SAND2014-1723C

Sensor Authentication in Collaborating Sensor Networks

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***Abstract*— In this paper, we address a new security problem in the realm of collaborating sensor networks. By collaborating sensor networks, we refer to the networks of sensor networks collaborating on a mission, with each sensor network is independently owned and operated by separate entities. Such networks are practical where a number of independent entities can deploy their own sensor networks in multi-national, commercial, and environmental scenarios, and some of these networks will integrate complementary functionalities for a mission. In the scenario, we address an authentication problem wherein the goal is for the Operator O^i of Sensor Network S^i to correctly determine the number of active sensors in Network S^i. Such a problem is challenging in collaborating sensor networks where other sensor networks, despite showing an intent to collaborate, may not be completely trustworthy and could compromise the authentication process. We propose two authentication protocols to address this problem. Our protocols rely on Physically Unclonable Functions, which are a hardware based authentication primitive exploiting inherent randomness in circuit fabrication. Our protocols are light-weight, energy efficient, and highly secure against a number of attacks. To the best of our knowledge, ours is the first paper that addresses a practical security problem in collaborating sensor networks.**

***Index Terms*— Sensor Networks, Collaboration, Authentication, Physically Unclonable Functions, Security**

I. Introduction

Wireless Sensor Networks are proving to be indispensable technologies in many settings. In the near future, it is likely that sensor networks will not be operating entirely independently, but will rather collaborate with peer networks owned and operated by other entities to collaborate on mission tasks. However, when missions involve multiple countries and/or commercial perspectives, complete trust between collaborating networks is not practical. Consider the following two scenarios:

- A Multi-Nation Scenario – There is an abundant amount of natural phenomena that can occur in which several countries are affected. Earthquakes can affect numerous regions across multiple countries, volcanic debris can cover hundreds of square miles, and tsunamis can reach entire coastlines. Detection of these events in order to provide advance warning and aid is significantly important to all the countries vulnerable to such a disaster, and by collaborating with nearby countries, larger sensor networks can be deployed to detect such phenomena as they form and occur at further distances. However, complete trust is improbable as each country will still also possess goals and agendas for the networks that may not necessarily be exposed to the other collaborating countries.

- A Commercial/Environmental Scenario – With commercial and environmental applications of sensor networks like soil monitoring, healthcare, etc., becoming feasible, there is an interest today in sensor-clouds [1, 2, 3, 4] where multiple independent sensor networks are integrated into a cloud framework providing services not possible with a single sensor network. It is likely that individual networks, from competing businesses and organizations may compromise overall functionality of the integrated network and services for selfish gains, despite showing an intent to collaborate.

A. Problem Addressed

In this paper, we address the following problem - Given n collaborating S^1, S^2, S^3, …, S^n, how can the Operator O^i of Network S^i correctly authenticate active sensors in its network.

This problem is clearly unique to scenarios where multiple sensor networks collaborate, and is practical, since knowing which are active (i.e., functioning) sensors in its own network is critical for network operators. Note here that the solution to this problem is not trivial in the presence of other untrusted sensor networks. When Operator O^i of Network S^i issues a query requesting sensors that are active in its network to report, sensors in another network S^j can masquerade as sensors in Network S^i, packets can be dropped, corrupted, or replayed during forwarding, and malicious entities may also fake O^i.

B. Our Contributions

We propose two handshaking protocols to solve the above problem in this paper. Our protocols rely on Physically Unclonable Functions (PUFs). PUFs are circuits in hardware that provide hardware based authentication of a device. Briefly, given a challenge, a PUF circuit generates a verifiable response. The salient feature of the PUF design is that since their behavior is based on inherent randomness of physical hardware during fabrication, their behavior is not predictable before hand, nor is the behavior clonable. Depending on the hardware characteristics and physical property exploited like circuit delays, voltage values at power-up, ring oscillator frequencies, PUFs have been designed with a large number of challenge response pairs up to 2^{64} with minimal increases in

circuit overhead and latency [5]. Our protocols use a combination of PUF responses, XOR encryption and aggregation to address the authentication problem, while being resilient to a variety of attacks.

II. Preliminaries

In this section, we present important preliminaries related to our authentication problem and proposed protocols. In Section II-A, we present the overall system model. The problem formulation is presented in Section II-B. Section II-C discusses attacks compromising the authentication problem. A brief overview of Physically Unclonable Functions, which form the core technology used in our authentication protocols, is presented next in Section II-D. Table 1 summarizes important parameters and definitions used in the paper.

A. System Model

In this paper, we are concerned with a network of independently operated but collaborating sensor networks. Figure 1 illustrates a simple case, where there are three sensor networks collaborating in a deployment field. Let us denote these sensor networks as S^1, S^2, S^3. For illustration, let us assume that S^1 is a network of temperature sensors, S^2 is a network of infra-red sensors, and S^3 is a network of seismic sensors. These three sensor networks are independently owned and operated by O^1, O^2, and O^3 respectively, and are expected to collaborate on the field, and communicate with each other. A practical application in this scenario is intruder sensing via fusing information from multiple sensors in multiple networks, despite each sensor network independently executing its own mission.

All sensors are assumed to be static. A sensor in one network may use sensors in another network during routing. A sensor in one network may or not be interested in the information communicated by a sensor in another network. There is some key management scheme that is used by the sensors to protect their communications from eavesdropping by external adversaries. Since sensors can be faulty/ fail/ or be energy depleted, the number of active sensors in any network can change over time. Because of the collaborative nature of the sensor networks, each one is assumed to be able to read to some extent the messages sent by another sensor network.

B. Problem Formulation

The problem we address in the above system model is the following. How can Operator O^i correctly determine which are the active sensors in its own Network S^i whenever it wishes to. We can see from Figure 1, the number of sensors in Networks S^1, S^2, and S^3 are 7, 9, and 5 respectively. However, as time goes on, sensors in a particular network may become faulty, may fail, or may be become energy depleted. If a significant number of sensors in a particular Network S^i does become in-active, Operator O^i may desire to know this so that corrective action can be subsequently taken to mitigate network deficiency. Note that in practice, such a query from O^i will not arrive very often. It is expected to be generated over longer time intervals, or when O^i suspects any major change in the network state.

C. Attacks Compromising Authentication

The adversary that we are concerned about is the untrusted ally with whom our sensor network is cooperating. This adversary is distinct from a typical attacker in that he already possesses some knowledge about the sensor network prior to launching attacks, whereas the typical attacker would normally begin executing his attacks blindly. Some of the information that this adversary has initially can include the location of sensors within the network, encryption keys used by the sensors, and sensing capabilities of the sensors. This information grants the adversary unique opportunities for its attacks that may not have otherwise been present.

Our adversary is able to launch a wide variety of attacks against the sensor network to prevent/ compromise correct authentication. Eavesdropping attacks can be used to learn secrets and vulnerabilities of sensors in the network. Masquerade and reflection attacks can be use to trick sensors and / or the operator into revealing secrets and responses to the authentication process. The adversary can also launch DOS, jamming, and routing attacks to disrupt and deny communications in the sensor network. Finally, the attacker can try to physically tamper with the sensor to gain control and gather information.

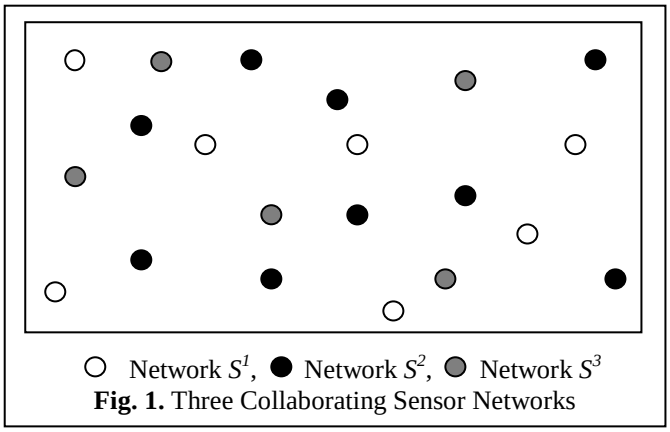

Fig. 1. Three Collaborating Sensor Networks

Table 1. Important Parameters used in proposed Protocols and their Definitions

Notation	Definition
S^i	i^{th} sensor network
O^i	Operator of Sensor Network S^i
$s_k^{\ i}$	Sensor s_k belonging to the i^{th} Sensor Network
r	Query round
$N_{r,k}^{\ \ i}$	Nonce shared between sensor $s_k^{\ i}$ and O^i for Round r
$Y_k^{\ i}$, $Z_k^{\ i}$	Two secret keys shared between Sensor $s_k^{\ i}$ and O^i
$PUF_k^{\ i}$	Physically Unclonable Function of Sensor $s_k^{\ i}$
$C_{(r,k)}^{\ \ i}$	Challenge Vector for Sensor $s_k^{\ i}$ in Round r
$A_{(r,k)}^{\ \ i}$	Authentication Challenge for Sensor $s_k^{\ i}$ in Round r
$PUF_k^{\ i}(C_{(r,k)}^{\ \ i})$	PUF response of Sensor $s_k^{\ i}$ to Challenge $C_{(r,k)}^{\ \ i}$ in Round r

Additionally, it is important to note what advantages an adversary could gain from the collaboration in the sensor networks. With the encryption keys, the adversary can use eavesdropping attacks to learn a wider array of secrets and information, including what messages are used to trigger different events and whether there are any secondary encryption schemes being used. Knowledge of the sensor locations allows the adversary to more easily use jamming attacks while minimizing the effect on their own sensors. Knowing the sensing capabilities of the sensors also allows the adversary more precision in creating gaps in the target sensor network. While not an attack per se, it allows for the adversary to compromise the mission of the sensor network. Note that these are additional issues to consider in collaborating sensor networks although not addressed in this paper.

D. Physically Unclonable Functions

Our proposed solution to the authentication problem proposes leveraging Physically Unclonable Functions. We assume each sensor in a network is provisioned with its own Physical Unclonable Function (PUF). A PUF is an innovative circuit primitive that provides a mechanism to extract secrets leveraging from physical randomness in hardware fabrication of integrated circuits (ICs) [11, 12, 13, 5, 14, 15]. More specifically, a PUF is a hardware primitive who behavior is determined by the physical structure of the hardware itself and its construction. The randomness of fabrication during circuit constructions makes no two circuits exactly the same. While a particular circuit exhibits repeatable behavior, predicting its performance before hand is not possible, and cloning of the circuit is highly impractical. Typically, PUFs are used in a challenge-response mechanism, wherein given a Challenge *C*, the PUF for a particular device will respond with a Response *R*. While *R* is repeatable for the same *C*, guessing or cloning the circuit to derive *R* is not possible hence providing a straightforward mechanism for hardware based authentication.

A number of properties of ICs today lend themselves to creating PUFs. An Optical PUF can be generated as a result of speckle patterns (intensity patterns produced by the mutual interference of a set of wave fronts) emanated when a laser beam shines on an optical material [16]. These patterns are random, unique, and unclonable, hence realizing an optical physically unclonable, hence realizing an optical PUF. Another type of PUF is called a Coating based PUF, where above a normal IC, a network of metal wires is laid out in a comb shape. The space between and above the comb structure is filled with an opaque material and randomly doped with dielectric particles. Because of the random placement, size, and dielectric strength of the particles, the capacitance between each couple of metal wires will be random up to a certain extent. A number of PUFs exploiting other physical properties that exhibit randomness during circuit fabrications have been designed exploiting inherent randomness during circuit fabrications. These include delay based PUF exploits random variations in delays of wires and gates on silicon [11, 12], oscillator frequencies [11, 13, 5], voltage values during power-up of SRAM (Static Random Access Memory) [14, 15].

Table 2. Properties of Physically Unclonable Functions

PUF Type	No. of Gates	No. of Bits	Response Time	Energy Per Response
Optical PUF [11, 12]		10^5	1ms	
Delay based Arbiter [11, 12]	450	2^{64}	5ns	0.239pJ
Ring Frequency Oscillator [11, 13, 5]	1159	496	1650ns	244.2pJ
SRAM Voltage based PUF [14, 15]	256	2^{50}	11ns	

With advances in hardware miniaturization, PUFs are becoming increasingly practical, with minimal overhead in space and energy expenditure. For instance, it is estimated that implementing a delay circuit requires about 6 to 8 gates for each input bit, and oscillating counter circuit that measures delay requires about 33 gates. Therefore, a 64-bit input delay PUF requires only about 545 gates [5]. A typical coating PUF has been implemented in [17] with just 1000 gates, and the optical PUF implemented in [16] can yield upto 10^6 challenge-response pairs with a delay of around 1 ms per authentication. The use of 256 SRAM blocks has been shown to yield 100 bits of true randomness each time the memory is powered up [15]. Note that the reliance on PUFS on subtle inherent physical variations during fabrication means that they are inherently sensitive to physical tampering [18, 19, 13, 20], and can be easily detected with incorrectly received responses after a circuit is tampered. Table 2 summarizes some PUF implementations and their properties.

III. Our Basic 3-way Handshaking Protocol

We now present our basic 3-way handshaking protocol for authentication in collaborating sensor networks. We first present the description of the protocol, followed by an analysis on the security performance against attacks. We also assume that the total number of active sensors in Network S^i is m.

A. Protocol Description

Protocol 1 presents our basic 3-way handshaking protocol. The protocol is executed each time (or round) when the Operator O^i intends to authenticate sensors belonging to network S^i. Consider an arbitrary Round *r*. Operator O^i will broadcast a query consisting of a Challenge Vector for that round:

$$\begin{bmatrix} {N_{(r,1)}}^i \| {Y_1}^i \oplus {C_{(r,1)}}^i \| {Z_1}^i \oplus {A_{(r,1)}}^i \\ {N_{(r,2)}}^i \| {Y_2}^i \oplus {C_{(r,2)}}^i \| {Z_2}^i \oplus {A_{(r,2)}}^i \\ \cdots \\ {N_{(r,m)}}^i \| {Y_m}^i \oplus {C_{(r,m)}}^i \| {Z_m}^i \oplus {A_{(r,m)}}^i \end{bmatrix}$$

where $N_{(r,k)}{}^{i}$ is a nonce shared between Operator O^i and Sensor $s_k{}^{i}$. Once a sensor $s_k{}^{i}$ verifies that the nonce received is expected, it proceeds with the following steps. Otherwise, the message is discarded. Note that the nonce for the first round is pre-stored on sensor $s_k{}^{i}$. This completes the first part of the handshaking protocol. Using its secret keys pre-distributed keys $Y_k{}^{i}$ and $Z_k{}^{i}$, sensor $s_k{}^{i}$ extracts two challenges $C_{(r,k)}{}^{i}$ and $A_{(r,k)}{}^{i}$. Here $C_{(r,k)}{}^{i}$ denotes the challenge issued by the operator whose response from $s_k{}^{i}$ will then be used to authenticate it, while $A_{(r,k)}{}^{i}$ denotes the subsequent challenge whose response from O^i will enable sensor $s_k{}^{i}$ verify that its response was indeed received by O^i correctly. Once a sensor $s_k{}^{i}$ extracts $C_{(r,k)}{}^{i}$, it will compute a Response $P_{(r,k)}{}^{i}$ which is the output of the sensor's physically unclonable function, i.e., $P_{(r,k)}{}^{i} = PUF_k{}^{i}(C_{(r,k)}{}^{i})$. This response along with the sensor ID is then routed back to Operator O^i as $[s_k{}^{i} \parallel P_{(r,k)}{}^{i} \oplus Y_k{}^{i}]$. This completes the second part of the handshaking protocol.

Once Operator O^i receives responses (after a tolerable delay), it will verify if the received $P_{(r,k)}{}^{i}$ is the expected one for Sensor $s_k{}^{i}$. For every sensor whose response was correctly authenticated, the operator will derive $Q_{(r,k)}{}^{i} = PUF_k{}^{i}(A_{(r,k)}{}^{i})$. For any sensor $s_j{}^{i}$ whose response cannot be verified as correct, $Q_{(r,j)}{}^{i}$ is set to a random bit string. This prevents any attackers targeting the unverified node to learn any information about the protocol by the absence of a message or data value. Operator O^i will broadcast this response to all sensors in the network in order to convince sensors receipt of their responses, along with the nonce for the next round. The message transmitted is

$$\begin{bmatrix} Q_{(r,1)}{}^{i} \oplus Y_1{}^{i} \parallel Q_{(r,1)}{}^{i} \oplus N_{(r+1,1)} \oplus Z_1{}^{i} \\ Q_{(r,2)}{}^{i} \oplus Y_2{}^{i} \parallel Q_{(r,2)}{}^{i} \oplus N_{(r+1,2)}{}^{i} \oplus Z_2{}^{i} \\ \cdots \\ Q_{(r,m)}{}^{i} \oplus Y_m{}^{i} \parallel Q_{(r,m)}{}^{i} \oplus N_{(r+1,m)}{}^{i} \oplus Z_m{}^{i} \end{bmatrix}$$

Each sensor $s_k{}^{i}$ can now verify if its message was indeed received correctly by verifying the correctness of $Q_{(r,k)}{}^{i}$, based on the challenge $A_{(r,k)}{}^{i}$ that it already possesses. Each sensor will also be able to successfully extract the expected Nonce $N_{(r+1,k)}{}^{i}$ for the next round $r + 1$. If $Q_{(r,k)}{}^{i}$ for sensor $s_k{}^{i}$ is not the expected value, this means that O^i did not receive the sensor's response due to possible packet drop or corruption enroute. Hence Sensor $s_k{}^{i}$ will send its original $P_{(r,k)}{}^{i}$ via multiple routing paths to the operator expecting an acknowledgement. If an acknowledgement from O^i still does not arrive, the sensor can practically consider itself in-active due to a broken communication link with the operator. This completes the 3-way handshaking protocol.

B. Analysis of the Proposed Protocol

In this section, we present a security analysis of Protocol 1 against attacks discussed earlier.

Eavesdropping Attacks: The attacker can eavesdrop on any communication in the network. However, the adversary will not be able to infer any information that could compromise the authentication process. By observing the PUF responses $P_{(r,k)}{}^{i}$ of sensor $s_k{}^{i}$ in Round r, the adversary will not be able to infer anything useful about the current or subsequent communication since PUF responses cannot be predicted in advance or cloned. Such an attack can be easily thwarted if Operator O introduces dummy entries in its queries, and if sensors send dummy message during query responses. Dummy queries will not be processed, while dummy responses from sensors will be identified by the operator and discarded. The downside though may be increased overhead during the messages forwarding.

Also, an eavesdropping adversary may capture messages from the operator. However, since messages are encrypted using secret keys $Y_k{}^{i}$ and $Z_k{}^{i}$ for sensor $s_k{}^{i}$, the adversary will not be able to infer Challenges $C_{(r,k)}{}^{i}$ or $A_{(r,k)}{}^{i}$ for Round r (Step

Protocol 1 Basic 3-way Handshaking Protocol in Round r

1: Operator O^i sends $\begin{bmatrix} N_{(r,1)}{}^{i} \parallel Y_1{}^{i} \oplus C_{(r,1)}{}^{i} \parallel Z_1{}^{i} \oplus A_{(r,1)}{}^{i} \\ N_{(r,2)}{}^{i} \parallel Y_2{}^{i} \oplus C_{(r,2)}{}^{i} \parallel Z_2{}^{i} \oplus A_{(r,2)}{}^{i} \\ \cdots \\ N_{(r,m)}{}^{i} \parallel Y_m{}^{i} \oplus C_{(r,m)}{}^{i} \parallel Z_m{}^{i} \oplus A_{(r,m)}{}^{i} \end{bmatrix}$ to sensors
2: **End 1-way handshake**
3: Each Sensor $s_k{}^{i}$ executes the following steps
4: IF $N_{(r,k)}{}^{i}$ is as expected
5: Extract $C_{(r,k)}{}^{i}$ and $A_{(r,k)}{}^{i}$
6: Compute $P_{(r,k)}{}^{i} = PUF_k{}^{i}(C_{(r,k)}{}^{i})$
7: $s_k{}^{i}$ sends $[s_k{}^{i} \parallel P_{(r,k)}{}^{i}]$ to O^i
8: ELSE Reject Request
9: END IF
10: **End 2-way handshake**
11: Operator O^i executes the following steps for each Sensor $s_k{}^{i}$
12: IF received $P_{(r,k)}{}^{i}$ matches expected response
13: Authenticated Sensor $s_k{}^{i}$ as Active
14: Compute $Q_{(r,k)}{}^{i} = PUF_k{}^{i}(A_{(r,k)}{}^{i})$
15: ELSE
16: Consider Sensor $s_k{}^{i}$ as Inactive
17: Set $Q_{(r,k)}{}^{i}$ = Random bit string
18: END IF
19: Operator O^i $\begin{bmatrix} Q_{(r,1)}{}^{i} \oplus Y_1{}^{i} \parallel Q_{(r,1)}{}^{i} \oplus N_{(r+1,1)}{}^{i} \oplus Z_1{}^{i} \\ Q_{(r,2)}{}^{i} \oplus Y_2{}^{i} \parallel Q_{(r,2)}{}^{i} \oplus N_{(r+1,2)}{}^{i} \oplus Z_2{}^{i} \\ \cdots \\ Q_{(r,m)}{}^{i} \oplus Y_1{}^{i} \parallel Q_{(r,m)}{}^{i} \oplus N_{(r+1,m)}{}^{i} \oplus Z_m{}^{i} \end{bmatrix}$
20: Each Sensor $s_k{}^{i}$ executes the following steps
21: IF $Q_{(r,k)}{}^{i} = PUF_k{}^{i}(A_{(r,k)}{}^{i})$
22: Extract Nonce $N_{(r+1,1)}{}^{i}$ for Round $r + 1$
23: ELSE Send $P_{(r,k)}{}^{i}$ to O^i via multiple routing paths
24: END IF
25: **End 3-way handshake**

1). Similarly, the adversary can eavesdrop on the response message of the operator for Round *r* (Step 19). The adversary could then attempt to discover information by observing the plain text nonce in the next round. First, the adversary will not be able to infer $N_{(r+1,k)}{}^{i}$ for Sensor $s_k{}^{i}$ from any passive observations in Round r due to encryption. Also, by performing operations $Q_{(r,k)}{}^{i} \oplus Y_k{}^{i} \oplus Q_{(r,k)}{}^{i} \oplus N_{(r+1,k)}{}^{i} \oplus Z_k{}^{i} \oplus N_{(r+1,k)}{}^{i}$, the adversary will only be able to infer $Y_k{}^{i} \oplus Z_k{}^{i}$, which itself yields no useful information about the keys stored.

Masquerading Attacks: Attackers may impersonate sensors in the network during querying. However, a masquerading sensor will not be to generate the correct PUF response. Such messages will be identified as fake by the operator and discarded automatically. Note that since PUFs cannot be cloned due to their inherent randomness during fabrication, circuit cloning attacks are infeasible.

Reflection Attacks: Reflection attacks are not a threat to the authentication process in Protocol 1, since the challenges and response of sensors and the operator are different. Sensors will respond with the PUF value only upon correctly verifying the nonce from the operator which are not exposed to the adversary. Similarly the adversary will never gain knowledge of, or generate the PUF value that can be used for a subsequent authentication process. Even if the adversary captures the PUF response for a challenge, the same challenge is very unlikely to be used again for sufficiently long challenge bit sequences. As pointed earlier in Table 2, up to 2^{64} challenge-responses are feasible with PUFs today. Hence reflection attacks are addressed in Protocol 1.

Packet Drop/ Packet Corruption Attacks: In a network of collaborating sensor networks, any of the messages sent by the operator or the sensor may travel through sensors belonging to other networks. In this scenario the message may be dropped, potentially disrupting the authentication process. This can be easily detected because, at each phase of the protocol, a message is expected by either the operator or the sensor. If that message does not arrive, the sensor and/or operator can resend its previous message with or without modifications to the routing path until a set number of retry attempts is met, at which point the sensor can be considered inactive due to the inability to successfully communicate with the sensor. The same responses and consequences will also be used if a packet corruption attack is used instead. In either case, this does not compromise the correctness of Protocol 1. These attacks are similar to a denial of service attack except that instead targeting the sensor, the routing path is targeted.

Replay and Selective Forwarding Attacks: Replay and Selective Forwarding attacks can be launched by other malicious sensors that have eavesdropped on previous packets. However, since the PUF responses are unique to every challenge, there is no incentive for adversaries to launch such attacks. An adversary that attempts to launch replay or selective forwarding attacks will be ignored by the sensors, since the expected nonce will never match. The energy consumed for comparing a sequence of bits is very minimal in sensors. Furthermore, if repeated replay and selective forwarding attacks are launched, it is easy for sensors to detect the presence of an adversary and notify the operator who can then take other corrective actions.

Denial of Service Attacks: In the event that attackers are able to jam one or more sensors in the network, their responses will not be able to reach the operator. As long as a jamming attack continues, the sensor being jammed is practically useless, and hence it will not be considered as an active sensor by the operator.

Physical Attacks: As pointed earlier in the section, PUFs provide an inherent resilience against physical tampering [18, 19, 13, 20]. When adversaries physically tamper with sensors, the physical characteristics of the circuit will be altered, and the PUF responses to challenges will also be altered. Upon receiving incorrect PUF responses to challenges, the operator will subsequently identify a physically tampered sensor as inactive.

As shown, our protocol is highly resilient against a variety of attacks. While some of the attacks can disrupt and block communications with a given sensor, the allied adversary is still unable to break the authentication protocol outlined above. This also holds true for an external adversary since their attacks will not have the level of access available to the allied adversary.

IV. Our Aggregated 3-way Handshaking Protocol

Our basic 3-way handshaking protocol presented above is robust against a number of attacks compromising authentication in collaborating sensor networks. However, the major limitation of Protocol 1 is that each sensor individually forwards its response to the operator. This will introduce significant communication overhead in large scale networks, which our proposed 3-way Aggregated Protocol described below alleviates without compromising security performance. We also assume that the total number of active sensors in Network S^i is m.

A. Protocol Description

Protocol 2 presents our aggregated 3-way handshaking protocol. This protocol considers a sensor network clustered into a certain number of clusters. Each sensor belongs to one cluster with a cluster-head. The operator is assumed to know which sensor belongs to which cluster, which could be known just after deployment as sensors generate clusters among themselves using techniques in [21, 22]. Protocol 2 is executed each time (or round) when the Operator O^i intends to authenticate sensors belonging to network S^i. Consider an arbitrary Round *r*. The operator will broadcast a query vector containing the nonce and encrypted challenge vectors for each sensor. This completes the first part of the handshaking protocol.

After computing the PUF response $P_{(r,k)}{}^{i} = PUF_k{}^{i}(C_{(r,k)}{}^{i})$, each sensor will forward its response to its cluster-head. Consider Cluster *j* for illustration. The cluster-head will aggregate all responses in its cluster using the XOR function to compute $G_{(r,j)}{}^{i}$ for Cluster *j*. It will then broadcast $G_{(r,j)}{}^{i}$ and responding sensor IDs to its upstream cluster-head and all sensors in its cluster. The upstream cluster-head will once

Protocol 2 Aggregated 3-way Handshaking Protocol in Round r

1: A Sensor Network Clustered into J Clusters

2: Operator $O^i \begin{bmatrix} N_{(r,1)}{}^i \,||\, Y_1{}^i \oplus C_{(r,1)}{}^i \,||\, Z_1{}^i \oplus A_{(r,1)}{}^i \\ N_{(r,1)}{}^i \,||\, Y_1{}^i \oplus C_{(r,1)}{}^i \,||\, Z_1{}^i \oplus A_{(r,1)}{}^i \\ \\ N_{(r,m)}{}^i \,||\, Y_m{}^i \oplus C_{(r,m)}{}^i \,||\, Z_m{}^i \oplus A_{(r,m)}{}^i \end{bmatrix} *$

3: **End 1-way handshake**

4: Each Sensor $s_k{}^i$ executes the following steps

5: IF $N_{(r,1)}{}^i$ is as expected

6: IF Sensor $s_k{}^i$ is a NOT a Cluster-Head

7: Extract $C_{(r,k)}{}^i$ and $A_{(r,k)}{}^i$

8: Compute $P_{(r,k)}{}^i = PUF_k{}^i(C_{(r,k)}{}^i)$

9: $s_k{}^i$ [$s_k{}^i \,||\, P_{(r,k)}{}^i$] Cluster-Head

10: ELSE IF Sensor $s_k{}^i$ is a Cluster-Head of Cluster j

11: Extract $C_{(r,k)}{}^i$ and $A_{(r,k)}{}^i$

12: Compute $P_{(r,k)}{}^i = PUF_k{}^i(C_{(r,k)}{}^i)$

13: Compute $G_{(r,j)}{}^i = P_{(r,k)}{}^i \oplus P_{(r,j)}{}^i \;\forall$ responding sensors $s_j{}^i$ in Cluster j

14: Forward $G_{(r,j)}{}^i$, Sensor IDs to Peer Sensors and Upstream Cluster-Head

15: END IF

16: ELSE Reject Request

17: END IF

18: **End 2-way handshake**

19: Operator O^i executes the following steps for each Sensor $s_k{}^i$

20: Compute $\forall$ responding sensors $s_k{}^i$, $\oplus P_{(r,k)}{}^i$

21: IF Response matches Expected Response

22: Authenticated All Sensor IDs received as Active

23: Compute $Q_{(r,k)}{}^i = PUF_k{}^i(A_{(r,k)}{}^i)$

24: ELSE % malicious behavior detected

25: Operator computes $\forall$ responding sensors $s_k{}^i$ in Cluster j, $G_{(r,j)}{}^i = \oplus P_{(r,k)}{}^i$

26: Operator $O^i \begin{bmatrix} G_{(r,1)}{}^i \\ G_{(r,2)}{}^i \\ \dots \\ G_{(r,m)}{}^i \end{bmatrix} *$

27: FOR Each Cluster j in the Network

28: FOR Each sensor $s_k{}^i$ in Cluster j

29: Report $P_{(r,k)}{}^i = PUF_k{}^i(C_{(r,k)}{}^i)$ to Operator

30: END FOR

31: END FOR

32: Operator can identify malicious sensors and consider them inactive

33: Operator sets $Q_{(r,k)}{}^i$ = Random bit string $\forall$ inactive sensors $s_k{}^i$

34: END IF

35: Operator $O^i \begin{bmatrix} Q_{(r,1)}{}^i \oplus Y_1{}^i \,||\, Q_{(r,1)}{}^i \oplus N_{(r+1,1)}{}^i \oplus Z_1{}^i \\ Q_{(r,2)}{}^i \oplus Y_2{}^i \,||\, Q_{(r,2)}{}^i \oplus N_{(r+1,2)}{}^i \oplus Z_2{}^i \\ \dots \\ Q_{(r,m)}{}^i \oplus Y_1{}^i \,||\, Q_{(r,m)}{}^i \oplus N_{(r+1,m)}{}^i \oplus Z_m{}^i \end{bmatrix}$

36: Each Sensor $s_k{}^i$ executes the following steps

37: IF $Q_{(r,k)}{}^i = PUF_k{}^i(A_{(r,k)}{}^i)$

38: Extract Nonce $N_{(r+1,\,1)}{}^i$ for Round $r + 1$

39: ELSE Send $P_{(r,k)}{}^i$ to Operator via multiple routing paths

40: END IF

41: **End 3-way handshake**

again perform aggregation and this process continues towards the operator. Each sensor in Cluster j will store $G_{(r,j)}{}^{i}$ for subsequent verification in the event of a packet corruption. This completes the second part of the handshaking protocol.

Upon receiving the aggregated response and all responding sensor ids, the operator will compute $\oplus P_{(r,k)}{}^{i}$ for responding sensors $s_k{}^{i}$. If this value matches the aggregated response received from the immediate downstream cluster-head(s), the authentication process is completed and all responding sensors are considered active. Otherwise, at least one or more sensors generated a malicious response or an intermediary malicious sensor processed a packet and corrupted it. In either case, the operator will broadcast the expected aggregated responses to each cluster. When a sensor receives $G_{(r,j)}{}^{i}$ from the operator for its cluster, it will compare the correctness of its own aggregated response that was forwarded to it by its own cluster-head. If the compared values match, then there was no malicious sensor in its cluster and the sensor ignores the message. If on the other hand, the compared values do not match, then the sensors in the cluster will send their individual responses to the operator and the operator can now detect the malicious response, since the sensor that was the source of the malicious behavior will not be able to generate the correct PUF response. Similarly, corruptions of packets by intermediate sensors can also be detected. After this step, all active sensors will be correctly authenticated and the operator will send an authentication response along with an encrypted form of the nonce to be used for the next round of authentication. This completes the 3-way handshaking protocol.

B. Analysis of the Proposed Protocol

Due to space limitations, we do not present a detailed analysis of security properties of Protocol 2. Fundamentally, we save a significant amount of communication overhead in Protocol 2 compared to Protocol 1 due to aggregation. However, note that the security features provided by Protocol 1 are also provided by Protocol 2. Due to the aggregation performed, some attacks become slightly more effective or useful, but they still do not compromise the authentication process. Routing attacks become more useful as there are 2 more message transmissions that can be targeted by the adversary, but these still have the same results as described in Protocol 1. Masquerade attacks are also slightly harder to detect due to the increased complexity. This is due to the slight delay between when a malicious sensor is detected and when it is identified, but identification of malicious nodes will still occur regardless of the efforts of the adversary. The remaining attacks as described in Protocol 1 will have similar outcomes in Protocol 2.

V. Discussions of Improving Scalability and Malicious sensor Identification

Currently, when a single, aggregated response is returned to the operator containing a malicious response, the entire cluster tree is queried to identify the exact sensors that have been compromised. This introduces considerable overhead into the network and also provides more opportunities for the adversary to compromise the authentication process by targeting the messages being transmitted. By modifying how the PUF responses are XOR'ed together, malicious sensors can be detected before steps 25 – 32 and / or reduce the number of potentially compromised nodes that must be checked. Instead of $\oplus$ all $P_{(r,k)}{}^{i}$, each cluster head $\oplus$ its $P_{(r,k)}{}^{i}$ with each received response and then forwards this group response to the upstream cluster head. This results in each leaf sensor being $\oplus$ with all its cluster heads in its tree branch. Additionally, each cluster head can be uniquely identified by its sensor groupings. This allows for the operator to identify where in the sensor network a malicious response was inserted, reducing the number of sensors that must be queried if a cluster head is compromised and providing immediate detection of compromised leaf sensors. The scalability of the network is also improved as this greatly reduces the communication overhead that would be incurred from querying entire cluster branches and improves detection as more leaf sensors and cluster heads are added. The only downside to this fix is that the base communication overhead in the aggregated PUF responses is increased by the number of leaf sensors.

VI. Conclusions

In this paper, we addressed the problem of authentication in collaborating sensor networks. Our protocols are based on Physically Unclonable Functions, an innovative circuit primitive that provides a mechanism to extract secrets leveraging from physical randomness in hardware fabrication of integrated circuits (ICs). Our protocols are light-weight, efficient, correct and highly resilient to a variety of attacks. Addressing other security, privacy problems in collaborating sensor networks is part of future work.

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Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. (**SAND2014-1723C**)