starting point, rather than physical hardware capabilities or other factors taking the leading role. Further research is also required to uncover hitherto undetected channels by which privacy may be violated, so that they can be taken into account in future SDP schemes.

In this section, we have discussed open research challenges and future perspectives in the field of SDP. In the next section, we provide the concluding remarks of our work.

VIII. CONCLUSION

In this survey, we proposed a system model and consistent terminology to facilitate meaningful comparison and analysis of SDP schemes. Our system model is based on the three key components drawn from the design space of SDP: physical channels, HCI channels and application classes.

With regard to PHY channels, the survey revealed that data confidentiality of the physical medium is very hard to

guarantee in practice. Emerging communication technologies such VLC and mm-Waves offer improved security properties. Other opportunities arise from the use of sensing of the shared environment by nearby devices.

With regard to HCI channels, the importance was highlighted of building pairing schemes resilient to: (a) user misbehavior, (b) observation of user actions during the pairing process and (c) honest-but-curious adversaries. It is only when these potential threats are properly considered, that HCI channels can play a trusted role in SDP schemes.

We also introduced application classes as a means of classification of SDP use-cases. Through the identification of the target application class, considerable insight can be gained that can be used to guide the design of SDP schemes to optimize the security-usability trade-off for a particular use-case. This stands in contrast to the current practice of beginning with physical hardware capabilities, instead of with the target use-cases. This shift to use-case oriented design was also identified as a necessary advance of the art. It is only by making this change, that SDP schemes within an application can be better compared in the future, whether qualitatively or quantitatively, allowing for evidence-based design and comparison of SDP schemes. Until this occurs, SDP schemes will likely continue to fail to address the security, privacy and usability requirements of the various use-cases.

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REFERENCES

- [1] T. M. Anandan, "The Business of Automation, Betting on Robots," September 2016. [Online]. Available: http://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/The-Business-of-Automation-Betting-on-Robots/content_id/6076
- [2] Grand View Research, Inc., "Personal/Consumer Electronics Market Analysis By Product (Smartphones, Tablets, Desktops, Laptops/Notebooks, Digital Cameras, Hard Disk Drives, E-readers) And Segment Forecasts To 2020," September 2016. [Online]. Available: <http://www.grandviewresearch.com/industry-analysis/personal-consumer-electronics-market>
- [3] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Generation Computer Systems*, vol. 29, pp. 1645–1660, 2013.
- [4] Q. Jing, A. V. Vasilakos, J. Wan, J. Lu, and D. Qiu, "Security of the internet of things: Perspectives and challenges," *Wireless Networks*, vol. 20, pp. 2481–2501, 2014.
- [5] S. Sicari, A. Rizzardi, L. A. Grieco, and A. Coen-Porisini, "Security, privacy and trust in Internet of Things: The road ahead," *Computer Networks*, vol. 76, pp. 146–164, 2015.
- [6] F. Stajano and R. Anderson, "The resurrecting duckling: Security issues for ad-hoc wireless networks," in *International Workshop on Security Protocols*. Springer, 1999, pp. 183–194.

- [7] D. Balfanz, D. K. Smetters, P. Stewart, and H. C. Wong, "Talking to Strangers: Authentication in Ad-Hoc Wireless Networks," in *Network and Distributed System Security Symposium (NDSS)*, 2002.
- [8] A. Kumar, N. Saxena, G. Tsudik, and E. Uzun, "A comparative study of secure device pairing methods," *Pervasive and Mobile Computing*, vol. 5, pp. 734–749, 2009.
- [9] A.-S. K. Pathan, *Security of self-organizing networks: MANET, WSN, WMN, VANET*. CRC press, 2010.
- [10] S. Mirzadeh, H. Cruickshank, and R. Tafazolli, "Secure device pairing: A survey," *IEEE Communications Surveys & Tutorials*, vol. 16, pp. 17–40, 2014.
- [11] R. Kainda, I. Flechais, and A. Roscoe, "Usability and security of out-of-band channels in secure device pairing protocols," in *30th IEEE Symposium on Security and Privacy (S&P)*. ACM, 2009, p. 11.
- [12] A. Kobsa, R. Sonawalla, G. Tsudik, E. Uzun, and Y. Wang, "Serial hook-ups: a comparative usability study of secure device pairing methods," in *5th Symposium on Usable Privacy and Security (SOUPS)*. ACM, 2009, p. 10.
- [13] M. K. Chong, R. Mayrhofer, and H. Gellersen, "A Survey of User Interaction for Spontaneous Device Association," *ACM Computing Surveys (CSUR)*, vol. 47, pp. 8:1–8:40, 2014.
- [14] M. K. Chong and H. Gellersen, "Usability classification for spontaneous device association," *Personal and Ubiquitous Computing*, vol. 16, pp. 77–89, 2012.
- [15] E. Uzun, N. Saxena, and A. Kumar, "Pairing devices for social interactions: a comparative usability evaluation," in *ACM Conference on Human Factors in Computing Systems (CHI)*. ACM, 2011, pp. 2315–2324.
- [16] A.-R. Sadeghi, C. Wachsmann, and M. Waidner, "Security and privacy challenges in industrial internet of things," in *52nd Design Automation Conference (DAC)*. IEEE, 2015, pp. 1–6.
- [17] Wi-Fi Alliance, "Wi-Fi Simple Configuration Technical Specification Version 2.0.5," September 2016. [Online]. Available: https://www.wi-fi.org/download.php?file=/sites/default/files/private/Wi-Fi_Simple_Configuration_Technical_Specification_v2.0.5.pdf
- [18] Bluetooth, SIG, "Security, Bluetooth Low Energy," September 2016. [Online]. Available: <https://www.bluetooth.com/~/media/files/specification/bluetooth-low-energy-security.ashx?la=en>
- [19] M. Miettinen, N. Asokan, T. D. Nguyen, A.-R. Sadeghi, and M. Sobhani, "Context-based zero-interaction pairing and key evolution for advanced personal devices," in *ACM Conference on Computer and Communications Security (CCS)*. ACM, 2014, pp. 880–891.
- [20] I. Ahmed, Y. Ye, S. Bhattacharya, N. Asokan, G. Jacucci, P. Nurmi, and S. Tarkoma, "Checksum gestures: continuous gestures as an out-of-band channel for secure pairing," in *ACM International Joint Conference on Pervasive and Ubiquitous Computing (UBICOMP)*. ACM, 2015, pp. 391–401.
- [21] W. Wang, L. Yang, and Q. Zhang, "Touch-and-guard: secure pairing through hand resonance," in *ACM International Joint Conference on Pervasive and Ubiquitous Computing (UBICOMP)*. ACM, 2016, pp. 670–681.
- [22] L. Yang, W. Wang, and Q. Zhang, "Secret from Muscle: Enabling Secure Pairing with Electromyography," in *14th ACM Conference on Embedded Network Sensor Systems (SenSys)*. ACM, 2016, pp. 28–41.
- [23] S. Li, A. Ashok, Y. Zhang, C. Xu, J. Lindqvist, and M. Gruteser, "Whose move is it anyway? Authenticating smart wearable devices using unique head movement patterns," in *IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE, 2016, pp. 1–9.
- [24] X. Liang, T. Yun, R. Peterson, and D. Kotz, "LightTouch: Securely Connecting Wearables to Ambient Displays with User Intent," in *IEEE International Conference on Computer Communications (INFOCOM)*. IEEE, 2017.
- [25] D. Schürmann, A. Brüsch, S. Sigg, and L. Wolf, "BANDANA-Body area network device-to-device authentication using natural gAit," in *IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE, 2017, pp. 190–196.
- [26] J. Grubert, M. Kranz, and A. Quigley, "Challenges in mobile multi-device ecosystems," *mUX: The Journal of Mobile User Experience*, vol. 5, p. 5, 2016.
- [27] A. Varshavsky, A. Scannell, A. LaMarca, and E. De Lara, "Amigo: Proximity-based authentication of mobile devices," *Ubiquitous Computing (UbiComp)*, pp. 253–270, 2007.
- [28] D. Schürmann and S. Sigg, "Secure communication based on ambient audio," *IEEE Transactions on Mobile Computing*, vol. 12, pp. 358–370, 2013.
- [29] C. Zhao, S. Yang, X. Yang, and J. McCann, "Rapid, user-transparent, and trustworthy device pairing for D2D-enabled mobile crowdsourcing," *IEEE Transactions on Mobile Computing (TMC)*, 2016.
- [30] M. Rostami, A. Juels, and F. Koushanfar, "Heart-to-heart (H2H): authentication for implanted medical devices," in *ACM Conference on Computer and Communications Security (CCS)*. ACM, 2013, pp. 1099–1112.
- [31] H. T. T. Truong, X. Gao, B. Shrestha, N. Saxena, N. Asokan, and P. Nurmi, "Comparing and fusing different sensor modalities for relay attack resistance in zero-interaction authentication," in *IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE, 2014, pp. 163–171.
- [32] C. Soriente, G. Tsudik, and E. Uzun, "BEDA: Button-Enabled Device Pairing," *IACR Cryptology ePrint Archive*, vol. 2007, p. 246, 2007.
- [33] —, "HAPADEP: human-assisted pure audio device pairing," in *11th International Conference on Information Security (ISC)*. Springer, 2008, pp. 385–400.
- [34] R. Prasad and N. Saxena, "Efficient device pairing using "human-comparable" synchronized audiovisual patterns," in *International Conference on Applied Cryptography and Network Security (ACNS)*. Springer, 2008, pp. 328–345.
- [35] I. Ion, M. Langheinrich, P. Kumaraguru, and S. Čapkun, "Influence of user perception, security needs, and social factors on device pairing method choices," in *6th Symposium on Usable Privacy and Security (SOUPS)*. ACM, 2010, p. 6.
- [36] T. Nguyen and J. Leneutre, "Formal analysis of secure device pairing protocols," in *IEEE 13th International Symposium on Network Computing and Applications (NCA)*. IEEE, 2014, pp. 291–295.
- [37] K. Haataja and P. Toivanen, "Two practical man-in-the-middle attacks on bluetooth secure simple pairing and countermeasures," *IEEE Transactions on Wireless Communications*, vol. 9, pp. 384–392, 2010.
- [38] A. Studer, T. Passaro, and L. Bauer, "Don't bump, shake on it: The exploitation of a popular accelerometer-based smart phone exchange and its secure replacement," in *27th Annual Computer Security Applications Conference (ACSAC)*. ACM, 2011, pp. 333–342.
- [39] T. Halevi and N. Saxena, "Acoustic eavesdropping attacks on constrained wireless device pairing," *IEEE Transactions on Information Forensics and Security*, vol. 8, pp. 563–577, 2013.
- [40] S. A. Anand, P. Shrestha, and N. Saxena, "Bad Sounds Good Sounds: Attacking and Defending Tap-Based Rhythmic Passwords Using Acoustic Signals," in *International Conference on Cryptology and Network Security (CANS)*. Springer, 2015, pp. 95–110.
- [41] M. T. Goodrich, M. Sirivianos, J. Solis, G. Tsudik, and E. Uzun, "Loud and clear: Human-verifiable authentication based on audio," in *26th IEEE International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2006, pp. 10–10.
- [42] D. Dolev and A. Yao, "On the security of public key protocols," *IEEE Transactions on Information Theory*, vol. 29, pp. 198–208, 1983.
- [43] Bluetooth, SIG, "Simple pairing whitepaper," 2006. [Online]. Available: http://mclean-linsky.net/joel/cv/Simple%20Pairing_WP_V10r00.pdf
- [44] Sophos Ltd., "Doctors disabled wireless in Dick Cheney's pacemaker to thwart hacking," July 2017. [Online]. Available: <https://nakedsecurity.sophos.com/2013/10/22/doctors-disabled-wireless-in-dick-cheney-s-pacemaker-to-thwart-hacking/>
- [45] E. Marin, D. Singelée, F. D. Garcia, T. Chothia, R. Willems, and B. Preneel, "On the (in) security of the latest generation implantable cardiac defibrillators and how to secure them," in *32nd Annual Computer Security Applications Conference (ACSAC)*. ACM, 2016, pp. 226–236.
- [46] A. Dix, "Human-computer interaction," in *Encyclopedia of database systems*. Springer, 2009, pp. 1327–1331.
- [47] R. D. Straw, *The ARRL antenna book: the ultimate reference for amateur radio antennas*. Amer Radio Relay League, 2003.
- [48] J. Terzic, E. Terzic, R. Nagarajah, and M. Alamgir, *Ultrasonic fluid quantity measurement in dynamic vehicular applications*. Springer, 2013.
- [49] W. Kim, Y. Shin, and S. Seol, "Smart phone assisted personal IoT service," *Advanced Science and Technology Letters*, vol. 110, pp. 61–66, 2015.
- [50] J. Suomalainen, "Smartphone assisted security pairings for the internet of things," in *4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*. IEEE, 2014, pp. 1–5.
- [51] Google, Inc., "Nexus tech specs," September 2016. [Online]. Available: <https://support.google.com/nexus/answer/6102470?hl=en>

- [52] M. D. Aime, G. Calandriello, and A. Liroy, "Dependability in wireless networks: Can we rely on WiFi?" *IEEE Symposium on Security and Privacy (S&P)*, vol. 5, pp. 23–29, 2007.
- [53] F. Fund, "Run a Man-in-the-Middle attack on a WiFi hotspot," <https://witestlab.poly.edu/blog/conduct-a-simple-man-in-the-middle-attack-on-a-wifi-hotspot/>, 03 2016.
- [54] E. Bayraktaroglu, C. King, X. Liu, G. Noubir, R. Rajaraman, and B. Thapa, "Performance of IEEE 802.11 under Jamming," *ACM Mobile Networks and Applications*, vol. 18, pp. 678–696, 2013.
- [55] M. Schulz, F. Gringoli, D. Steinmetzer, M. Koch, and M. Hollick, "Massive Reactive Smartphone-Based Jamming using Arbitrary Waveforms and Adaptive Power Control," in *10th ACM Conference on Security and Privacy in Wireless and Mobile Networks (WiSec)*. ACM, 2017.
- [56] Z. Lu, X. Lu, W. Wang, and C. Wang, "Review and evaluation of security threats on the communication networks in the smart grid," in *Military Communications Conference (MILCOM)*. IEEE, 2010, pp. 1830–1835.
- [57] Wi-Fi Alliance, "Wi-fi protected setup specification, version 1.0h," December 2006.
- [58] S. Čapkun, M. Čagalj, R. Rengaswamy, I. Tsigkogiannis, J.-P. Hubaux, and M. Srivastava, "Integrity codes: Message integrity protection and authentication over insecure channels," *IEEE Transactions on Dependable and Secure Computing*, vol. 5, pp. 208–223, 2008.
- [59] S. Gollakota, N. Ahmed, N. Zeldovich, and D. Katabi, "Secure in-band wireless pairing," in *USENIX Security Symposium*, 2011, pp. 1–16.
- [60] J. P. Dunning, "Taming the blue beast: A survey of bluetooth based threats," *IEEE Security & Privacy*, vol. 8, pp. 20–27, 2010.
- [61] D. Steinmetzer, J. Chen, J. Classen, E. Knightly, and M. Hollick, "Eavesdropping with periscopes: Experimental security analysis of highly directional millimeter waves," in *IEEE Conference on Communications and Network Security (CNS)*. IEEE, 2015, pp. 335–343.
- [62] T. Kasper, D. Oswald, and C. Paar, "Wireless security threats: Eavesdropping and detecting of active RFIDs and remote controls in the wild," in *19th International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*. IEEE, 2011, pp. 1–6.
- [63] A. Czeskis, K. Koscher, J. R. Smith, and T. Kohno, "RFIDs and secret handshakes: defending against ghost-and-leech attacks and unauthorized reads with context-aware communications," in *15th ACM Conference on Computer and Communications Security (CCS)*. ACM, 2008, pp. 479–490.
- [64] Y. Zhang and P. Kitsos, *Security in RFID and sensor networks*. Auerbach Publications, 2009.
- [65] A. Francillon, B. Danev, and S. Capkun, "Relay Attacks on Passive Keyless Entry and Start Systems in Modern Cars," in *Network and Distributed System Security Symposium (NDSS)*, 2011.
- [66] C. Castelluccia and G. Avoine, "Noisy tags: A pretty good key exchange protocol for RFID tags," in *International Conference on Smart Card Research and Advanced Applications (CARDIS)*. Springer, 2006, pp. 289–299.
- [67] G. T. Amariuca, C. Bergman, and Y. Guan, "An automatic, time-based, secure pairing protocol for passive RFID," in *International Workshop on Radio Frequency Identification: Security and Privacy Issues (RFIDSec)*. Springer, 2011, pp. 108–126.
- [68] R. Zhou and G. Xing, "nShield: a noninvasive NFC security system for mobile devices," in *12th annual international conference on Mobile systems, applications, and services (MobiSys)*. ACM, 2014, pp. 95–108.
- [69] L. Francis, G. Hancke, K. Mayes, and K. Markantonakis, "Practical NFC peer-to-peer relay attack using mobile phones," in *International Workshop on Radio Frequency Identification: Security and Privacy Issues (RFIDSec)*. Springer, 2010, pp. 35–49.
- [70] NFC Forum and Bluetooth, SIG, "Bluetooth Secure Simple Pairing Using NFC," September 2016. [Online]. Available: http://members.nfc-forum.org/apps/group_public/download.php/18688/NFCForum-AD-BTSSP_1_1.pdf
- [71] J. Classen, J. Chen, D. Steinmetzer, M. Hollick, and E. Knightly, "The Spy Next Door: Eavesdropping on High Throughput Visible Light Communications," in *2nd International Workshop on Visible Light Communications Systems (VLCS)*. ACM, 2015, pp. 9–14.
- [72] R. Roman and J. Lopez, "KeyLED-Transmitting sensitive data over out-of-band channels in wireless sensor networks," in *5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems*. IEEE, 2008, pp. 796–801.
- [73] M. Gauger, O. Saukh, and P. J. Marrón, "Enlighten me! secure key assignment in wireless sensor networks," in *6th IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS)*. IEEE, 2009, pp. 246–255.
- [74] T. Kovačević, T. Perković, and M. Čagalj, "Flashing displays: user-friendly solution for bootstrapping secure associations between multiple constrained wireless devices," *Security and Communication Networks*, 2015.
- [75] B. Zhang, K. Ren, G. Xing, X. Fu, and C. Wang, "SBVLC: Secure barcode-based visible light communication for smartphones," *IEEE Transactions on Mobile Computing (TMC)*, vol. 15, pp. 432–446, 2016.
- [76] M. Rahman, U. Topkara, and B. Carunar, "Seeing is not believing: visual verifications through liveness analysis using mobile devices," in *29th Annual Computer Security Applications Conference (ACSAC)*. ACM, 2013, pp. 239–248.
- [77] TV-B-Gone, "How Does TV-B-Gone Work?" September 2016. [Online]. Available: <http://www.tvbgone.com/using-your-tv-b-gone/how-does-tv-b-gone-work/>
- [78] B. Shrestha, N. Saxena, H. T. T. Truong, and N. Asokan, "Contextual Proximity Detection in the Face of Context-Manipulating Adversaries," *CoRR*, vol. abs/1511.00905, 2015.
- [79] D. Halperin, T. S. Heydt-Benjamin, B. Ransford, S. S. Clark, B. Defend, W. Morgan, K. Fu, T. Kohno, and W. H. Maisel, "Pacemakers and implantable cardiac defibrillators: Software radio attacks and zero-power defenses," in *IEEE Symposium on Security and Privacy (S&P)*. IEEE, 2008, pp. 129–142.
- [80] R. Mayrhofer and H. Gellersen, "On the Security of Ultrasound as Out-of-band Channel," in *IEEE International Parallel and Distributed Processing Symposium (IPDPS)*. IEEE, 2007, pp. 1–6.
- [81] J. Clulow, G. P. Hancke, M. G. Kuhn, and T. Moore, "So near and yet so far: Distance-bounding attacks in wireless networks," in *European Workshop on Security in Ad-hoc and Sensor Networks*. Springer, 2006, pp. 83–97.
- [82] R. Mayrhofer, M. Hazas, and H. Gellersen, "An authentication protocol using ultrasonic ranging," 2006.
- [83] N. Saxena, M. B. Uddin, J. Voris, and N. Asokan, "Vibrate-to-unlock: Mobile phone assisted user authentication to multiple personal RFID tags," in *IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE, 2011, pp. 181–188.
- [84] S. A. Anand and N. Saxena, "Vibreaker: Securing Vibrational Pairing with Deliberate Acoustic Noise," in *9th ACM Conference on Security & Privacy in Wireless and Mobile Networks (WiSec)*. ACM, 2016, pp. 103–108.
- [85] T. Schultes, M. Grau, D. Steinmetzer, and M. Hollick, "DEMO: Far Away and Yet Nearby-A Framework for Practical Distance Fraud on Proximity Services for Mobile Devices," in *9th ACM Conference on Security & Privacy in Wireless and Mobile Networks (WiSec)*. ACM, 2016, pp. 205–207.
- [86] N. O. Tippenhauer, C. Pöpper, K. B. Rasmussen, and S. Capkun, "On the requirements for successful GPS spoofing attacks," in *18th ACM Conference on Computer and Communications Security (CCS)*. ACM, 2011, pp. 75–86.
- [87] L. Cai, K. Zeng, H. Chen, and P. Mohapatra, "Good Neighbor: Ad hoc Pairing of Nearby Wireless Devices by Multiple Antennas," in *Network and Distributed System Security Symposium (NDSS)*, 2011.
- [88] T. J. Pierson, X. Liang, R. Peterson, and D. Kotz, "Wanda: securely introducing mobile devices," in *35th Annual IEEE International Conference on Computer Communications (INFOCOM)*. IEEE, 2016, pp. 1–9.
- [89] R. Jin, L. Shi, K. Zeng, A. Pande, and P. Mohapatra, "MagPairing: Exploiting magnetometers for pairing smartphones in close proximity," in *IEEE 13th International Symposium on Network Computing and Applications (NCA)*. IEEE, 2014, pp. 445–453.
- [90] M. Adeyeye and P. Gardner-Stephen, "The Village Telco project: a reliable and practical wireless mesh telephony infrastructure," *Journal on Wireless Communications and Networking (EURASIP)*, vol. 2011, p. 78, 2011.
- [91] P. Gardner-Stephen, "The serval project: Practical wireless ad-hoc mobile telecommunications," Flinders University, Adelaide, South Australia, Tech. Rep., 2011.
- [92] Google, Inc., "Wi-Fi Peer-to-Peer," July 2017. [Online]. Available: <https://developer.android.com/guide/topics/connectivity/wifip2p.html>
- [93] W. Shen, B. Yin, X. Cao, L. X. Cai, and Y. Cheng, "Secure device-to-device communications over WiFi direct," *IEEE Network*, vol. 30, pp. 4–9, 2016.
- [94] M. X. Gong, B. Hart, and S. Mao, "Advanced wireless lan technologies: IEEE 802.11 ac and beyond," *ACM GetMobile: Mobile Computing and Communications*, vol. 18, pp. 48–52, 2015.

- [95] S. Banerji, "On IEEE 802.11: Wireless LAN Technology," *CoRR*, vol. abs/1307.2661, 2013.
- [96] M. Atenas, S. Sendra, M. Garcia, and J. Lloret, "IPTV Performance in IEEE 802.11 n WLANs," in *IEEE Global Telecommunications Conference and Exhibition (GLOBECOM)*. IEEE, 2010, pp. 929–933.
- [97] Motorola, Inc., "5GHz IEEE 802.11a For Interference Avoidance," September 2016. [Online]. Available: http://www.motorolasolutions.com/content/dam/msi/docs/business/_documents/static_files/interference_tb_0809.pdf
- [98] A. B. M. Musa and J. Eriksson, "Tracking Unmodified Smartphones Using Wi-Fi Monitors," in *10th ACM Conference on Embedded Network Sensor Systems (SenSys)*. ACM, 2012, pp. 281–294.
- [99] C. Ware, J. Judge, J. Chicharo, and E. Dutkiewicz, "Unfairness and capture behaviour in 802.11 adhoc networks," in *IEEE International Conference On Communications (ICC)*. IEEE, 2000, pp. 159–163.
- [100] Bluetooth SIG, Inc., "Bluetooth technology basics," September 2016. [Online]. Available: <https://www.bluetooth.com/what-is-bluetooth-technology/bluetooth-technology-basics>
- [101] K. Scarfone and J. Padgett, "Guide to bluetooth security," *NIST Special Publication*, vol. 800, p. 121, 2008.
- [102] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.
- [103] K.-C. Huang and Z. Wang, *Millimeter wave communication systems*. John Wiley & Sons, 2011.
- [104] IEEE Standards Association, "802.11ad-2012 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," September 2016. [Online]. Available: <https://standards.ieee.org/findstds/standard/802.11ad-2012.html>
- [105] Wi-Fi Alliance, "Wi-Fi CERTIFIED WiGig," September 2016. [Online]. Available: <http://www.wi-fi.org/discover-wi-fi/wi-fi-certified-wigig>
- [106] S. Shankar N., D. Dash, H. E. Madi, and G. Gopalakrishnan, "WiGig and IEEE 802.11ad - For multi-gigabyte-per-second WPAN and WLAN," *CoRR*, vol. abs/1211.7356, 2012.
- [107] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges," *Wireless Networks*, vol. 21, pp. 2657–2676, 2015.
- [108] SiBEAM, Inc., "SiBEAM Captures World's First 60GHz Millimeter-wave Smartphone Design Win in Letv's Flagship Smartphone, Le Max," September 2016. [Online]. Available: <http://www.sibeam.com/en/News/2015/201505LetvsFlagshipSmartphoneLeMax.aspx>
- [109] HP Development Company, L.P., "HP Elite x2 1011 G2 - Connecting to the Wireless Dock," September 2016. [Online]. Available: http://h20564.www2.hp.com/hpsc/doc/public/display?docId=emr_na-c04587366#N10026
- [110] S. A. Weis, "RFID (radio frequency identification): Principles and applications," *System*, vol. 2, 2007.
- [111] EBV Elektronik, "RFID Selection Guide," September 2016. [Online]. Available: <https://cdn-shop.adafruit.com/datasheets/rfid+guide.pdf>
- [112] D. Sen, P. Sen, and A. M. Das, *RFID for energy & utility industries*. Pennwell Books, 2009.
- [113] D. Ma and N. Saxena, "A context-aware approach to defend against unauthorized reading and relay attacks in RFID systems," *Security and Communication Networks*, vol. 7, pp. 2684–2695, 2014.
- [114] S. Drimer, S. J. Murdoch *et al.*, "Keep Your Enemies Close: Distance Bounding Against Smartcard Relay Attacks," in *16th USENIX Security Symposium*, 2007, pp. 7:1–7:16.
- [115] G. Ho, D. Leung, P. Mishra, A. Hosseini, D. Song, and D. Wagner, "Smart locks: Lessons for securing commodity internet of things devices," in *11th ACM Asia Conference on Computer and Communications Security (AsiaCCS)*. ACM, 2016, pp. 461–472.
- [116] A. Ranganathan and S. Capkun, "Are We Really Close? Verifying Proximity in Wireless Systems," *IEEE Security & Privacy (S&P)*, vol. 15, pp. 52–58, 2017.
- [117] J. Thrasher, "How is RFID Used in Real World Applications?" September 2016. [Online]. Available: <http://blog.atlasrfidstore.com/what-is-rfid-used-for-in-applications>
- [118] NearFieldCommunication.org, "How NFC Works," September 2016. [Online]. Available: <http://nearfieldcommunication.org/how-it-works.html>
- [119] K. Markantonakis, L. Francis, G. Hancke, and K. Mayes, "Practical relay attack on contactless transactions by using nfc mobile phones," *Radio Frequency Identification System Security (RFIDsec)*, vol. 12, p. 21, 2012.
- [120] M. Roland, J. Langer, and J. Scharinger, "Applying relay attacks to Google Wallet," in *5th International Workshop on Near Field Communication (NFC)*. IEEE, 2013, pp. 1–6.
- [121] M. Maass, U. Müller, T. Schons, D. Wegemer, and M. Schulz, "NFC-Gate: an NFC relay application for Android," in *8th ACM Conference on Security & Privacy in Wireless and Mobile Networks (WiSec)*. ACM, 2015, p. 27.
- [122] M. Mehrnezhad, F. Hao, and S. F. Shahandashti, "Tap-Tap and Pay (TTP): Preventing the Mafia Attack in NFC Payment," in *International Conference on Research in Security Standardisation (SSR)*. Springer, 2015, pp. 21–39.
- [123] I. Gurulian, C. Shepherd, K. Markantonakis, R. N. Akram, and K. Mayes, "When Theory and Reality Collide: Demystifying the Effectiveness of Ambient Sensing for NFC-based Proximity Detection by Applying Relay Attack Data," *arXiv preprint arXiv:1605.00425*, 2016.
- [124] S. Arnon, *Visible light communication*. Cambridge University Press, 2015.
- [125] IEEE Standards Association, "802.15.7-2011 Part 15.7: Short-Range Wireless Optical Communication Using Visible Light," September 2016. [Online]. Available: <https://standards.ieee.org/findstds/standard/802.15.7-2011.html>
- [126] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15.7 visible light communication: modulation schemes and dimming support," *IEEE Communications Magazine*, vol. 50, pp. 72–82, 2012.
- [127] A. T. Hussein, M. T. Alresheedi, and J. M. Elmirghani, "20 Gb/s Mobile Indoor Visible Light Communication System Employing Beam Steering and Computer Generated Holograms," *IEEE Journal of Lightwave Technology*, vol. 33, pp. 5242–5260, 2015.
- [128] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Communications Surveys & Tutorials*, vol. 17, pp. 2047–2077, 2015.
- [129] T. Perkovic, M. Cagalj, T. Mastelic, N. Saxena, and D. Begusic, "Secure initialization of multiple constrained wireless devices for an unaided user," *IEEE transactions on Mobile Computing*, vol. 11, pp. 337–351, 2012.
- [130] J. Rigg, "Smartphone concept incorporates LiFi sensor for receiving light-based data," September 2016. [Online]. Available: <https://www.engadget.com/2014/01/11/oledcomm-lifi-smartphone-concept/>
- [131] S. D. Perli, N. Ahmed, and D. Katabi, "Pixnet: interference-free wireless links using lcd-camera pairs," in *16th annual international conference on Mobile computing and networking (MobiCom)*. ACM, 2010, pp. 137–148.
- [132] T. Hao, R. Zhou, and G. Xing, "COBRA: color barcode streaming for smartphone systems," in *10th International Conference on Mobile Systems, Applications, and Services (MobiSys)*. ACM, 2012, pp. 85–98.
- [133] A. Wang, S. Ma, C. Hu, J. Huai, C. Peng, and G. Shen, "Enhancing reliability to boost the throughput over screen-camera links," in *20th annual international conference on Mobile computing and networking (MobiCom)*. ACM, 2014, pp. 41–52.
- [134] Q. Wang, M. Zhou, K. Ren, T. Lei, J. Li, and Z. Wang, "Rain bar: Robust application-driven visual communication using color barcodes," in *35th IEEE International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2015, pp. 537–546.
- [135] J. Niu, F. Gu, R. Zhou, G. Xing, and W. Xiang, "VINCE: Exploiting visible light sensing for smartphone-based NFC systems," in *IEEE Conference on Computer Communications (INFOCOM)*. IEEE, 2015, pp. 2722–2730.
- [136] A. Barredo, "A comprehensive look at smartphone screen size statistics and trends," September 2016. [Online]. Available: <https://medium.com/@somospostpc/a-comprehensive-look-at-smartphone-screen-size-statistics-and-trends-e61d77001ebe#.hg2igim7n>
- [137] Statista, "Global shipments of smartphones with a screen size of 5 inches or larger from 2012 to 2016 (in million units)," September 2016. [Online]. Available: <http://www.statista.com/statistics/253350/shipments-of-smartphones-with-screen-size-5-inches-orlarger/>
- [138] A. Dziech, J. Bialas, A. Glowacz, P. Korus, M. Leszczuk, A. Miatolalski, and R. Baran, "Overview of recent advances in CCTV processing chain in the INDECT and INSIGMA projects," in *8th International Conference on Availability, Reliability and Security (ARES)*. IEEE, 2013, pp. 836–843.
- [139] E. T. Won, D. Shin, D. Jung, Y. Oh, T. Bae, H. Kwon, C. Cho, J. Son, D. O'Brien, T. Kang *et al.*, "Visible light communication: tutorial," *Project: IEEE P*, vol. 802, 2008.

- [140] J. Hallberg and M. Nilsson, "Positioning with bluetooth, IRDA and RFID," Master's thesis, Computer Science and Engineering, Luleå University of technology, 2002.
- [141] Infrared Data Association, "What is infrared?" September 2016. [Online]. Available: <http://www.irda.org/>
- [142] Hackaday.com, "Hackaday TV-B-Gone Kit (v1.2)," September 2016. [Online]. Available: <http://store.hackaday.com/products/hackaday-tv-b-gone-kit>
- [143] C. Burns, "Which phones let me control any TV?" September 2016. [Online]. Available: <http://www.slashgear.com/which-phones-let-me-control-any-tv-24338249/>
- [144] S. Rosen and P. Howell, *Signals and systems for speech and hearing*. Brill, 2011.
- [145] A. Madhavapeddy, R. Sharp, D. Scott, and A. Tse, "Audio networking: the forgotten wireless technology," *International Conference on Pervasive Computing*, vol. 4, pp. 55–60, 2005.
- [146] M. Hanspach and M. Goetz, "On Covert Acoustical Mesh Networks in Air," *CoRR*, vol. abs/1406.1213, 2014.
- [147] E. Lee, H. Kim, and J. W. Yoon, "Various Threat Models to Circumvent Air-Gapped Systems for Preventing Network Attack," in *International Workshop on Information Security Applications (WISA)*. Springer, 2015, pp. 187–199.
- [148] B. Carrara and C. Adams, "On acoustic covert channels between air-gapped systems," in *International Symposium on Foundations and Practice of Security (FPS)*. Springer, 2014, pp. 3–16.
- [149] HyperPhysics, "Sound Propagation," September 2016. [Online]. Available: <http://hyperphysics.phy-astr.gsu.edu/hbase/sound/sprop.html#c1>
- [150] Shure, Inc., "Microphone Techniques for Recording," September 2016. [Online]. Available: http://cdn.shure.com/publication/upload/837/microphone_techniques_for_recording_english.pdf
- [151] R. Mayrhofer, J. Fuß, and I. Ion, "UACAP: A unified auxiliary channel authentication protocol," *IEEE Transactions on Mobile Computing*, vol. 12, pp. 710–721, 2013.
- [152] HyperPhysics, "Ultrasonic Sound," September 2016. [Online]. Available: <http://hyperphysics.phy-astr.gsu.edu/hbase/sound/usound.html#c1>
- [153] KATHO, "MHz-ultrasound in air : a physical miracle?" September 2016. [Online]. Available: <http://www.katho.be/apps.aspx?smid=2688>
- [154] S. J. O'Malley and K.-K. R. Choo, "Bridging the air gap: Inaudible data exfiltration by insiders," in *20th Americas Conference on Information Systems (AMCIS)*, 2014, pp. 7–10.
- [155] F. Legendre, "How Google Nearby (really) works and what else it does?" September 2016. [Online]. Available: <http://blog.p2pk.it/how-google-nearby-really-works-and-what-else-it-does/>
- [156] R. L. Rivest and A. Shamir, "How to expose an eavesdropper," *Communications of the ACM*, vol. 27, pp. 393–394, 1984.
- [157] S. J. Bolanowski Jr, G. A. Gescheider, R. T. Verrillo, and C. M. Checkosky, "Four channels mediate the mechanical aspects of touch," *The Journal of the Acoustical Society of America*, vol. 84, pp. 1680–1694, 1988.
- [158] N. Roy, M. Gowda, and R. R. Choudhury, "Ripple: Communicating through physical vibration," in *12th USENIX Symposium on Networked Systems Design and Implementation (NSDI)*, 2015, pp. 265–278.
- [159] Bump Technologies, "Bump," September 2016. [Online]. Available: <http://bu.mp/>
- [160] T. Halevi, D. Ma, N. Saxena, and T. Xiang, "Secure proximity detection for NFC devices based on ambient sensor data," in *European Symposium on Research in Computer Security (ESORICS)*. Springer, 2012, pp. 379–396.
- [161] B. Shrestha, N. Saxena, H. T. T. Truong, and N. Asokan, "Drone to the rescue: Relay-resilient authentication using ambient multi-sensing," in *International Conference on Financial Cryptography and Data Security (FC)*. Springer, 2014, pp. 349–364.
- [162] Google, Inc., "Sensors Overview," September 2016. [Online]. Available: https://developer.android.com/guide/topics/sensors/sensors_overview.html
- [163] E. Kaplan and C. Hegarty, *Understanding GPS: principles and applications*. Artech house, 2005.
- [164] K. Fitchard, "Sensing Samsung: The evolution of sensors in the Galaxy S series," September 2016. [Online]. Available: <https://opensignal.com/blog/2016/02/19/sensing-samsung-the-evolution-of-sensors-in-the-galaxy-s-series/>
- [165] N. Roy and R. Roy Choudhury, "Listening Through a Vibration Motor," in *14th ACM Annual International Conference on Mobile Systems, Applications, and Services (MobiSys)*. ACM, 2016, pp. 57–69.
- [166] W. Wang, J. Lin, Z. Wang, Z. Wang, and L. Xia, "vBox: Proactively Establishing Secure Channels Between Wireless Devices Without Prior Knowledge," in *European Symposium on Research in Computer Security (ESORICS)*. Springer, 2015, pp. 332–351.
- [167] D. Ma, N. Saxena, T. Xiang, and Y. Zhu, "Location-aware and safer cards: enhancing RFID security and privacy via location sensing," *IEEE Transactions on Dependable and Secure Computing (TDSC)*, vol. 10, pp. 57–69, 2013.
- [168] N. Patwari and S. K. Kasera, "Robust location distinction using temporal link signatures," in *13th annual ACM international conference on Mobile computing and networking (MobiCom)*. ACM, 2007, pp. 111–122.
- [169] A. Kalamandeen, A. Scannell, E. de Lara, A. Sheth, and A. LaMarca, "Ensemble: cooperative proximity-based authentication," in *8th international conference on Mobile systems, applications, and services (MobiSys)*. ACM, 2010, pp. 331–344.
- [170] S. Mathur, R. Miller, A. Varshavsky, W. Trappe, and N. Mandayam, "Proximate: proximity-based secure pairing using ambient wireless signals," in *9th international conference on Mobile systems, applications, and services (MobiSys)*. ACM, 2011, pp. 211–224.
- [171] Y. Liu, S. C. Draper, and A. M. Sayeed, "Exploiting channel diversity in secret key generation from multipath fading randomness," *IEEE Transactions on Information Forensics and Security*, vol. 7, pp. 1484–1497, 2012.
- [172] L. Shi, M. Li, S. Yu, and J. Yuan, "BANA: body area network authentication exploiting channel characteristics," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 31, pp. 1803–1816, 2013.
- [173] W. Wang, Z. Wang, W. T. Zhu, and L. Wang, "WAVE: Secure Wireless Pairing Exploiting Human Body Movements," in *IEEE Trust-com/BigDataSE/ISPA (TRUSTCOM)*. IEEE, 2015, pp. 1243–1248.
- [174] W. Xi, C. Qian, J. Han, K. Zhao, S. Zhong, X.-Y. Li, and J. Zhao, "Instant and Robust Authentication and Key Agreement among Mobile Devices," in *ACM Conference on Computer and Communications Security (CCS)*. ACM, 2016, pp. 616–627.
- [175] M. Zafer, D. Agrawal, and M. Srivatsa, "Limitations of generating a secret key using wireless fading under active adversary," *IEEE/ACM Transactions on Networking (TON)*, vol. 20, pp. 1440–1451, 2012.
- [176] M. A. Sasse, S. Brostoff, and D. Weirich, "Transforming the "weakest link"-a human/computer interaction approach to usable and effective security," *BT Technology Journal*, vol. 19, pp. 122–131, 2001.
- [177] A. Jaimes and N. Sebe, "Multimodal human-computer interaction: A survey," *Computer Vision and Image Understanding*, vol. 108, pp. 116–134, 2007.
- [178] S. Das, A. D. Kramer, L. A. Dabbish, and J. I. Hong, "Increasing security sensitivity with social proof: A large-scale experimental confirmation," in *ACM Conference on Computer and Communications Security (CCS)*. ACM, 2014, pp. 739–749.
- [179] S. Das, E. Hayashi, and J. I. Hong, "Exploring capturable everyday memory for autobiographical authentication," in *ACM International Joint Conference on Pervasive and Ubiquitous Computing (UBI-COMP)*. ACM, 2013, pp. 211–220.
- [180] S. Das, G. Laput, C. Harrison, and J. I. Hong, "Thumprint: Socially-Inclusive Local Group Authentication Through Shared Secret Knocks," in *ACM Conference on Human Factors in Computing Systems (CHI)*. ACM, 2017, pp. 3764–3774.
- [181] B. Schneier, *Secrets and lies: digital security in a networked world*. John Wiley & Sons, 2011.
- [182] D. Besnard and B. Arief, "Computer security impaired by legitimate users," *Computers & Security*, vol. 23, pp. 253–264, 2004.
- [183] D. Liginlal, I. Sim, and L. Khansa, "How significant is human error as a cause of privacy breaches? An empirical study and a framework for error management," *Computers & Security*, vol. 28, pp. 215–228, 2009.
- [184] A. Perrig and D. Song, "Hash visualization: A new technique to improve real-world security," in *International Workshop on Cryptographic Techniques and E-Commerce*, 1999, pp. 131–138.
- [185] M. Sethi, M. Antikainen, and T. Aura, "Commitment-based device pairing with synchronized drawing," in *IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE, 2014, pp. 181–189.
- [186] S. Kraemer and P. Carayon, "Human errors and violations in computer and information security: The viewpoint of network administrators and security specialists," *Applied Ergonomics*, vol. 38, pp. 143–154, 2007.
- [187] N. Saxena and M. B. Uddin, "Secure pairing of "Interface-constrained" devices resistant against rushing user behavior," in *International*

- Conference on Applied Cryptography and Network Security (ACNS)*. Springer, 2009, pp. 34–52.
- [188] A. Gallego, N. Saxena, and J. Voris, “Playful security: A computer game for secure wireless device pairing,” in *16th International Conference on Computer Games (CGAMES)*. IEEE, 2011, pp. 177–184.
- [189] J. Bonneau, C. Herley, P. C. Van Oorschot, and F. Stajano, “The quest to replace passwords: A framework for comparative evaluation of web authentication schemes,” in *2012 IEEE Symposium on Security and Privacy (S&P)*. IEEE, 2012, pp. 553–567.
- [190] H.-C. Hsiao, Y.-H. Lin, A. Studer, C. Studer, K.-H. Wang, H. Kikuchi, A. Perrig, H.-M. Sun, and B.-Y. Yang, “A study of user-friendly hash comparison schemes,” in *Annual Computer Security Applications Conference (ACSAC)*. IEEE, 2009, pp. 105–114.
- [191] C. Kray, D. Nesbitt, J. Dawson, and M. Rohs, “User-defined gestures for connecting mobile phones, public displays, and tabletops,” in *12th international conference on Human computer interaction with mobile devices and services (MobileHCI)*. ACM, 2010, pp. 239–248.
- [192] R. Kanda, I. Flechais, and A. Roscoe, “Two heads are better than one: security and usability of device associations in group scenarios,” in *6th Symposium on Usable Privacy and Security (SOUPS)*. ACM, 2010, p. 5.
- [193] C. Gehrman, C. J. Mitchell, and K. Nyberg, “Manual authentication for wireless devices,” *RSA Cryptobites*, vol. 7, pp. 29–37, 2004.
- [194] V. Roth, W. Polak, E. Rieffel, and T. Turner, “Simple and effective defense against evil twin access points,” in *1st ACM Conference on Wireless Network Security (WiSec)*. ACM, 2008, pp. 220–235.
- [195] C. Castelluccia and P. Mutaf, “Shake Them Up!: A Movement-based Pairing Protocol for CPU-constrained Devices,” in *3rd International Conference on Mobile Systems, Applications, and Services (MobiSys)*. ACM, 2005, pp. 51–64.
- [196] R. Mayrhofer and H. Gellersen, “Shake Well Before Use: Authentication Based on Accelerometer Data,” in *International Conference on Pervasive Computing*. Springer, 2007, pp. 144–161.
- [197] B. Groza and R. Mayrhofer, “SAPHE: simple accelerometer based wireless pairing with heuristic trees,” in *10th International Conference on Advances in Mobile Computing & Multimedia (MoMM)*. ACM, 2012, pp. 161–168.
- [198] T. Kindberg and K. Zhang, “Validating and securing spontaneous associations between wireless devices,” *Information Security*, vol. 2851, pp. 44–53, 2003.
- [199] F. X. Lin, D. Ashbrook, and S. White, “RhythmLink: securely pairing I/O-constrained devices by tapping,” in *24th annual ACM symposium on User Interface Software and Technology (UIST)*. ACM, 2011, pp. 263–272.
- [200] J. M. McCune, A. Perrig, and M. K. Reiter, “Seeing-is-believing: Using camera phones for human-verifiable authentication,” in *IEEE Symposium on Security and Privacy (S&P)*. IEEE, 2005, pp. 110–124.
- [201] R. Mayrhofer and M. Welch, “A human-verifiable authentication protocol using visible laser light,” in *2nd International Conference on Availability, Reliability and Security (ARES)*. IEEE, 2007, pp. 1143–1148.
- [202] N. Saxena, J.-E. Ekberg, K. Kostiaainen, and N. Asokan, “Secure device pairing based on a visual channel: Design and usability study,” *IEEE Transactions on Information Forensics and Security*, vol. 6, pp. 28–38, 2011.
- [203] M. Farb, Y.-H. Lin, T. H.-J. Kim, J. McCune, and A. Perrig, “Safeslinger: easy-to-use and secure public-key exchange,” in *19th annual international conference on Mobile computing & networking (MobiCom)*. ACM, 2013, pp. 417–428.
- [204] L. Li, X. Zhao, and G. Xue, “A proximity authentication system for smartphones,” *IEEE Transactions on Dependable and Secure Computing (TDSC)*, vol. 13, pp. 605–616, 2016.
- [205] K. B. Rasmussen and S. Capkun, “Implications of radio fingerprinting on the security of sensor networks,” in *3rd International Conference on Security and Privacy in Communications Networks and the Workshops (SecureComm)*. IEEE, 2007, pp. 331–340.
- [206] S. Jarecki and X. Liu, “Fast secure computation of set intersection,” in *International Conference on Security and Cryptography for Networks (SCN)*. Springer, 2010, pp. 418–435.
- [207] E. Uzun, K. Karvonen, and N. Asokan, “Usability analysis of secure pairing methods,” in *International Conference on Financial Cryptography and Data Security*. Springer, 2007, pp. 307–324.
- [208] T. Halevi and N. Saxena, “Keyboard acoustic side channel attacks: exploring realistic and security-sensitive scenarios,” *International Journal of Information Security*, vol. 14, pp. 443–456, 2015.
- [209] A. Davis, M. Rubinstein, N. Wadhwa, G. J. Mysore, F. Durand, and W. T. Freeman, “The visual microphone: passive recovery of sound from video,” *ACM Transactions on Graphics (SIGGRAPH)*, vol. 33, pp. 79:1–79:10, 2014.
- [210] M. Backes, T. Chen, M. Duermuth, H. P. Lensch, and M. Welk, “Tempest in a teapot: Compromising reflections revisited,” in *30th IEEE Symposium on Security and Privacy (S&P)*. IEEE, 2009, pp. 315–327.
- [211] Q. Yue, Z. Ling, X. Fu, B. Liu, K. Ren, and W. Zhao, “Blind recognition of touched keys on mobile devices,” in *ACM Conference on Computer and Communications Security (CCS)*. ACM, 2014, pp. 1403–1414.
- [212] D. Mukhopadhyay, M. Shirvanian, and N. Saxena, “All your voices are belong to us: Stealing voices to fool humans and machines,” in *European Symposium on Research in Computer Security (ESORICS)*. Springer, 2015, pp. 599–621.
- [213] B. Shrestha, M. Mohamed, and N. Saxena, “Walk-Unlock: Zero-Interaction Authentication Protected with Multi-Modal Gait Biometrics,” *CoRR*, vol. abs/1605.00766, 2016.
- [214] M. Juuti, C. Vaas, I. Sluganovic, H. Liljestrand, N. Asokan, and I. Martinovic, “STASH: Securing transparent authentication schemes using prover-side proximity verification,” in *14th IEEE International Conference on Sensing, Communication, and Networking (SECON)*. IEEE, 2017, pp. 1–9.
- [215] Wi-Fi Alliance, “Wi-Fi Direct,” September 2016. [Online]. Available: <http://www.wi-fi.org/discover-wi-fi/wi-fi-direct>
- [216] T. Cooper and R. LaSalle, “Guarding and growing personal data value,” September 2016. [Online]. Available: https://www.accenture.com/_acnmedia/PDF-4/Accenture-Guarding-and-Growing-Personal-Data-Value-POV-Low-Res.pdf
- [217] D. Christin, A. Reinhardt, S. S. Kanhere, and M. Hollick, “A survey on privacy in mobile participatory sensing applications,” *Journal of Systems and Software*, vol. 84, no. 11, pp. 1928–1946, 2011.
- [218] O. Huhta, S. Udar, M. Juuti, P. Shrestha, N. Saxena, and N. Asokan, “Pitfalls in Designing Zero-Effort Deauthentication: Opportunistic Human Observation Attacks,” in *23rd Network and Distributed System Security Symposium NDSS*, 2016.
- [219] K. K. Rachuri, T. Hossmann, C. Mascolo, and S. Holden, “Beyond location check-ins: Exploring physical and soft sensing to augment social check-in apps,” in *IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE, 2015, pp. 123–130.