Resilient Intermediary-Based Key Exchange Protocol for IoT

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Due to the limited resources of Internet of Things (IoT) devices, Symmetric Key Cryptography (SKC) is typically favored over resource-intensive Public Key Cryptography (PKC) to secure communication between IoT devices. To utilize SKC, devices need to execute a key exchange protocol to establish a session key before initiating communication. However, existing SKC-based key exchange protocols assume communication devices have a pre-shared secret or there are trusted intermediaries between them; neither is always realistic in IoT.

We introduce a new SKC-based key exchange protocol for IoT devices. While also intermediary-based, our protocol fundamentally departs from existing intermediary-based solutions in that intermediaries between two key exchange devices may be malicious, and moreover, our protocol can detect cheating behaviors and identify malicious intermediaries. We prove our protocol is secure under the universally composable model, and show it can detect malicious intermediaries with probability 1.0. We implemented and evaluated our protocol on different IoT devices. We show our protocol has significant improvements in computation time and energy cost. Compared to the PKC-based protocols ECDH, DH, and RSA, our protocol is 2.3 to 1591 times faster on one of the two key exchange devices and 0.7 to 4.67 times faster on the other.

CCS Concepts: • **Security and privacy → Key management**; **Symmetric cryptography and hash functions**; • **Theory of computation** → *Cryptographic protocols*.

Additional Key Words and Phrases: Internet of Things, key exchange, malicious intermediary

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1 INTRODUCTION

Due to advances in lightweight computing and networking technologies, the Internet of Things (IoT) has rapidly penetrated into our lives. However, because a compromised IoT system can lead to disastrous results [23, 35, 43], a key challenge facing IoT is that IoT networks must support secure communications channels to protect message integrity and confidentiality, thus resistant to both message tampering and eavesdropping. To establish secure communication channels, a general solution for IoT devices is to employ cryptographic algorithms. For instance, IoT devices can either employ public key cryptography (PKC) or symmetric key cryptography (SKC) to establish secure communication channels between them. However, IoT devices are highly heterogeneous and usually have extremely limited resources

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such as memory, battery, and computing power. Due to the expensive operations and longer key sizes of PKC, many IoT devices are not capable of performing PKC and have to resort to SKC. A central question with using SKC, however, is key exchange; that is, any two IoT devices must exchange a common secret key in order to encrypt and decrypt messages between them.

Non-cryptographic solutions have been proposed for secret key exchange between IoT devices. A typical solution is using a secure secondary communication channel, which however usually requires additional hardwares or sensors [24, 42] that IoT devices may not be equipped with. Other non-cryptographic solutions include jamming [3] and proximity [31]. The jamming solution requires a special entity—*jammer*—to jam the channel and the proximity solution needs IoT devices to be physically close to each other (e.g., 6cm); both are often unrealistic.

Cryptographic key exchange solutions can be various methods using PKC (e.g., Diffie-Hellman, ECC, RSA) or methods not using PKC. The former's demand on resources and computing power is often beyond the reach of IoT devices. For example, in our experiments, we observed that devices with resources of CPU clock less than 32MHZ, flash memory size less than 64KB, and RAM size less than 16KB, are failed to perform PKC-based key exchange protocols. The latter are methods using SKC. In contrast to using PKC, SKC-based key exchange has a better performance with significantly lower usage of resources and computational power, thus is often preferred to PKC-based key exchange in resource-constrained environments. However, to use SKC for key exchange, *if* only two communication parties are involved and no pre-shared private secret, SKC alone is not sufficient to establish a key exchange protocol via public channels, even if one-way function exists [20]. There are two approaches in using SKC for key exchange between two parties: using a pre-shared secret between the two parties, or using the help of intermediary parties between the two parties. Here, we also call an intermediary party a *helper* in the rest of the paper. As an IoT network is often composed of hundreds or even thousands of devices, doing the former approach for every pair of devices is daunting. The latter approach is more feasible, which we focus on in this paper.

To the best of our knowledge, all existing SKC-based key exchange protocols with intermediary helpers rely on an assumption in their adversary model that the intermediaries must be honest or semi-honest, where the intermediaries do not tamper with messages in a protocol or abort the protocol and follow all instructions in a key exchange protocol (Intermediaries in the honest model are trustworthy while intermediaries in the semi-honest model are not fully trustworthy and may attempt to obtain useful information from the protocol). This assumption is usually stringent and often unrealistic. A stronger adversary model is the malicious model in which intermediaries can arbitrarily deviate from a protocol. If intermediary parties are compromised by malicious adversaries, they can tamper with messages between the key exchange parties. IoT devices may not detect the compromise and they may either fail to exchange a secret key between them or leak useful information pertaining to the key to adversaries. Key exchange parties could try to sign their messages, but signing with PKC is too expensive for IoT devices, and signing with SKC requires the key exchange parties to have a shared key between them which they have yet to agree on.

Furthermore, to our best knowledge, none of the previous intermediary-based key exchange protocols have formally proved that their protocol is secure under the Universally Composable (UC) security model, or UC-secure [9]. Here, a UC-secure key exchange protocol means even when it is used by multiple key exchange sessions simultaneously or when it is combined with other protocols (e.g., when it is embedded in another protocol), the protocol is still secure (e.g., no information can leak from one session to another session or leak from the key exchange protocol to another protocol).

In this work, we design, prove, and evaluate a new intermediary-based key exchange protocol for devices with limited resources—especially IoT devices—to successfully and securely agree upon a secret session key. In particular, we apply

the cut-and-choose technique to identify the malicious helpers without using any PKC primitives. Cut-and-choose is widely adopted in multi-party computation (MPC) [1, 25] to achieve security against malicious parties. Its main idea is to let one party construct different versions of a secret message and have the other party randomly check some of them and use the rest of them. In our protocol, we first let an IoT device create a bunch of test keys, and then let the other IoT device randomly pick a subset of test keys to detect malicious helpers and use the remaining test keys to derive a real secret session key for communication between the two devices. Our main contributions include:

- Our protocol advances SKC-based key exchange. Unlike any previous intermediary-based solution, our protocol is the first one that does *not* rely on the trustworthiness of helper parties. Also, the protocol does not leak any useful information to the helper parties. If some helpers are malicious and do not follow the protocol, the two devices will still be able to establish a session key without leaking any useful information.
- Our protocol introduces a novel design that can efficiently identify the malicious helpers when they tamper messages going through them, even if they collude or selectively tamper messages.
- With the SK-security framework and the UC model, we formally prove that our protocol is secure against malicious intermediary helpers in both the stand-alone model and the UC model.
- We derive the best possible setting (e.g., the number of intermediary helpers and secure channels needed) for an intermediary-based key exchange protocol to be secure. We also show how two communication devices authenticate each other with the help from intermediaries before the key exchange starts.
- We conduct a theoretical analysis of our protocol and show its failure probability is easily negligible with a reasonable setup and its malicious helper detection probability can be 1.0 even when a malicious helper only tampers a small number of messages.
- We provide empirical evaluations for our protocol. We implemented our protocol and emulated different IoT devices on Mininet to evaluate its performance against three widely used PKC-based protocols: RSA, Diffie-Hellman, and Elliptic Curve Diffie-Hellman. For two parties doing key exchange, our experiments demonstrated that our protocol achieves 2.3 to 1591 times faster on one party and 0.7 to 4.67 times faster on the other.

Note that this paper extends and improves our previous conference paper [18] by discussing the optimal setting for a secure intermediary-based key exchange protocol. In addition, we enhanced the key derivation process and further formally proved that our protocol is secure in a stronger security model—the UC model. We also conduct additional theoretical analysis to explain the experimental setting in our evaluation, and finally provide some use cases of our protocol in practice.

The rest of this paper is organized as follows. Section 2 reviews the related work on previous key exchange protocols in IoT environments and summarizes their limitations and drawbacks. Section 3 introduces the basic design of the intermediary-based key exchange protocol with secret sharing scheme, and shows the network configurations in the basic design. Section 4 describes our resilience design that can detect malicious behaviors and identify cheating intermediaries with the cut-and-choose technique. Section 5 proves the security of our protocol against malicious intermediaries in the UC model. Section 6 provides a theoretical analysis of our protocol's efficacy, resiliency, and overhead. Section 7 shows the experimental results of our protocol's performance and network overhead. Section 8 illustrates some real-world use cases that apply our protocol in practical applications. Finally, Section 9 concludes this paper.

2 RELATED WORK

A secure key exchange protocol is a core cryptographic primitive in building secure communication channels [10]. Various standard public key cryptography (PKC) schemes are sufficient to implement a secure key exchange protocol in traditional networks. However, due to the limited resources of IoT devices, these schemes are not suitable for many IoT environments. Many previous approaches were introduced to improve the efficiency of PKC, such as more efficient variants of Elliptic Curve schemes [8, 12]. A proposed SEMECS scheme in [41] improves the Elliptic Curve-based PKC solution by eliminating some expensive operations in ECC such as scalar multiplication or addition. In addition, Ozmen and Yavuz [30] propose Designated Boyko-Peinado-Venkatesan (DBPV) solution which significantly improves the energy consumption for IoT devices. The result shows that their solution is up to 7 times better than standard PKC solutions in terms of the battery life and computation time. The computational cost *during* key exchange can also be reduced by performing pre-computations *before* key exchange [30]. However, improvements on PKC-based methods are limited, mostly insufficient in addressing the resource limitations of IoT devices with extremely constrained resources. Below we focus on previous approaches that mainly use SKC.

One key exchange solution without PKC is using physical unclonable function (PUF) [44, 45]. The main idea is that IoT devices can leverage the unique and unpredictable characteristics of the PUF to authenticate each other and generate a shared secret. However, PUF-based solution requires specialized hardware to function and devices must be embedded with a PUF, which is often unrealistic for many IoT devices.

Another key exchange solution without PKC is using a pre-shared secret. For example, the approach in [22] and [36] assume that all nodes in the same network share a common master key, from which any two nodes can derive their session key. However, if any node is compromised, it will expose the master key and therefore threaten the confidentiality of the entire network. To address this issue, some approaches (such as those in [14, 27]) instead use a password between a client and all its servers as a pre-shared secret, where every server has a share of the password. The servers collectively use the password to authenticate the client and then derive a session key for the client to communicate with any one of the servers. Here, unless more than a threshold number of servers are compromised, a compromised server node will not leak the password. Unfortunately, these password-based approaches still employ PKC. Also, like the pre-shared master key, they still have a single point-of-failure (the password), and they cannot identify which server(s), if any, are compromised.

Instead of one common pre-shared secret among all nodes, Chan *et al.* [17] suggest each node pre-store a set of keys randomly selected from a universal key space, where the sets of any two nodes overlap. When a node decides to start a communication session with another node, it must identify all the common keys it shares with that node and then derive a session key between them from the common keys. If an attacker subverts a node, the attacker can only learn the keys in the node's set of keys, while the session key remains secure. However, the procedure to identify common keys between different nodes could leak useful information about the universal key space and eventually the information of the session keys between nodes. In a similar work [26], every node is associated with a set of polynomials in a universal pool of random bivariate polynomials. Any two nodes need to derive their session key by first identifying their common bivariate polynomials, which however could leak useful information of the pool and also the information of the session keys.

Different from using a pre-shared secret, another solution is to use help from a trusted third party. Hummen *et al.* [19] suggested that as long as an IoT device maintains a key associated with an external trusted server, it then can use the help of the trusted server to derive a new secret session key for its communication with another party. This approach

drastically reduces the computations of IoT devices. Yet, the trusted server is a major point of failure. If it is compromised, it could obtain all secret keys.

Instead of placing trust into a single third party, researchers proposed solutions using multiple intermediary helpers. Solutions in [21, 32–34] use the neighboring nodes of key exchange parties as intermediary helpers, whereas for the solution in [17], multiple independent communication paths between two communication nodes can be regarded as intermediary helpers. A party can initiate a key exchange with another party by splitting a *secret* into multiple *secret shares* and sending each share to a different intermediary helper, where each share leaks no information of the original secret. Every intermediary helper then forwards the share it receives to the other key exchange party, which subsequently assembles all the shares it receives to derive the original secret, and both parties can then use the same secret to derive their session key. However, these intermediary-based solutions assume all intermediaries are trusted or at least *semi-honest*. In other words, *all* intermediaries must follow the protocol honestly. If any intermediary becomes malicious and deviates from the protocol, such as discarding a secret share or tampering a secret share before forwarding it, the whole key exchange could fail and the malicious intermediary may learn certain information of the secret, potentially weakening the confidentiality strength of the session key. Furthermore, the communication nodes cannot detect which intermediary helpers are compromised by the adversary.

3 BASIC DESIGN

Not only does our intermediary-based key exchange solution eliminate all PKC operations and only rely on SKC operations, it also significantly differs from prior intermediary-based solutions and adds new features. In particular, we describe the basic design of our key exchange solution in this section and focus on the resiliency against malicious intermediaries in the next section.

3.1 Settings and Assumptions

Every IoT device, say P_A, communicates with another IoT device, say P_B, via a public channel, which is not secure as messages through the channel could be eavesdropped or tampered. P_A and P_B thus need to exchange a session key to protect their communication, where P_A is the **key exchange initiator** and P_B is **key exchange responder**. P_A and P_B are honest and follow their key exchange protocol between themselves. Finally, both parties are resource-constrained IoT devices and can only perform SKC operations (i.e., no PKC operations).

Between P_A and P_B are n intermediary helper parties H_i ($i = 1, \ldots, n$) (Fig. 1) that will assist the key exchange. A helper can be a gateway device, a smart phone, or another IoT device. Further, P_A and P_B each set up a secure channel with every helper through a registration process, which can establish a shared secret between an IoT device and a helper and use the shared secret to set up a secure channel between them for their communication. (Note this registration process is not suitable for two IoT devices to exchange a session key as it will need to register every IoT device at its every communication party, a much larger overhead than registering a device at all its helpers.) Finally, unlike P_A and P_B who are honest, a helper may be malicious. We assume there are less than t helpers in total which are malicious.

Before they start key exchange, P_A and P_B authenticate each other, as follows. For P_A to authenticate itself to P_B, P_A composes an authentication message about its identity and sends it to every helper (through its secure channel with the helper). Every helper then verifies the message; if the message is verified, the helper then sends a claim to P_B (through its secure channel with P_B) that the other side is indeed P_A. On the side of P_B, upon the receipt of claims from all the helpers, P_B can then decide if P_A is authenticated based on its authentication policy, which, for example, may require (a) all the claims vouch for P_A, or (b) the majority of claims vouch for P_A, or (c) no more than a threshold

number or percentage of claims vouch for an identity that is not P_A. Clearly, except for policy (a), if some helpers are malicious, P_B can still authenticate P_A. P_B can authenticate itself to P_A in the same way.

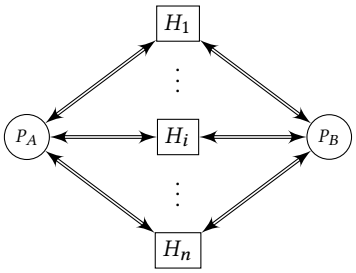


Fig. 1. The settings of key exchange. P_A and P_B are communication devices and H_i ($i = 1, \ldots, n$) are intermediary helpers. A double-headed arrow indicates a secure channel between an IoT device and a helper, and they can send messages to each other.

3.2 Key Exchange Protocol π

We now describe the key exchange protocol π to illustrate the basic design of our key exchange solution. It leverages a standard *t-out-of-n secret sharing scheme* [37] in which a secret S is composed of n shares and a collection of at least $t (t \leq n)$ shares must be present in order to reconstruct S. Any collection that has less than t shares does not leak any information about S. The main idea of π is for the key exchange initiator P_A to split a secret into n shares and for the key exchange responder P_B to receive at least t shares separately through t helpers and reconstruct the original secret, thus P_A and P_B are able to use the same secret to derive their session key. The protocol is as follows.

(a) **Initialization.** P_A initializes the key exchange with P_B by sending P_B a message (INIT, sid) (via a public channel) where INIT contains P_A's security parameters (including ciphers and parameters available for key exchange and ciphers and key lengths for its communication with P_B) and sid is the ID of the current key exchange session. P_B then sends back (INITCONFIRM, sid) (via a public channel) where INITCONFIRM contains a subset of P_A's security parameters that P_B agrees with for their key exchange.
(b) **Choose secret and its shares.** P_A randomly chooses a secret S and invokes a t-out-of-n secret sharing scheme to obtain n shares of S: $\{s_i | i = 1, \ldots, n\}$.
(c) **Transfer secret shares.** P_A sends s_i to H_i ($i = 1, \ldots, n$), which then forwards s_i to P_B after receiving s_i.
(d) **Derive secret from shares.** Upon receipt t shares among $\{s_i | i = 1, \ldots, n\}$, P_B then uses the t-out-of-n secret sharing scheme to reconstruct S.
(e) **Derive session key.** P_A and P_B both compute $k_{sid} = f(S, 0)$, where f is a pseudorandom function agreed by P_A and P_B during initialization. k_{sid} is then the session key for P_A and P_B.
(f) **Verify session key.** Furthermore, P_A and P_B each compute $S' = f(S, 1)$, and P_B sends an acknowledgement message $M = g(\text{“CONFIRM”}, sid, P_A, P_B, S')$ to P_A where g is a message authentication function (also agreed by P_A and P_B during initialization). Upon the receipt of M, P_A checks if M is also $g(\text{“CONFIRM”}, sid, P_A, P_B, S')$. If so, P_A knows both parties agree on k_{sid} as their session key, and P_A can start its communication with P_B; otherwise, P_A either aborts the protocol or initiates another instance of π.

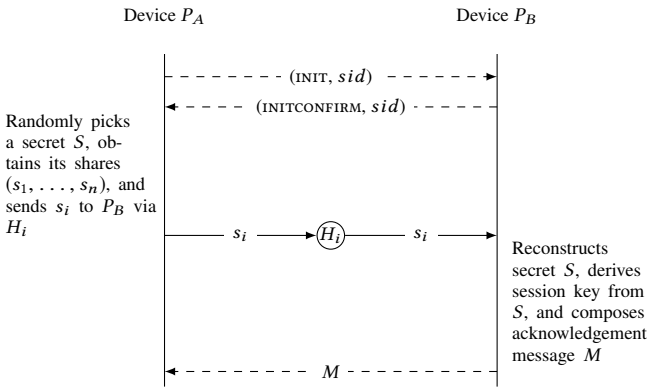


Fig. 2. Key exchange protocol π. Each dashed line means a message is sent via a public channel. Each solid line means a message is sent via an intermediary helper party. The single-headed arrows indicate the direction of message movement.

3.3 Agreement of Helpers for n-Helper Protocol

The protocol π requires the two key exchange devices to have secure channels with the same set of helper parties. However, this requirement can be a challenge in the real world since every device can choose helpers based on its preferences. It is possible that when two devices start key exchange, they do not have the same n helpers in common. For example, in Fig. 3, although P_A and P_B wish to use three helpers, P_A only has secure channels with H_1 and H_2, and P_B only has secure channels with H_2 and H_3. We therefore design a helper discovery process to enable two key exchange IoT devices P_A and P_B to agree on the same set of helpers before they invoke the n-helper protocol.

First of all, P_A and P_B need to determine which n helpers they need to agree on to use for their key exchange. Denote $\mathcal{C}$ this set of n helpers. Also denote $\mathcal{A}$ and $\mathcal{B}$ the initial sets of helpers of P_A and P_B, respectively. First, P_A sends an initialization message to P_B. Compared to the message in Fig 2, the initialization message here contains extra information which includes A and the number of helpers (i.e., n) needed for the key exchange. P_B then identifies the common helpers it has with P_A, i.e., $\mathcal{A} \cap \mathcal{B}$. If $|\mathcal{A} \cap \mathcal{B}| \geq n$, P_B randomly picks n helpers from $\mathcal{A} \cap \mathcal{B}$ and assigns them to $\mathcal{C}$. Otherwise, besides the common helpers, P_B randomly selects n-$|\mathcal{A} \cap \mathcal{B}|$ helpers from $\mathcal{A} \cup \mathcal{B} \setminus \mathcal{A} \cap \mathcal{B}$ and places all these helpers into $\mathcal{C}$. Clearly, now $|\mathcal{C}|$=n. P_B also notifies P_A of $\mathcal{C}$.

Both P_A and P_B then try to add new helpers that are in $\mathcal{C}$ but not in $\mathcal{A}$ and $\mathcal{B}$, respectively. To do so, they each use their current helpers to establish a secure channel with every new helper. Assume P_A needs to add a new helper H_{new}. P_A then treats H_{new} as a key exchange responder in a completely new key exchange session and runs an independent instance of an $|\mathcal{A}|$-helper key exchange protocol with helpers from $\mathcal{A}$. Here, H_{new} needs to have a secure channel with each helper in $\mathcal{A}$. If H_{new} is traditional device with enough computational resources, this is trivial since H_{new} can simply apply conventional PKC techniques to build secure channels between each other. As a result, P_A and H_{new} can agree on a common secret key and P_A can use the key to establish a secure channel with H_{new}, thus also establishing H_{new} as a new helper. The procedure for P_B to add a new helper is exactly the same.

However, if H_{new} is an IoT device with constrained resources, then it builds secure channels with other helpers as follows.

(1) First, H_{new} builds communication channels with other helpers through the assistance of the key exchange parties. Since we assume that key exchange parties are honest, H_{new} can transfer secret keys to other helpers via the key exchange party P_B.
(2) For each remained helper H_i that H_{new} does not have secure channel with, it checks if has enough helpers to conduct key exchange with H_i. If so, it invokes a key exchange protocol to build a secure channel with H_i. Otherwise, H_{new} skips this step.
(3) H_{new} checks if it has enough helpers to conduct key exchange with P_A. If so, it invokes a key exchange protocol to build a secure channel with P_A and P_A adds H_{new} as a new helper. Otherwise, H_{new} skips this step.

Back to the example in Fig. 3, we can see here $n = 3$, $\mathcal{A} = \{H_1, H_2\}$, $\mathcal{B} = \{H_2, H_3\}$. Upon the initialization message from P_A, P_B determines $C = \{H_1, H_2, H_3\}$ and also notifies P_A about C. If H_3 is a rich-resource device, P_A then adds H_3 as a new helper. To do so, first H_3 builds secure channels with H_1 and H_2 with PKC. Then P_A uses its current helpers H_1 and H_2 to conduct a key exchange with H_3 and uses the secret key to establish a secure channel with H_3 and thus have H_3 as a new helper. P_B also uses the same procedure and adds H_1 as a new helper. As a result, P_A and P_B both use helpers specified by C.

If H_3 is a resource-constrained IoT device, H_3 first shares a secret key with H_2 via P_B and thus establishes a secure channel with H_2. Then H_3 checks if it has enough helpers to continue establishing a secure channel with H_1. If so, H_3 invokes our protocol to exchange a secret key with H_1. Otherwise, H_3 stops the process of building secure channels with other helpers and checks if it has enough helpers to continue establishing a secure channel with P_A. If so, P_A conducts a key exchange with H_3 and add H_3 as a new helper.

Finally, P_A and P_B complete the helper discovery process and continue the key exchange protocol. If P_A and P_B are not able to find enough helpers to assist the key exchange, they could choose either reduce the number of helpers to continue the key exchange protocol, or they both output fail and exit the protocol.

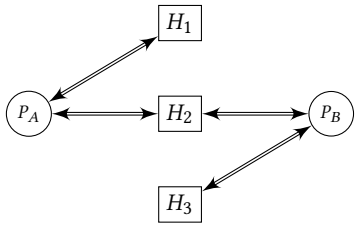


Fig. 3. P_A and P_B do not share the same set of helper parties. The double-headed arrows indicate a secure channel between an IoT device and a helper, and they can send messages to each other.

3.4 Optimal Network Configuration

As shown in Fig. 1, protocol π relies on the existence of n helpers and pre-established secure channels between communication devices and helpers. One concern here is that what are the minimum numbers of helpers and secure channels for protocol π to successfully exchange a key between two devices. In this section, we show that without PKC, π with two helpers and four secure channels is the optimal intermediary-based key exchange protocol that uses the fewest number of intermediary helpers and secure channels.

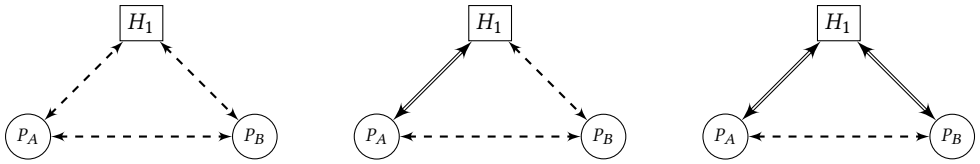
To prove π's optimality, we explore the possibility of other cases that use one helper (Fig. 4), two helpers (Fig. 5), and three or more helpers (Fig. 6). (We omit settings that are isomorphic to each other.) Compared to protocol π with two

helper parties and four secure channels, these cases either utilize fewer helper parties or fewer secure channels, and we show below that if only using SKC, these cases are not sufficient to implement a key exchange protocol.

Theorem 1. *The key exchange protocol π with two helpers and four secure channels is the optimal intermediary-based key exchange protocol for two parties to establish a session key in that π uses the fewest number of intermediary helpers and secure channels.*

We analyze cases with one helper, two helpers, and three or more helpers separately below.

3.4.1 One-Helper Cases. Cases with one helper include cases 4a, 4b, and 4c in Fig. 4. We focus on showing 4c is impossible to have a secure key exchange protocol without using PKC. The impossibility of 4c implies the impossibility of 4a and 4b because 4c has a stronger setting with more secure channels. The proof follows the fact that whatever messages that are transferred over the network, these messages are also obtained by the helper H_1. In Fig. 4c, since the communication channel between P_A and P_B is public, H_1 can eavesdrop on all messages on this channel. In addition, H_1 has as much (or more) computational power as P_A and P_B, since our protocol does not rely on PKC, whatever can be learned or computed by P_A or P_B can also be learned by H_1. Therefore, it is impossible for P_A and P_B to share a common secret session key without leaking it to H_1.

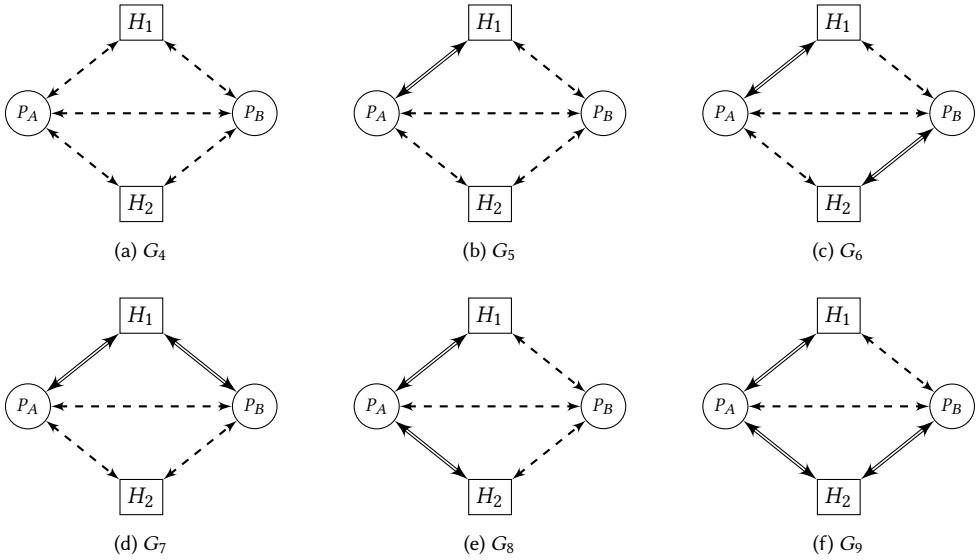


(a) G_1 (b) G_2 (c) G_3

Fig. 4. Different network settings for one helper. A solid (*resp. dashed*) double-headed arrow indicates that an IoT device and a helper can communicate with each other through a secure (*resp. public*) channel.

3.4.2 Two-Helper Cases. For two-helper cases, we first look at cases 5a, 5b, 5c. Here we only show that 5c is impossible to achieve secure key exchange since the impossibility of case 5c also implies the impossibility of cases 5a and 5b because case 5c has a stronger setting with more secure channels. We show that case 5c can be reduced to the case of no helper. Assume that we have a secure key exchange protocol π for case 5c, now we construct a secure key exchange protocol π' for two communication parties with no helper as follows. Consider the components $C_A = (P_A, H_1)$ and $C_B = (P_B, H_2)$, we create new parties P'_A and P'_B to simulate the behavior of C_A and C_B respectively. Namely, for all operations that P_A and H_1 perform in π, P'_A behaves the same. P'_B also behaves the same as P_B and H_2 in π. Since π is a secure key exchange protocol against malicious adversaries, π' is also a secure key exchange protocol for parties P'_A and P'_B. However, it contradicts the result of Impagliazzo-Rudich [20] that without PKC, no secure key exchange protocol exists while only the two communication parties are involved. Therefore, there is no such protocol π for case 5c.

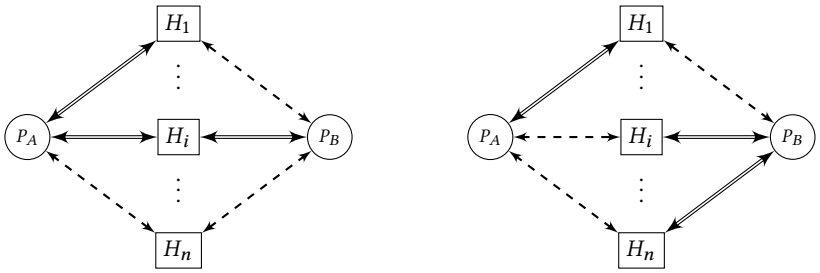
We now look at cases 5d, 5e, 5f. Case 5f follows a similar argument as in case 4c. In case 5f, the communication channel between P_B and H_1 is a public channel. H_2 can eavesdrop all messages that are transferred between H_1 and P_B. Thus, H_2 obtains all the information in this case. Since H_2 has more computational power than P_B, whatever P_B computes or receives can also be computed or obtained by H_2. Therefore, it is impossible for P_A and P_B to share a common secret session key without leaking it to H_2.



(a) G_4 (b) G_5 (c) G_6

(d) G_7 (e) G_8 (f) G_9

Fig. 5. Different network settings for two helpers. A solid (*resp. dashed*) double-headed arrow indicates that an IoT device and a helper can communicate with each other through a secure (*resp. public*) channel.



(a) G_{10}: there is a secure path between P_A and P_B. (b) G_{11}: there is no secure path between P_A and P_B

Fig. 6. Different network settings for more than two helpers. 6b has no secure path between P_A and P_B. A solid (*resp. dashed*) double-headed arrow indicates that an IoT device and a helper can communicate with each other through a secure (*resp. public*) channel.

3.4.3 Cases with Three or More Helpers. To show the impossibilities, we divide all cases into two categories which depend on whether there is a *secure path* from P_A to P_B. Namely, a secure path from P_A to P_B indicates that there is a secure channel from P_A to a helper H_i and also a secure channel from the same helper H_i to P_B (e.g., Fig. 6a). Notice that we only consider the cases with three secure channels since there are more than two helpers. Also, the the impossibility of cases with three secure channels implies the impossibility of cases that has two or fewer secure channels.

For all cases without a secure path from P_A to P_B as in Fig. 6b, they follow a similar argument to case 5c. We can reduce these cases to the no helper case as follows. For all helpers that P_A has secure channels with, we group them into a component C_A with P_A and let a new party P'_A to simulate the behavior of C_A. For all other helpers, including helpers that P_B has no secure channels with, we also group them into a component C_B with P_B and let a new party P'_B to simulate the behavior of C_B. Thus, if there is a secure key exchange protocol for these cases, we can also construct a secure key exchange protocol for P'_A and P'_B which contradicts to the Impagliazzo-Rudich result.

For all cases that have a secure path from P_A to P_B, the argument is similar to case 5f. Assume the secure path passes through the helper H_i. Since the number of secure channels is less than or equal to three, there is no other secure path from P_A to P_B. Without loss of generality, if the third secure channel connects to P_A, then H_i can eavesdrop on all messages P_B receives and obtains all information that P_B can compute. Therefore, it is impossible for P_A and P_B to share a common secret session key without leaking it to H_i.

4 RESILIENCY DESIGN

4.1 Overview

Protocol π is not resilient against malicious helpers. If a helper tampers or forges a share before sending it to P_B and P_B uses it with other shares to reconstruct the secret (S), P_B will not derive the same secret that P_A has, resulting in the failure of the key exchange. Moreover, P_A and P_B cannot detect or identify malicious helpers. A typical approach to this problem is to sign every share, but signing with PKC is too expensive for IoT devices, and signing with SKC requires P_A and P_B to have a session key between them already, which they have yet to agree on.

We design a new protocol π^A that advances π with resiliency. Without using any PKC operation, π^A enables key exchange devices to try to detect and identify malicious helpers. The main design idea of π^A is derived from the cut-and-choose technique widely used in secure multi-party computation. The cut-and-choose technique lets one party construct different versions of a message and have the other party randomly checks some of them and use the rest of them. In π^A, P_A generates a number of random keys which we call **test keys**, P_B use some of them called **opening keys** to identify malicious helpers via an efficient and effective design, and P_A and P_B use the rest of them called **evaluation keys** to derive the session key.

4.2 Key Exchange Protocol π^A: General Design

π^A is composed of three phases. We overview them here and elaborate them in Section 4.3.

Initialization phase. As opposed to choosing one secret S as in π, P_A now generates a number of test keys. For every test key, π^A invokes a standard t-out-of-n secret sharing scheme to split it into n shares, sends each share to a different helper, which then forwards the share to P_B. Note that with the assumption that there are less than t helpers in total which are malicious (Section 3.1), the security property of the t-out-of-n secret sharing scheme guarantees that the malicious helpers, even if they collude, will not be able to have t or more shares to learn any useful information of any test key.

Cut-and-choose phase. This phase is focused on identifying malicious helpers and dropping shares from them. P_B first randomly chooses half of the test keys as opening keys and the other half test keys as evaluation keys and also notifies P_A its choice. P_A then retransmits a copy of every share of every opening key to P_B via a helper rather than the original helper that forwarded the share, where the helper is randomly chosen each time. P_B then inspects every helper and compares every share of an opening key forwarded by the helper against the share's copy retransmitted via another helper. If there are t or more helpers that disagree with the helper, P_B then regards the helper as malicious. Otherwise, i.e., if this helper was *not* malicious, every helper who disagreed with the helper is then malicious; with t or more disagreements, there would be then t or more malicious helpers, which contradicts the assumption that at most $t-1$ helpers are malicious (Section 3.1).

If more than n-t helpers are malicious, P_B aborts the protocol. Otherwise, P_B drops all the shares forwarded by every helper identified as malicious, some of which could be shares of an evaluation key. P_B finally reconstructs every

evaluation key with its remaining shares. Although it is still likely that some remaining shares are compromised and as a result evaluation keys reconstructed with them are also compromised, the likelihood is low given that most remaining shares are authentic.

Session key derivation phase. P_A randomly chooses a secret, uses each evaluation key to encrypt the secret separately, and sends each encrypted secret to P_B. P_B then uses the corresponding evaluation key to decrypt every encrypted secret. Although P_B may not reconstruct some evaluation keys correctly due to compromised shares, it can treat the decryption output with the majority agreement as the secret. P_A and P_B can therefore use the secret to derive their session key.

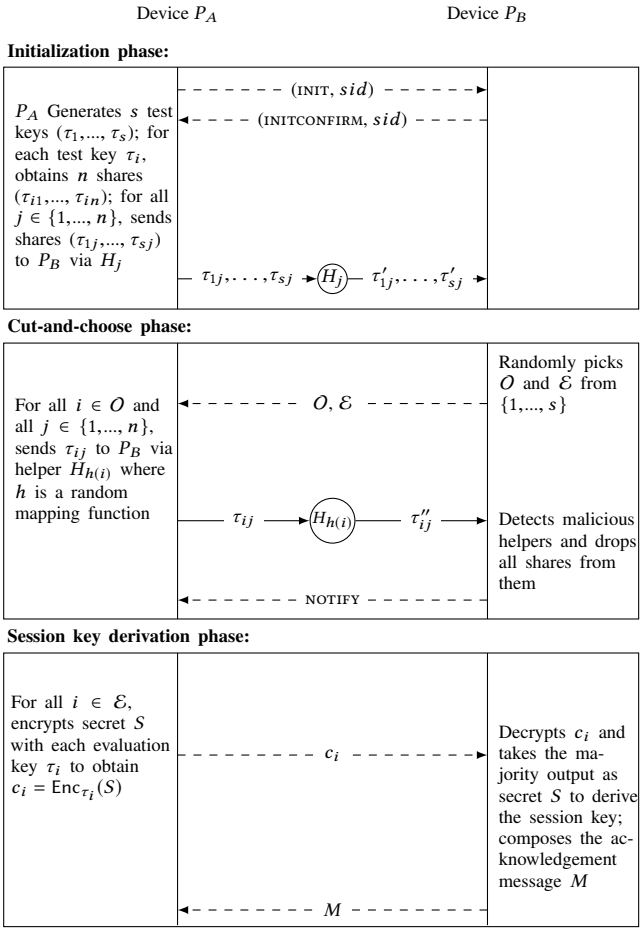


Fig. 7. Key exchange protocol π^A. Each dashed line means a message is sent via a public channel. Each solid line means a message is sent via an intermediary helper party.

4.3 Key Exchange Protocol π^A: Protocol

The protocol π^A is as follows.

[Initialization phase.] This phase is the same as π's Initialization (see Section 3.2), except that the INIT also contains the number of test keys from P_A. Plus, P_A sends test keys to P_B as follows:

- P_A randomly generates s test keys $\mathcal{T} = (\tau_1, \tau_2, \cdots, \tau_s)$, where every test key is of an equal length.
- For every $\tau_i \in \mathcal{T}$, P_A invokes the t-out-of-n secret sharing scheme to obtain its n shares $(\tau_{i1}, \tau_{i2}, \cdots, \tau_{in})$.
- For every test key τ_i and its every share τ_{ij}, P_A sends τ_{ij} to helper H_j, which then forwards the share to P_B. Helper H_j will thus receive and forward a set of shares $(\tau_{1j}, \tau_{2j}, \cdots, \tau_{sj})$.
- For each τ_i, P_B receives shares $(\tau'_{i1}, \tau'_{i2}, \cdots, \tau'_{in})$. (We use notation τ'_{ij} instead of τ_{ij} since a share may be tampered by a corrupted helper.)

[Cut-and-choose phase.] P_B now processes all the test key shares it has received:

- Based on the total number of test keys, P_B randomly chooses half of test key indexes, denoted as $\mathcal{O}$, to be the indexes of opening keys and the other half, denoted as $\mathcal{E}$, to be the indexes of evaluation keys. P_B sends $(\mathcal{O}, \mathcal{E})$ to P_A (via a public channel).
- On P_A, upon the receipt of $\mathcal{O}$ and $\mathcal{E}$, for every τ_{ij} $(i \in \mathcal{O})$ it forwarded, retransmit a copy of τ_{ij} to P_B via helper $H_{h(i)}$, where h is a random mapping function and $\forall i \in \mathcal{O}, h(i) \neq j$.
- On P_B, for every helper H_j $(j = 1, \ldots, n)$, compare every τ'_{ij} $(i \in \mathcal{O})$ it received from H_j with its retransmitted copy from helper $H_{h(i)}$ to see if they match. If for helper H_j there are t or more helpers that disagree with H_j, H_j is then a malicious helper and P_B drops all the test key shares from H_j.
- If more than n-t helpers cheated, P_B aborts the protocol. Otherwise, for every $i \in \mathcal{E}$, P_B knows at least t shares from $(\tau'_{i1}, \tau'_{i2}, \cdots, \tau'_{in})$ still remain. With these remaining shares, P_B thus uses the t-out-of-n secret sharing scheme to reconstruct τ'_i. Here, P_B regards τ'_i as τ_i (which may not be the same if at least one share used is tampered but not found in the previous step).
- P_B sends (NOTIFY) to P_A to let P_A enter the next phase (via a public channel).

[Session key derivation phase.] P_A and P_B now generate their session key as follows:

- P_A randomly chooses a secret S, encrypts S with each evaluation key τ_i separately, $i \in \mathcal{E}$, to obtain ciphertext c_i=$\mathsf{Enc}_{\tau_i}(S)$, and sends each c_i to P_B (via a public channel).
- For each ciphertext c_i $(i \in \mathcal{E})$ received, P_B decrypts it using the evaluation key τ'_i.
- P_B takes the majority output from the previous step as the secret S.
- P_A and P_B truncate the secret into two halves, and let pwd be the first half and $salt$ be the second half. P_A and P_B invoke PBKDF2 (Password-Based Key Derivation Function 2) to compute

$$K_{sid} = PBKDF2(f, pwd, salt, 256, 2 * l)$$

  and set K^0_{sid} be the first l bits of K_{sid} and K^1_{sid} be the last l bits.
- P_B sends an acknowledgement message $M = g(\text{“CONFIRM”}, sid, P_A, P_B, K^1_{sid})$ to P_A where g is a message authentication function that is agreed by P_A and P_B during initialization. Upon the receipt of M, P_A checks if M is also $g(\text{“CONFIRM”}, sid, P_A, P_B, K^1_{sid})$. If so, P_A confirms that both parties agree on K^0_{sid} as their session key, and P_A can start its communication with P_B; otherwise, P_A either aborts the protocol or initiates another instance of π^A.

To improve the security, when P_A and P_B invoke the protocol for the first time and agree on K^0_{sid} where $sid = 0$, they store it internally in their memory as the master key. To derive a session key from the master key, P_A and P_B follow a similar idea that they truncate K^0_0 into two halves and apply PBKDF2 to derive K^0_1 as the session key. For a subsequent communication session i with $i > 1$, P_A and P_B will derive the session key K^0_i from K^0_{i-1} with the same mechanism.

5 SECURITY PROOF OF π^A

We now formally prove the security of protocol π^A. We first introduce the formal definitions of session key security (SK-security) and t-out-of-n secret sharing scheme, and then prove π^A's security.

5.1 Definitions

5.1.1 Session Key Security. We adopt the **session key security (SK-security)** [7], which formally defines the security of a key exchange protocol. We choose this definition because it is conceptually simple and easy to use when analyzing and proving the security of a key exchange protocol. In addition, adopting SK-security also helps define the key exchange protocol security in the universally composable (UC) model, which we will describe in Section 5.1.2. The intuition behind the SK-security is that it means an adversary cannot distinguish a session key from a randomly chosen value.

To define SK-security, we first define a game $\textsc{Game}^{\mathcal{I}}_{\mathcal{A}}$ between a *simulator* $\mathcal{I}$ and an adversary $\mathcal{A}$. Let k be a session key and $c \in \{0, 1\}$ be a coin, $\textsc{Game}^{\mathcal{I}}_{\mathcal{A}}$ is defined in two steps:

- $\mathcal{I}$ first generates the session key k and then tosses the random coin c. $\mathcal{I}$ receives $c \xleftarrow{R} \{0, 1\}$ where $\xleftarrow{R}$ means randomly choosing a value from a set. If c is 0, $\mathcal{I}$ provides the real session key k to $\mathcal{A}$; otherwise $\mathcal{I}$ randomly chooses a value $k' \xleftarrow{R} \{0, 1\}^{|k|}$ from the session key space and returns k' to $\mathcal{A}$.
- With the received value k or k', $\mathcal{A}$ outputs a result c' as its guess for the value c. If $c' = c$ then $\mathcal{I}$ outputs 1 ($\mathcal{I} \rightarrow 1$); otherwise, $\mathcal{I}$ outputs 0 ($\mathcal{I} \rightarrow 0$).

Definition 1. *A key exchange protocol* Π *is SK-secure against adversary* $\mathcal{A}$ *if it satisfies the following properties:*

- *Correctness.* After running Π, the two honest parties establish the same session key only with a negligible probability of failure.
- *Indistinguishability.* The probability that adversary $\mathcal{A}$ outputs a correct c' that equals to c is $\frac{1}{2} + \epsilon(\lambda)$ where $\epsilon(\lambda)$ is a negligible function in λ. Or, in an equivalent expression, assuming $\mathrm{ADV}^{\Pi}_{\mathcal{A}}(\lambda)$ be the advantage of adversary $\mathcal{A}$ to win the game $\textsc{Game}^{\mathcal{I}}_{\mathcal{A}}$, we then have $\mathrm{ADV}^{\Pi}_{\mathcal{A}}(\lambda) = |Pr[\mathcal{I} \rightarrow 1] - \frac{1}{2}| = \epsilon(\lambda)$.

5.1.2 Universally Composable Model. UC model provides a stronger security definition for a key exchange protocol than SK-security. The SK-security defines the key exchange security in the *standalone model* that a key exchange protocol is secure only when a single instance of the protocol runs in isolation. In contrast, UC model guarantees that a key exchange protocol remains secure even if it is used by multiple key exchange sessions simultaneously or when it is combined with other protocols (e.g., when it is embedded in another protocol). That is, no information can leak from one session to another session or leak from the key exchange protocol to another protocol. Clearly, a key exchange protocol that is UC-secure has a stronger guarantee and is thus more desired. We refer to the original paper of Canetti [9] for more details and formal definition of UC model.

5.1.3 Secret Sharing Scheme.

Definition 2. *A* t*-out-of-*n *secret sharing scheme* Σ *consists of the following two algorithms:*

- *Share distribution algorithm* Share. A randomized algorithm that takes a secret message m as input and outputs a sequence of n shares: $\mathbb{M} = (m_1, \cdots, m_n)$.
- *Secret reconstruction algorithm* Reconstruct. A deterministic algorithm that takes an input of a collection of t or more shares and outputs the secret message m.

A secure secret sharing scheme should satisfy the property of *correctness* such that for all $U \subseteq \{1, \cdots, n\}$ with $|U| \geq t$, it holds that $Pr[\textsc{Reconstruct}(m_i|i \in U) = m] = 1$. For any $U \subseteq \{1, \cdots, n\}$ with $|U| < t$, no information will be learned from those shares.

To formalize the security of Σ, let $m, m' \in \mathcal{M}$ be two different messages from the message space $\mathcal{M}$. The challenger (i.e., the simulator) $\mathcal{I}$ invokes the $\textsc{Share}$ algorithm on m, m' and obtains $\mathbb{M} \leftarrow \textsc{Share}(m)$, $\mathbb{M}' \leftarrow \textsc{Share}(m')$.

$\mathcal{I}$ also tosses a random coin $b \in \{0, 1\}$. If $b = 0$, $\mathcal{I}$ returns $(m_i|i \in U)$ to the adversary $\mathcal{A}$. Otherwise $\mathcal{I}$ returns $(m'_i|i \in U)$. With the received set of shares, $\mathcal{A}$ outputs a result b' as its guess for the value b. If $b' = b$ then $\mathcal{I}$ outputs 1; otherwise, $\mathcal{I}$ outputs 0.

We define the advantage of the adversary $\mathcal{A}$ in this game as:

$$\text{ADV}^{\Sigma}_{\mathcal{A}} = |Pr[\mathcal{I} \rightarrow 1] - \frac{1}{2}|$$

Definition 3. *A t-out-of-n secret sharing scheme Σ is secure over message space $\mathcal{M}$ if $\text{ADV}^{\Sigma}_{\mathcal{A}}$ is a negligible function.*

An instance of implementation of a t-out-of-n secret sharing scheme is Shamir's secret sharing scheme [37]. The idea behind this scheme is that $d + 1$ points can determine a unique degree-d polynomial. We refer to [37] for more details.

5.2 Security Proof

With SK-security, we first prove that π (specified in Section 3.2) is secure against malicious helpers, and then prove π^A (specified in Section 4.3) is also secure according to an advanced theorem in SK-security.

Proof. We first prove π is secure. We assume in π all helper parties are semi-honest and they follow the protocol and forward messages correctly (i.e., thus messages are authentic). According to Definition 1, to prove this theorem we need to prove both the correctness and the indistinguishability of π.

The correctness of π follows the correctness of the t-out-of-n secret sharing scheme. Since for every $i \in \{1, \ldots, n\}$, helper H_i follows the protocol and forwards s_i correctly, both P_A and P_B will agree on the same secret S. This is guaranteed by the correctness property of a secret sharing scheme defined in Section 5.1.3. It is clear that as P_A and P_B are honest (Section 3.1), they can derive the session key $k_{sid} = f(S, 0)$ with probability one.

To show the indistinguishability property of π, we need to prove *no* adversary has a non-negligible advantage to distinguish a real session key k (i.e., k_{sid} in π) from a random value k'. To do so, we now prove the opposite is not possible. Specifically, we assume that there *was* such an adversary $\mathcal{A}$ against π and show with this assumption, we can construct a distinguisher $\mathcal{D}$ as follows that would violate Definition 3 about the security of the t-out-of-n secret sharing scheme. In another words, $\mathcal{D}$ can distinguish $(s_i|i \in U)$ from $(s'_i|i \in U)$ and output the correct b' with non-negligible probability.

The distinguisher $\mathcal{D}$ works as follows. Upon the input $[k^*, (s_i|i \in U)]$, where k^* is randomly chosen with probability $\frac{1}{2}$ between the real session key k (i.e., k_{sid} in π) and k' (a random string of length k), $\mathcal{D}$ invokes $\mathcal{A}$ which plays the same role as a helper in protocol π. After receiving the share s_i from P_A, $\mathcal{A}$ forwards it to P_B. Based on the input k^*, $\mathcal{A}$ determines whether k^*==k or $k^* \neq k$ and output $c' = 0$ or $c' = 1$, respectively. $\mathcal{D}$ then uses the output of c' from $\mathcal{A}$ as its guess for coin toss b, outputs b, and terminates.

Now we show the contradiction caused by the assumption above. Assume the adversary compromises a helper party and obtains one share from the helper, i.e., $(s_i|i \in U)$. Note that since we assume P_A an P_B are always honest *and* an adversary can only compromise up to $t - 1$ helpers, the adversary cannot obtain t shares of the secret. If the real session key k is chosen as the input k^* (i.e., $k^* == k$), s_i is a share of k^*. Otherwise, a random k' is chosen to be k^* and s_i is not

a share of k^*. Now, even though k^* is randomly chosen between k and k' with the same probability, $\mathcal{A}$ can guess if the input k^* is the real session key and output the correct c' with non-negligible advantage $\text{ADV}^{\Pi}_{\mathcal{A}}$, therefore $\mathcal{D}$ can base on c' from $\mathcal{A}$ to guess if m_i is a share of k^*, with non-negligible advantage $\text{ADV}^{\Pi}_{\mathcal{A}}$. Clearly, $\mathcal{D}$'s non-negligible advantage contradicts Definition 3. We thus prove the indistinguishability property of π.

Now that we proved both the correctness and the indistinguishability of π, according to Definition 1, π is secure.

Next we prove the security of π^A. We use the theorem that if a key exchange protocol (say Π) in which all key exchange messages are authentic satisfies SK-security, when the protocol is extended to become a new protocol (say Π') in which key exchange messages can be corrupted, the new protocol also satisfies SK-security if it can authenticate messages and discard corrupted ones [7, 11]. Here, when we extend π to π^A, we see in π every message is assumed authentic, while in π^A messages can be tampered by malicious helpers but P_B can identify and drop tampered messages (Section 4.2). Therefore, π^A also satisfies SK-security.

Finally, we prove π^A is secure under UC model. The proof follows the fact in [11] that a key exchange protocol is secure under the UC model if (1) the protocol is SK-secure in the stand-alone model *and* (2) if the protocol verifies at the end that the two parties agree on the same session key. From the proof above, we know (1) is true that π^A satisfies SK-security. For (2), as shown in the "Verify session key" step (see Section 3.2), P_B sends an acknowledgement message M to P_A, and then P_A checks the correctness of M to verify that P_A and P_B share the same value of S', thereby confirm that both parties agree on the same session key k_{sid}. Therefore, (2) is also true. We conclude that protocol π^A is secure under UC model. □

6 THEORETICAL PERFORMANCE ANALYSIS OF π^A

In this section we conduct a theoretical performance analysis of π^A. We analyze its failure probability, p_f, the lower bound of test keys s, the probability that a malicious helper can be detected, p_d, and the number of messages to send during a key exchange session, N.

6.1 Failure Probability (p_f)

π^A fails if P_A and P_B do not reach an agreement on their session key. Note that the failure is only a denial-of-service, while no secret or any useful information is leaked. π^A fails in two cases:

- Case 1: π^A fails if more than *n-t* helpers are malicious. As described in Sections 4.2 and 4.3, in this case P_B will *not* have enough shares to reconstruct evaluation keys, so it will abort the protocol with $p_f = 1$.
- Case 2: π^A fails if the majority of evaluation keys at P_B are corrupted (i.e., each of them is reconstructed using at least one corrupted share). Denote C the set of corrupted evaluation keys; given there are s test keys and half of them are evaluation keys, we can see in this case $|C| \geq \lceil s/4 \rceil$. As a result, in the session key derivation phase P_B will not be able to correctly decrypt the encrypted secret from P_A and derive the session key.

More specifically, Case 2 happens if $\forall \tau_i \in C$, τ_i would not be selected as an opening key during the cut-and-choose phase, which has a probability of 0.5, and τ_i is not correctly reconstructed. Denote p_r the probability that P_B correctly reconstructs an evaluation key. Now we have:

$$p_f = (0.5 \cdot (1 - p_r))^{|C|} \tag{1}$$

Since $|C| \geq \lceil s/4 \rceil$, we have

$$p_f \leq (0.5 \cdot (1 - p_r))^{\lceil s/4 \rceil} \tag{2}$$

From Equation (2), a higher p_r will result in a lower p_f. Moreover, $0.5 \cdot (1 - p_r)$ is less than 0.5 since p_r is no more than 1. Thus, the failure probability p_f declines exponentially as the number of test keys s increases, which we say p_f is negligible in s.

We now analyze p_r. Let p_c be the cheating probability of each one of the n helpers. The expected number of cheating parties is then $n \cdot p_c$. For each test key, P_B receives $n - (n \cdot p_c)$ correct shares. To reconstruct a test key, P_B needs to choose t correct shares. We thus have:

$$p_r = \prod_{i=0}^{t-1} \frac{n - i - n \cdot p_c}{n - i} \tag{3}$$

Note that for simplicity, here we assume all helpers have the same cheating probability p_c. If each helper H_i has a different cheating probability p_c^i, the expected number of cheating helpers is $\sum_{i=1}^{n} p_c^i$ rather than $n \cdot p_c$.

From Equation (3), p_r is affected by n, t, and p_c. If t and p_c are fixed, when n increases, p_r also increases. This is consistent with the intuition that if there are fixed number of malicious shares, increasing n means more helpers and thus more shares per evaluation key, which provides P_B a better chance to pick correct shares to reconstruct evaluation keys. On the other hand, if n and p_c are fixed, when t increases, p_r would decrease. This is because increasing t requires P_B to select extra shares to reconstruct every evaluation key, which means P_B would have a higher likelihood to pick malicious shares. Finally, if fixing n and t, a higher p_c would cause P_B to have a higher probability to pick malicious shares, thus decreasing p_r.

Finally, combines Equations (2) and (3), if p_f must be lower than an upper bound, while key exchange parties probably cannot control the value of p_c, they can adjust the values of parameters s, t, and n to meet the requirement.

6.2 Number of test keys (s)

In order to derive the session key with probability at least $1 - p_f$, P_B must correctly reconstruct enough number of evaluation keys. Recall that for a total number of s test keys, in the cut-and-choose phase, P_B chooses half of them as opening keys and the other half as evaluation keys. Then in the session key derivation phase, P_B needs to correctly reconstruct at least $s/4$ evaluation keys to obtain majority outputs.

For the $s/2$ evaluation keys, we consider the critical point case when half of evaluation keys (i.e., $s/4$) are not reconstructed correctly. In this case, P_B would not be able to obtain the secret in the session key derivation phase. From Equation (3), for each evaluation key, P_B can correctly reconstruct it with probability p_r. Thus, for $s/4$ evaluation keys, the probability that the critical point case happens is $(1 - p_r)^{s/4}$. Since p_f is the maximum acceptable probability that the critical point case happens, we must have $(1 - p_r)^{s/4} \leq p_f$. From this inequality, we can see the lower bound of test keys is:

$$s \geq 4 \cdot \log_{1-p_r} p_f. \tag{4}$$

6.3 Malicious Helper Detection Probability (p_d)

Now we discuss the probability that P_B can identify a malicious helper. We point out that if the number of test keys s and the t parameter in π^A's t-out-of-n secret sharing scheme satisfy that $s \geq 4t - 4$, P_B can always identify a malicious helper if it tampered at least $2t - 2$ shares in total of all opening keys We detail the analysis below.

In the cut-and-choose phase, for every helper H_j ($j = 1, \ldots, n$) P_B counts the number of other helpers that disagree with the helper in forwarding an opening key's share and identifies the helper as malicious if there are at least t helpers that disagree with H_j. Below we analyze the probability p_d that P_B can successfully identify a malicious helper H_j based on the number of shares that H_j tampered, Z. Recall every helper forwards one share per opening key, thus forwarding totally $s/2$ shares; clearly, $Z \leq s/2$.

(1) H_j *tampered at least* $2t-2$ *shares of opening keys* (i.e., $Z \geq 2t-2$). Here, because for each share tampered by H_j, P_A retransmitted a copy of its original value along a different helper, i.e., totally at least $2t-2$ helpers, even if all malicious helpers collude with H_j to not show disagreements (i.e., retransmitting a copy of a share's tampered value rather than its original value), given there are at most $t-1$ malicious helpers (including H_j), there are at least t benign helpers each of which will disagree with H_j, thus identifying H_j as malicious. i.e., $p_d = 1$.
Notice this case assumes $Z \geq 2t-2$. Given $Z \leq s/2$, we can obtain that s and t must satisfy $s \geq 4t-4$.

(2) H_j *tampered less than* t *shares of opening keys* (i.e., $Z < t$). In this case, P_B cannot identify H_j as malicious. I.e., $p_d = 0$. This is because H_j could be either benign or malicious. Specifically, while it is possible that H_j is malicious and all helpers that disagree with H_j are either benign or malicious, it is also possible that H_j is benign and all helpers that disagree with H_j, whose total number is less than t, are malicious. On the other hand, even though P_B cannot identify H_j as malicious in this case, the number of opening key shares that H_j can tamper must be less than t. Given P_B's random choice of opening keys and evaluation keys from the test keys, the number of evaluation key shares that H_j can tamper must also be less than t on average. Compared to total $s/2$ shares of all $s/2$ evaluation keys (one share per key) that H_j could have tampered, t is much less than $s/2$ as we set $s \geq 4t-4$ from (1) above. P_B would thus have a much higher probability to reconstruct evaluation keys correctly, thereby reducing the failure probability p_f.

(3) H_j *tampered* $t \leq Z \leq 2t-3$ *shares of opening keys.* In this case, P_B can identify a malicious helper with probability p_d and we show how to compute p_d as follows. Given that there are $s/2$ opening keys and H_j forwarded the j-th share of every opening key, H_j forwarded total $s/2$ shares. As P_A retransmitted each of these shares via a randomly chosen helper that is not H_j, we assume the total number of such helpers is Q. Clearly, $Q \leq s/2$. P_B will then check if each of these Q helpers disagrees with H_j, and determines H_j to be malicious if there are at least t disagreements. Denote x the number of disagreements. Assume the worst case where there are $t-1$ malicious helpers and they collude, while there are $n-t+1$ benign helpers (with totally n helpers) and $n-t+1 > t-1$ (or $n-t+1 \geq t$). To detect H_j is malicious, all x disagreements then must come from benign helpers, which has a probability

$$\frac{\binom{n-t+1}{x} \cdot \binom{t-2}{Q-x}}{\binom{n-1}{Q}}.$$

Here, while all Q helpers come from totally $n-1$ helpers (excluding H_j), x helpers are chosen from $n-t+1$ benign helpers and the rest $Q-x$ helpers are chosen from $t-2$ malicious helpers (excluding H_j with totally $t-1$ malicious helpers). Last, we know $x \geq t$ and x cannot be greater than Q, we then have in the worst case

$$p_d = \sum_{x=t}^{Q} \frac{\binom{n-t+1}{x} \cdot \binom{t-2}{Q-x}}{\binom{n-1}{Q}} \tag{5}$$

6.4 Message Overhead (N)

We now analyze how many messages P_A and P_B will need to send in one key exchange session with π^A. Indeed, the message overhead is one of the four metrics that is used in Section 7 to evaluate the efficiency of π^A. First, during the Initialization phase, there are two initialization messages (i.e., (INIT, *sid*) and (INITCONFIRM, *sid*)), plus n shares of s test keys where every share is a separate message, resulting in $n{\cdot}s{+}2$ messages. Then during the Cut-and-choose phase, P_B sends P_A two messages (i.e., $(\mathcal{O}, \mathcal{E})$ and (NOTIFY)), and P_A sends P_B a copy of every opening key's every share. With totally $s/2$ opening keys (we assume s is an even number for simplicity) and n shares for each opening key, this leads to

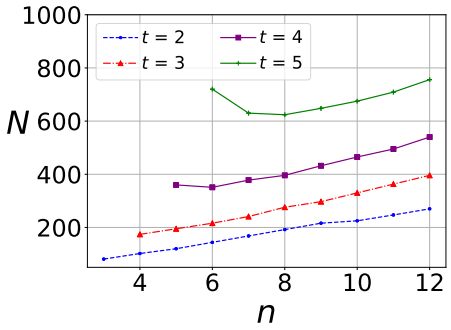


Fig. 8. Message overhead N over the number of required shares t and the number of intermediary helpers n.

$s/2 \cdot n + 2$ messages for this phase. Last, during the Session key derivation phase, P_A sends P_B $s/2$ ciphertexts, plus one final message from P_B for session key verification. Overall, there are $\frac{3n+1}{2}s + 5$ messages in total.

i.e.,

$$N = \frac{3n+1}{2}s + 5 \tag{6}$$

From Equation (6), N increases as n and s increase. If a lower message overhead is desired, one can lower the value of n and s (i.e., less helpers and test keys). On the other hand, from Section 6.1, lowering the values of n and s will increase p_f. Therefore, users need to adjust n and s to meet their specific requirements for p_f and N.

6.5 Graphical Analysis of π^A's Performance

Before conducting the experimental evaluation, we first perform a graphical analysis to show how the input parameters affect the performance of π^A. Based on the analysis of π^A in Section 6, here we use the message overhead N to theoretically evaluate the efficiency of π^A for efficiency in this section and also use N one of the four metrics for experimental evaluation in Section 7. From Equation(6), it is easy to see that N depends on n (number of intermediary helpers) and s (number of test keys). From Equation(4) and (3), s relies on n, t (number of required shares), and p_f (target failure probability). Since p_f is pre-configured by communication devices, we fix p_f and analyze how t and n affect N.

First we let P_A and P_B fix the failure probability p_f to be 0.005. This is the same failure probability due to the packet loss when we let P_A send a key to P_B directly and P_B replies with a confirm message (assuming no attacker exists). In our experiment, we emulate a Wi-Fi environment with a 0.3% packet loss probability which is a typical value in a Wi-Fi environment.

One possible concern here is that if the packet loss rate would affect the message overhead of π^A. In fact, our evaluation results show that the packet loss rate has very little impact on N unless it reaches a very large, unrealistic value, such as 30%. This is because unless the packet loss rate is large, packet loss is easily compensated by the inherent message redundancy in π^A, since π^A uses many redundant shares for every test key to reconstruct the key.

Fig. 8 shows how N is affected by t and n with p_f fixed at 0.005. In the evaluation, we set t ranging from 2 to 5 and n ranging from 3 to 12 which is enough to show the trend. In general, we can see that when t (i.e., more required shares) or n (i.e., more helpers) increases, N also increases (i.e., more messages). Intuitively, a larger n means P_A needs to generate more shares, thus increasing the number of messages to send. To see why N increases as t increases, recall that P_B needs all the t shares for the evaluation key reconstruction to be correct, a larger t means a higher possibility that at least one of the shares is tampered. To counter this risk, more test keys, and thus more messages, will be needed

to filter more tampered shares and increase the difficulty for malicious helpers to corrupt the majority evaluation keys. Notably, N increases dramatically when t becomes close to n. For example, when $n = 6$ and t changes from 4 to 5, N increases from 376 to 781. Here t plays a more important role than n in determining N, and it doubles the values of N.

To minimize the message overhead, a naive solution here is to choose t and n as small as possible. However, the values of t and n decide how "secure" the key exchange session should be. For example, if there are at most X malicious helpers that collude among themselves, t must be greater than X; otherwise, these X helpers could mislead P_B to reconstruct corrupted evaluation keys, where each of them is reconstructed using all the t shares that these helpers forged (note that every helper can and only can provide one share).

In addition, t and n also affect the malicious helper detection probability. From Equation 5, it shows that when t and n are small, it is almost impossible for communication devices to detect malicious helpers. This is because P_A and P_B must have enough benign helpers to retransmit shares and identify malicious helpers in the cut-and-choose phase. In addition, from Equation 4, the number of test keys s also depends on t and n, increasing the value of n may decrease the value of s, thereby decrease the total message overhead. For instance, when $t = 5$ and n changes from 6 to 7, N decrease from 781 to 623. This is because when increasing n with a fixed value of t, P_B would have a higher chance to choose the correct shares to reconstruct evaluation keys, thus reduce the number of required test keys to detect malicious helpers.

7 EXPERIMENTAL RESULTS

7.1 Experiment Design

We implemented π^A with python cryptography libraries and measured its performance, including its running time, CPU cycles, energy consumption, and bandwidth overhead, in experiments.

We set up our experiment devices and running environments as follows. For each key exchange session between a key exchange initiator P_A and a key exchange responder P_B, we selected three different types of resource-constrained devices: Raspberry Pi Zero W, Arduino Due, and SAM D21 Xplained. They are commonly used in the real word for IoT applications but have a different range of resource capacity. Table 1 describes their basic specifications. For the implementations of π^A and other three PKC-based key exchange protocols, we used Python 3.6.9 with cryptography library pycrypto 2.6.1. For the networking environment, we used the Mininet platform [16] on Ubuntu 18.04.4 to emulate a Wi-Fi environment, where every link is 10 Mbps with a 0.3% packet loss probability.

Table 1. Key exchange devices in experiments

	CPU	Memory	Voltage	Current draw
Raspberry Pi Zero W	1 GHZ	512 MB	5 V	500 mA
Arduino Due	84 MHZ	512 KB	1.8 V	77.5 mA
SAM D21 Xplained	48 MHZ	32 KB	1.62 V	7 mA

The main parameters to configure for our experiments are n, t, s, and the number of malicious helpers m. In our experiments, we first set the failure probability of π^A to be 0.005 which was pre-configured by P_A and P_B. With this setup, from Section 6.1 and Section 6.5, we can derive that π^A has the minimum message overhead when we set n to be 6, t to be 4, and s to be 28. In addition, P_A and P_B can always detect malicious helpers when m is no greater than 2.

We compare π^A_6 with traditional PKC-based key exchange protocols: RSA (Rivest–Shamir–Adleman), DH (Diffie-Hellman), and ECDH (Elliptic Curve Diffie-Hellman). We set the key length of π^A_6 to be 128, for which the equivalent

key lengths for RSA, Diffie-Hellman, and ECDH are 3072, 3072, and 256, respectively [6]. For ECDH, we use the curve SECP256R1 with ephemeral keys. For each PKC-based protocol, we do not include an authentication component; even so and even as π_6^A includes an authentication (Section 3.1), we show π_6^A outperforms them, many times tremendously.

We noticed that there are many state-of-the-art work [30, 41, 45] that improve the PKC-based key exchange solutions. It is imperative to also conduct a comprehensive comparison between our protocol and the state-of-the-art work. However, given the extensive landscape of existing PKC-based key exchange solutions, it is unfeasible to compare our protocol with all them. In addition, many of the work are hard to locate the original implementations or the implementations are not compatible with our running environment. Therefore, we leverage ECHD, DH, and RSA, which are the three most basic PKC-based solutions, as the benchmark for comparison. They can best help benchmark any proposed key exchange solution since any key exchange solution can also be simply compared against these three basic ones to not only know how much better it is against the three basic ones, but also how much better, or worse, than other key exchange solutions that also have been compared against these three.

7.2 Running Time

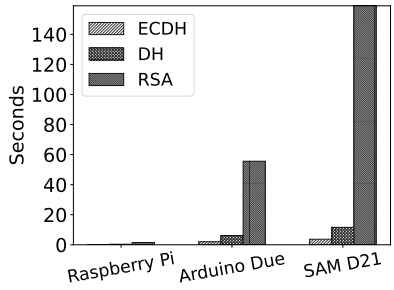
We measured the running time of π_6^A and the comparator key exchange protocols on both P_A and P_B. We recorded the time for running a complete session of each protocol on each device and took the average across 10 experiments. Fig. 9 shows the comparison results of π_6^A versus different comparator protocols. Specifically, Fig. 9a and Fig. 9c show the running time of PKC-based key exchange protocols, while Fig. 9b and Fig. 9d show the running time of $\pi_6^A(0)$, $\pi_6^A(1)$, and $\pi_6^A(2)$.

Fig. 9a and Fig. 9b illustrate that on P_A, π_6^A is much faster than its comparators, especially when P_A is an Arduino Due or SAM D21 whose resources are extremely limited. Using $\pi_6^A(2)$ as an example, which has the slowest running time among the three π_6^A configurations in our experiments, on Raspberry Pi Zero W, $\pi_6^A(2)$ in the worst case is 2.3 times faster than ECDH and 24.1 times faster than RSA; however, on SAM D21, $\pi_6^A(2)$ is 59.6 times faster than ECDH and 1591 times faster than RSA.

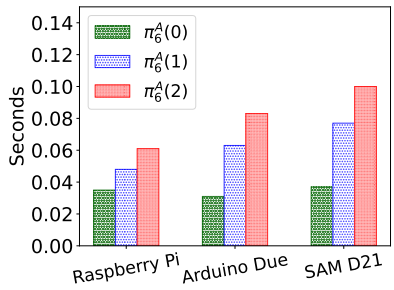
Fig. 9c and Fig. 9d show on P_B for all types of IoT devices, although its lead is less striking than that on P_A, π_6^A is still faster than other protocols. Again using $\pi_6^A(2)$ as an example, while on P_A $\pi_6^A(2)$ is 2.3 to 59.6 times faster than ECDH, on P_B it is still about 0.7 to 3.65 times faster than ECDH; with a Raspberry Pi Zero, the running time of $\pi_6^A(2)$ on P_B is 0.072 seconds while it takes ECDH 0.122 seconds. The lead reduction here is because P_B needs to perform more operations than P_A, including identifying malicious helpers, reconstructing evaluation keys, and decrypting multiple ciphertexts to obtain the secret. Nonetheless, π_6^A is faster than its comparator protocols on both devices in a key exchange.

7.3 CPU Cycles

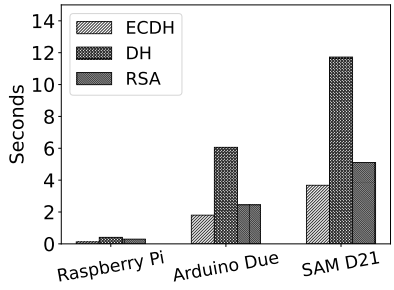
We also measured the CPU cycles of π_6^A and the comparator protocols on both P_A and P_B. As shown in Fig. 10, it takes the comparator protocols many times more CPU cycles than π_6^A to conduct a key exchange session. On P_A, for example, if it is a Raspberry Pi Zero W, it takes ECDH 4.87 times more CPU cycles than $\pi_6^A(2)$ in the worst case, where $\pi_6^A(2)$ is the most expensive among the three different configurations of π_6^A. Similarly, if it is a SAM D21, it takes 4.1 times more instead. On P_B, for example, if it is a Raspberry Pi Zero W, it takes ECDH 11.79 times more CPU cycles than $\pi_6^A(2)$, and if it is a SAM D21, it takes 104.7 times more instead. Again, even though π_6^A's operations on P_B are relatively heavier than P_A, similar to its running time performance on P_B, its CPU cycles on P_B still easily betters those of the comparator protocols.



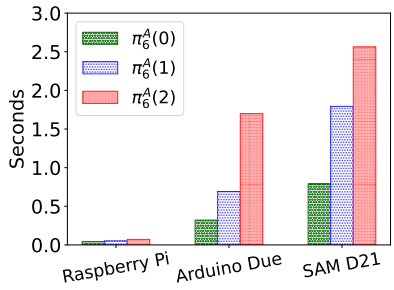
(a) Comparator protocols on device P_A



(b) π_6^A on device P_A

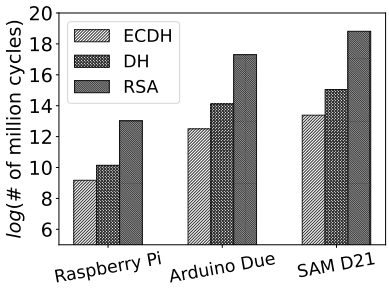


(c) Comparator protocols on device P_B

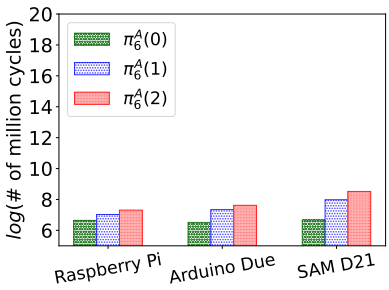


(d) π_6^A on device P_B

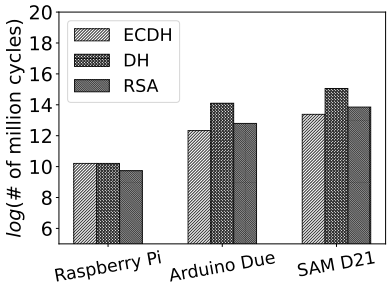
Fig. 9. Running time of key exchange protocols on devices P_A and P_B. Note that each subfigure uses a different maximum value for its Y-axis.



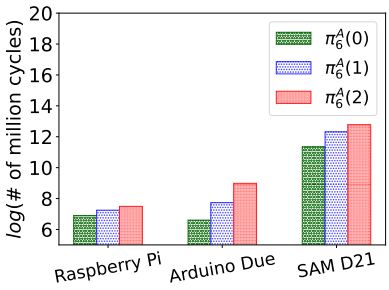
(a) Comparator protocols on device A



(b) π_6^A on device A

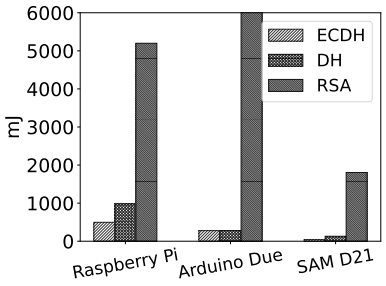


(c) Comparator protocols on device B

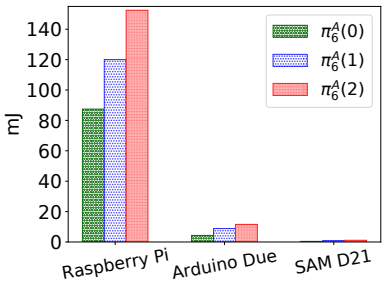


(d) π_6^A on device B

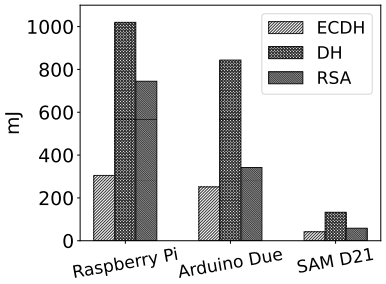
Fig. 10. CPU cycles of key exchange protocols on devices P_A and P_B.



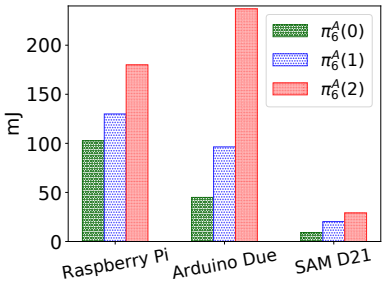
(a) Comparator protocols on device A



(b) π_6^A on device A



(c) Comparator protocols on device B



(d) π_6^A on device B

Fig. 11. Energy consumptions of key exchange protocols on devices P_A and P_B. Note that each subfigure uses a different maximum value for its Y-axis.

7.4 Energy Consumption

We measured π_6^A and the comparator protocols' energy consumption with the formula $E = U \cdot I \cdot T$ [4] where U is the voltage, I is the current intensity, and T is the time to complete a session of a key exchange protocol. The values of U and I are from Table 1. Notice we only consider the current intensity when devices are in the active mode. Fig. 11a and Fig. 11b show the energy consumption comparison results at P_A. We can see if P_A is a Raspberry Pi Zero, while the most energy-efficient PKC protocol ECDH consumes 497.5mJ, $\pi_6^A(2)$ in the worst case only consumes 152.5mJ, which is only about 30.6% of ECDH's energy consumption. In fact, the energy saving with π_6^A is even more significant if the device is resource-constrained. For example, if P_A is a SAM D21, while ECDH consumes 42mJ, $\pi_6^A(2)$ only consumes 0.41mJ, which is only 0.97% of ECDH's energy consumption.

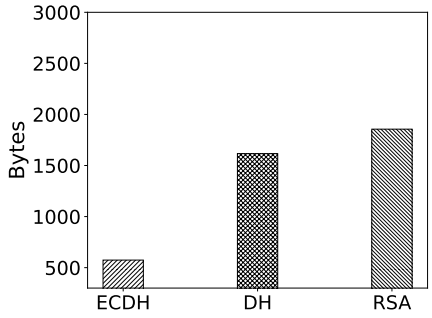
Fig. 11c and Fig. 11d show energy consumption comparison at P_B. We can see π_6^A again consumes much less energy than the PKC-based key exchange protocols. For example, if P_B is a Raspberry Pi Zero, the energy consumption of $\pi_6^A(2)$ on P_B is 59.1% of that of ECDH (180mJ versus 305mJ), and if P_B is a much more resource-constrained SAM D21, this number becomes 47.9% (20.1mJ versus 41.8mJ). Last, in $\pi_6^A(0)$ and $\pi_6^A(1)$ P_B consumes even less energy than the comparator protocols.

7.5 Bandwidth Overhead

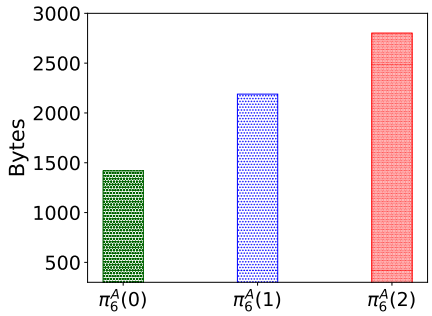
Finally, we measured the bandwidth overhead of π_6^A and its comparator key exchange protocols. In our experiments, the bandwidth overhead indicates the amount of messages that both parties need to transmit over the network in order to establish a session key. Fig. 12 illustrates the results. We can see that $\pi_6^A(1)$ and $\pi_6^A(2)$ incur more bandwidth than PKC protocols and $\pi_6^A(0)$ have more bandwidth overhead than ECDH, but less than RSA and Diffie-Hellman. On one hand, the number of messages in π_6^A is much more than that in the other three PKC-based protocols. On the other hand, the length of keys in π_6^A is much shorter (Section 7.1) and the size of messages in π_6^A is much smaller. As a result, overall the bandwidth overhead of π_6^A is comparable to that of the comparator protocols, especially when considering its vast improvements in running time and energy consumption. We also emphasize here that the bandwidth overhead in one key exchange session is independent of other key exchange sessions, thus not affected by other sessions. Even if an intermediary may be shared across multiple sessions, it is usually not an IoT device and not poor in bandwidth capacity, further assuring our design is scalable against the size of an IoT network.

8 USE CASES

In this section, we describe the practical application of our protocol by illustrating some real-world use cases. Specifically, we show the use of our protocol for two IoT devices to exchange a secret and establish secure communication channels in three scenarios of smart home, healthcare, and smart agriculture. Notice that prior to starting the key exchange protocol, the two communication IoT devices must initiate an authentication process to authenticate each other, as described in Section 3.1. Therefore, during the key exchange, we assume both devices are honest and correctly follow the protocol. In addition, in our use cases, IoT devices communicate with each other directly instead of through an intermediary hub. This is because direct communication between IoT devices can achieve better performance in terms of reliability, latency, bandwidth, and privacy [2, 28, 29, 39].



(a) Comparator protocols



(b) π_6^A

Fig. 12. Bandwidth usage of key exchange protocols.

8.1 Smart Home

Smart home technology refers to devices that provide residents with remote monitoring and management services of appliances and systems. Over the past few decades, smart home technology has developed rapidly and has become one of the critical solutions for energy efficiency, climate change, and innovation [38]. However, due to the resource-constrained nature of IoT devices in the smart home, secure communication between these devices is still a major challenge. If the devices are from the same manufacturer, two communicating devices could have a secret pre-installed by the manufacturer to establish a secure channel between them; however, most devices are often from different manufacturers.

Our protocol can be used by smart home devices to exchange secret keys and establish secure communication channels with each other, even if the devices are from different vendors. Suppose there is a light sensor that monitors the brightness in the house. It has established secure communication channels with some intermediary helpers. The helpers can be a gateway device, a desktop, or another smart device. For example, the light sensor may already have a secure communication channel with a smart humidifier because they share a secret pre-installed by the same manufacturer.

Now, let's say an occupant wants to install a new smart shade that needs to establish a secure channel with the light sensor. If the smart shade and the light sensor are from different manufacturers and do not have a pre-shared secret, then they can run our protocol to exchange a secret key and establish a secure channel. First, the smart shade needs to select some devices as its intermediary helpers. For example, it can use a desktop as an intermediary helper; the occupant can randomly create a secret key and hardcode the key into the smart shade and the desktop such that

they can establish a secure communication channel with the key. Note that we assume here that the occupant cannot simply hardcode a secret into the smart shade and the light sensor for important reasons; for example, (1) compared to hardcoding a key into a desktop, it would be difficult to reconfigure the light sensor when it is already set up and installed, and (2) since the smart shade may also need to communicate with other devices, it will also incur a large overhead to hardcode different keys into each of its communication parties. Also, the smart shade can use another smart device as an intermediary helper if it is from the same vendor as the smart shade and they share a pre-installed secret, where they can use the secret to set up a secure communication channel. Next, the smart shade initializes a key exchange request and sends it to the light sensor to agree on the same set of helpers for them. Then, they start the key exchange session and agree on a shared secret key. Finally, the smart shade and the light sensor can communicate securely using the secret key.

8.2 Healthcare

Healthcare is one of the most critical areas for IoT applications [5]. IoT devices used in healthcare, such as pacemakers, insulin pumps, and cochlear implants, can monitor the vital signs of a patient's health and synchronize the collected data with other devices. In particular, if some unusual activity is detected, a healthcare device can immediately report to a nearby medical machine for further analysis and response.

Suppose a pacemaker is implanted in a patient. Before implanting the pacemaker in the patient's chest, we can set up the pacemaker by selecting intermediary helpers and establishing a secure communication channel between the pacemaker and each helper. For example, the helpers can be different applications developed by different organizations or companies, such as the pacemaker's manufacturer. These applications are pre-installed on the patient's smart phone.

Suppose a medical machine needs to establish a secure communication channel with the pacemaker so that the pacemaker can synchronize and store its data on the machine. The medical machine then invokes our protocol to perform the key exchange with the pacemaker. First, the machine must register with the above applications to establish a secure communication channel with each helper (i.e., the applications). Then the machine initializes a key exchange request and sends it to the pacemaker so that they can agree on the same helpers. When the helpers are confirmed by the pacemaker, they start the key exchange session and agree on a common secret key. Finally, the pacemaker can synchronize its data to the medical machine using the secret key.

8.3 Smart Agriculture

Smart agriculture is another emerging paradigm that improves crop yields and production [15] by using IoT to monitor soil efficiency, temperature, humidity, etc. Meanwhile, smart agriculture is still experiencing a low level of security features. In order to build a robust and efficient smart agriculture system, it is critical to ensure the integrity and confidentiality of the data collected by IoT devices when transferring and processing them [13].

As a common setup, IoT devices in smart agriculture are often connected to a gateway or other edge node devices, which are used to store and process small amounts of data and relay data to cloud servers [13, 40]. Therefore, IoT devices can leverage edge node devices as their intermediary helpers.

For a new device, say a smart sprinkler, to join a smart agriculture system, it is essential that the sprinkler communicate with other devices, such as a smart soil moisture meter, through secure communication channels. To establish secure channels, the sprinkler can invoke our protocol to exchange a common secret key with other devices. First, the sprinkler can select some edge node devices as its helpers and set up a secure channel with each of them. For example, the sprinkler can select some edge node devices as its helpers according to their geographical location. Then, the system

randomly generates a different secret for each edge node device and hardcodes the secret into the sprinkler's memory and the edge node device, thereby setting up a secure channel with the edge nodes using the shared secret. Again, for the similar reasons described in Section 8.1, the system should not hardcode a secret directly between the sprinkler and the moisture meter. Then, the sprinkler can choose a set of helpers and initialize a key exchange request. However, different from the smart home system and healthcare system, a smart agriculture system has a much larger space. The sprinkler needs to choose nearby helpers according to their geographic locations. It is possible that the sprinkler and the moisture meter do not share the same set of helpers In this case, they must first invoke a helper agreement process, as described in Section 3.3, to agree on the the same helpers in common. For example, suppose at the beginning the sprinkler and the moisture meter have different helpers; say the sprinkler has helpers A and B and the moisture meter has helpers C and D. Since A, B, C, and D are edge node devices and well-resourced and they can build secure channels among themselves easily, the moisture meter can first build a secure channel with A by using C and D as their common helpers, thus adding A as a new helper of the moisture meter. Similarly, the moisture meter can add B as a new helper, and the smart sprinkler can add C and D as its new helpers, resulting that the moisture meter and the sprinkler having the same helpers A, B, C, and D. Finally, the smart sprinkler and the moisture meter can start the key exchange session and agree on a common secret key.

9 CONCLUSION AND FUTURE WORK

Internet of Things (IoT) devices have an essential need for secure communications between them, for which a key exchange protocol for them to establish a communication session key is a prerequisite. However, due to their often extremely constrained resources and computing power, many IoT devices are not capable of performing public key cryptography (PKC), making any key exchange solution that uses PKC infeasible. There have been lightweight, non-cryptographic solutions, but they are often unrealistic.

Key exchange solutions that only use symmetric key cryptography (SKC) can be divided into two categories: those using pre-shared secrets and those using intermediary parties. The former is daunting and hardly scalable when employed for an IoT network composed of hundreds or even thousands of devices. The latter so far relies on honest or semi-honest intermediary parties.

This work proposes a new SKC-based key exchange solution (π^A) using intermediary parties (also called helpers). It departs from the state of the art by assuming any intermediary party can be malicious. Its design makes it lightweight and deployable in IoT and resilient against malicious intermediary parties. In particular, under the cut-and-choose methodology, π^A introduces a new protocol design that not only can successfully establish a session key in the end, but also can efficiently identify malicious intermediary parties when they tamper messages going through them, even if they collude or selectively tamper messages.

This work provided both theoretical proof and analysis and empirical evaluations of π^A. From the proof π^A is shown to be secure against malicious helpers. From the analysis, π^A's failure probability is easily negligible with a reasonable setup and π^A's malicious helper detection probability can be 1.0 even when a malicious helper only tampers a small number of messages. From the empirical evaluations, π^A outperforms three widely used PKC-based key exchange protocols in terms of running time, CPU cycles, and energy consumption while its bandwidth overhead is comparable to them.

For the future work, we will implement an open-source library for the community. The library will be used by developers to apply our protocol in their IoT devices to enhance the security and efficiency for communications. In addition, our current experiment is conducted in an emulated Wi-Fi environment with Mininet platform. We will

integrate our protocol in real world use cases (as described in Section 8) and evaluate its performance also in terms of running time, CPU cycles, energy consumption, and bandwidth overhead.

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