SECURE DATA AGGREGATION SCHEME

FOR SENSOR NETWORKS

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Kavit Shah

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Electrical and Electronics Engineering

December 2014

Purdue University

Indianapolis, Indiana

This is the dedication.

ACKNOWLEDGMENTS

This is the acknowledgments.

PREFACE

This is the preface.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SYMBOLS

s Sensor node

N Query nonce

H Hash function

d Distance

D Data-item

X Random variable

δ Fanout of a sensor node

f Function

v Vertex

A An attack

α Resilient factor

xii

ABBREVIATIONS

SHA   Secure hash algorithm

SHIA   Secure hierarchical in-network aggregation

SIA   Secure information aggregation

ACK   Positive acknowledgment message

NACK   Negative acknowledgment message

BER   Bit error rate

ABSTRACT

Shah, Kavit Master, Purdue University, December 2014. Secure data aggregation scheme for sensor networks. Major Professor: Dr. Brian King.

This is the abstract.

1. INTRODUCTION

2. SENSOR NETWORKS BACKGROUND

Sensor networks are becoming ubiquitous in our day to day life. They are known also known as Internet of Things. In the following sections we show the applications and the rise of sensor networks. Then we describe why doing security in the sensor network presents the number of unique challenges and solutions to tackle those challenges.

2.1 Sensor Networks and Applications

In sensor networks, thousands of sensor nodes may interact with the physical environment and collectively monitor an area, generating a large amount of data to be transmitted and reasoned about. With the recent advances in sensor network research, we can use tiny and cheap sensor nodes to obtain a lot of useful information about physical environment. For example, we can use them to discover temperature, humidity, water quality, lightning condition, pressure, noise level, carbon dioxide level, oxygen level, soil moisture, magnetic field, characteristics of objects such as speed, direction, and size, the presence or absence of certain kinds of objects, and all kinds of values about machinery like mechanical stress level or movement [1]. These versatile types of sensors, allow us to use sensor network in a wide variety of scenarios. For example, sensor networks are used in habitat and environment monitoring, health care, military surveillance, industrial machinery surveillance, home automation, scientific data collection, emergency fire alarm systems, traffic monitoring, wildfire tracking, wildlife monitoring and many other applications.

Military Application Sensor networks can be used for enemy tracking, battlefield surveillance or target classification [2]. For example, *Palo Alto Research Center* tries to spot "interesting" vehicles (the vehicles marked specially) using motes equipped with microphones or steerable cameras [3]. The objective is to coordinate a number

of this kind of sensors in order to keep sensing the track of a chosen moving object minimizing any information gaps about the track that may occur.

Environmental Monitoring For example, *Meteorology and Hydrology in Yosemite National Park* [4], a sensor network was deployed to monitor the water system across and within the Sierra Nevada, especially regarding natural climate fluctuation, global warming, and the growing needs of water consumers. Research of the water system in the Sierra Nevada is difficult, because of its geographical structure. And sensor networks can be real blessing in such situation as they can operate with little or no human intervention.

Health Care Sensors can be used to monitor the patients round the clock. The most important criteria for the such networks are security and reliability. *CodeBlue* [5] is a system to enhance emergency medical care with the goal to have a seamless patient transfer between a disaster area and a hospital.

Sustainable Mobility With the driver less cars from companies like Google, connected and coordinated vehicles seems the future of transportation. Autonomous vehicle systems [6] describes how various various technologies in addition to the sensor networks is used in making sustainable mobility.

The application of a sensor network usually determines the design of the sensor nodes and the design of the network itself. As far as we know, there is no general architecture for sensor networks. Therefore, developing a protocol for sensor networks can certainly be challenging.

2.2   Energy Consumption

The sensor network's lifetime can be maximized by minimizing the power consumption of the sensor node's radio module. To estimate the power consumption, we have to consider the communication and computation power consumption at each sensor node. The radio module energy dissipation depends on two main parameters [7]. The first is $E_{elec}(J/b)$, the energy dissipated to run the transmit or receive electronics.

The second is $\varepsilon_{amp}(J/b \cdot m^2)$, the energy dissipated by the transmit power amplifier to achieve an acceptable noise ratio E_b/N_o at the receiver. We assume the d^2 energy loss for transmission between sensor nodes since the distances between sensors are relatively short [8]. To transmit a k - bit packet at distance d, the energy dissipated is:

$$E_{tx}(k,d) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^2 \qquad (2.1)$$

and to receive the k - bit packet, the radio expends

$$E_{rx}(k) = E_{elec} \cdot k \qquad (2.2)$$

For μAmp wireless sensor, $E_{elec} = 50nJ/b$ and $\varepsilon_{amp} = 100pJ/b \cdot m^2$.

To sustain the sensor network for longer time all aspects of the sensor network should be efficient. For example, the networking algorithm for routing should be such that it minimizes the distance d between the nodes. The signal processing algorithm should be such that it process the networking packets with less computations. It is shown in [7] that by distributing the Fast Fourier Transform (FFT) algorithm in the network requires less communication between the sensor nodes. Also, for minimal energy dissipation, a processor should operate at the lowest voltage for a given clock frequency.

2.3   Data Aggregation

The sensor nodes in the network often have limited resources, such as computation power, memory, storage, communication capacity and most significantly, battery power. Furthermore, data communications between nodes consume a large portion of the total energy consumption. The in-network data aggregation reduces the energy consumption by aggregating the data before sending it to the parent node in the network which reduces the communications between nodes. For example, in-network data aggregation of the SUM function can be performed as follows. Each intermediate sensor node in the network forwards a single sensor reading containing the sum of all

the sensor readings from all of its descendants, rather than forwarding each descendants' sensor reading one at a time to the base station. It is shown that the energy savings achieved by in-network data aggregation are significant [9]. The in-network data aggregation approach requires the sensor nodes to do more computations. But studies have shown that transmitting the data requires more energy than computing the data. Hence, in-network data aggregation is an efficient and a widely used approach for saving bandwidth by doing less communications between sensor nodes and ultimately giving longer battery life to sensor nodes in the network.

We define the following terms to help us define the goals of in-network data aggregation approach.

Definition 2.3.1 *[10]* **Payload** *is the part of the transmitted data which is the fundamental purpose of the transmission, to the exclusion of information sent with it such as meta data solely to facilitate the delivery.*

Definition 2.3.2 **Information rate** *for a given node is the ratio of the payloads, number of payloads sent divided by the number of payloads received.*

The goal of the aggregation process is to achieve the lowest possible information-rate. In the following sections, we show that lowering information-rate makes the intermediate sensor nodes (aggregator) more powerful. Also, it makes aggregated payload more fragile and vulnerable to various security attacks.

2.4   Bandwidth Analysis

Congestion is a widely used parameter while doing bandwidth analysis of networking applications. The congestion for any given node is defined as follows:

$$Node\ congestion = Edge\ congestion \cdot Fanout \tag{2.3}$$

Congestion is a useful factor while analyzing sensor network as it measures how quickly the sensor nodes will exhaust their batteries [11]. Some nodes in the sensor

network have more congestion than the others, the highly congested nodes are the most important to the the network connectivity. For example, the nodes closer to the base station are essential for the network connectivity. The failure of the highly congested nodes may cause the sensor network to fail even though most of the nodes in the network are alive. Hence, it is desirable to have a lower congestion on the highly congested nodes even though it costs more congestion within the overall sensor network.

To distribute the congestion uniformly across the network, we can construct an aggregation protocol where each node transmits a single payload Defined in 2.3.1 to its parent in the aggregation tree. In this approach, δ is dependent on the given aggregation tree. For example, an aggregation tree shown in Figure 2.1, with n nodes,
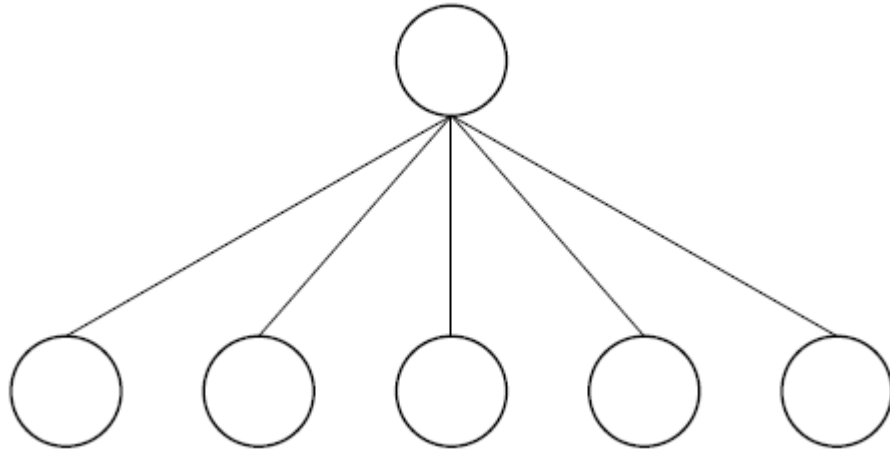
Fig. 2.1.: Star Network

organized in the star tree topology congestion is $O(n)$. And the network organized in the palm tree topology as shown in Figure 2.2 the congestion is $O(1)$. This approach can create some highly congested nodes in the aggregation tree which is undesirable. In most of the real world applications we cannot control δ as the aggregation tree is random. Hence, it is desirable to have uniform distribution of congestion across the aggregation tree.
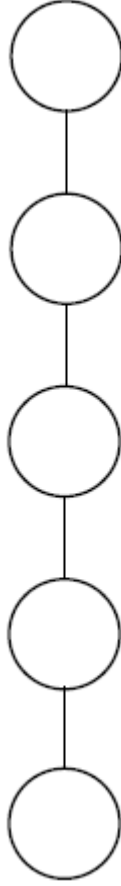
Fig. 2.2.: Palm Tree Network

2.5 Security in Sensor Networks

Here, we depict, what parameters should be taken into account while designing secure protocol for sensor networks. And how those parameters constrains protocol designer's choices of the protocol. Then we depict how data-aggregation can help overcome some of those limitation and some examples where security is ignored by making some strong network assumptions.

2.5.1   Physical Limitations

Sensor nodes are often deployed in open, hostile and unattended environments, so they are vulnerable to physical tampering due to the lower physical security. An adversary can obtain the confidential information from a compromised sensor and reprogram it with malicious software. The compromised node may then report an arbitrary false sensor readings to its parent node in the tree hierarchy, causing the final aggregation result to far deviate from the true aggregate result. This attack becomes more damaging when multiple adversaries succeeds in injecting false data into the network which may cause catastrophic consequences [12].

2.5.2   Hardware Limitations

As far as we know, one of the first hardware platform for developing sensor network application is MICA [13] developed by University of Berkeley. Another popular platform is Mote from Intel [14]. Due to lower manufacturing cost of sensor nodes, they have low speed processor, limited storage, a short range trans receiver. For example, the major specifications for the latest ZigBee chip supporting IEEE 802.15.4 standard, CC2538 from TexasInstruments are shown in Table 2.1. This chip can do most of the security algorithms but has really little amount of memory storage. It has limited output power which constraints its transmission range which forces us to use multi-hop routing in the network as one node can not communicate with the node outside of its transmission range. This hardware limitations constrains protocol designer's choice of algorithms for applications.

2.5.3   Transmission Medium

In sensor networks, a group of sensor nodes (or processors) communicate over the radio (e.g., Bluetooth, WLAN). Traditionally, wireless medium has the issues of in synchronization, hidden station and expose station terminal problems, distributed

	CC2538
Device Type	Wireless Micro controller
Frequency	2.4GHz
Processor Integration	ARM Cortex-M3
Flash	Up to 512 KB
RAM	Up to 32 KB
Security	AES-128/256;ECC-128/256; SHA2; RSA
RX Current	20 (mA)
Output Power	7 (dBm)
Data Rate(Max)	250 kbps
Type of Battery	AAA; AA; Rechargable(Li-ION)

Table 2.1.: System-on-Chip specifications for IEEE 802.15.4 from TexasInstruments

arbitration, directional antennas, bandwidth limitations, higher error rate, security, scalability etcetera. For example, wireless network has approximately 10^6 times higher bit error rate (BER) than wired network which causes frequent link loss and then path loss. Hence, making unstable routing in the network. Higher BER creates higher collision rate in the network, generating higher overhead of retransmission and lowering the channel utilization and the throughput of the network. This kind of transmission medium with constrained resources makes it challenging to design the secure data-aggregation protocol for sensor networks.

2.5.4   Mobility

As we know, sensor nodes communicate via radio and the availability of the transmission medium changes over time due to link failure, bandwidth limitations or change in network topology. Nodes may be able to move, which further contributes to the instability of the communication link. The mobility issue makes difficult to do the

routing in the network with the directional antennas in place. It also requires network to be agile enough to do the reconfiguration for the newer network topology. It impedes whiled doing the quality of service in the network. All these parameters combined contributes to making strong assumptions on the network topology while designing the secure data aggregation protocol for sensor networks.

2.5.5 In-network Data Aggregation

Designing secure data aggregation protocol for the wireless sensor network poses a numerous challenges due to resource limitations and inherent characteristics discussed in the previous subsections. One widely used approach to overcome the bandwidth limitation is to use in-network data aggregation. In-network data aggregation approach saves bandwidth by transmitting less payloads between sensor nodes. But that empowers an intermediate aggregate sensor nodes in the network by allowing it to control certain part of the network. For example, a malicious intermediate sensor node who does aggregation over all of its descendants payloads, needs to tamper with only one aggregated payload instead of tampering with all the payloads received from its descendants. Thus, a malicious intermediate sensor node needs to do less work to skew the final aggregated payload. An adversary controlling few sensor nodes in the network can cause the network to return unpredictable payloads, making an entire sensor network unreliable. Notice that the more descendants an intermediate sensor node has the more powerful it becomes.

Despite the fact that in-network aggregation makes an intermediate sensor nodes more powerful, some aggregation approaches requires strong network topology assumptions or honest behaviors from the sensor nodes. For example, in-network aggregation schemes in [11,15] assumes that all the sensor nodes in the network are honest. Secure Information Aggregation (SIA) of [16], provides security for the network topology with a single-aggregator model. Secure hierarchical in-network aggregation (SHIA) in sensor networks [17] presents the first and provably secure sensor network

data aggregation protocol for general networks and multiple adversaries. We discuss the details of the protocol in the next chapter. SHIA limits the adversary's ability to tamper with the aggregation result with the tightest bound possible but it does not help detecting an adversary in the network. Also, we claim that same upper bound can be achieved with compact label format defined in the next chapter.

3. NETWORKING AND CRYPTOGRAPHY TOOLS

Here we describe the networking and cryptographic tools used in this protocol. For example, we describe the Hash function, its properties and how it helps us achieve data integrity.

3.1   Hash Function

A hash function takes a message as its input and outputs a fixed length message called hash code. The hash code represents a compact image of the message like a digital fingerprint. Hash functions are used to achieve data integrity.

A hash function h should have the following properties:

- Compression - h maps an input x of arbitrary finite bitlength, to an output $h(x)$ of fixed bitlength n.

- Ease of computation - given h, x it is easy to compute $h(x)$.

- Preimage resistance - for all pre-specified outputs, it is computationally infeasible to find any input which hashes to that output, i.e., to find any preimage x' such that $h(x') = y$ when given y for which a corresponding input is not known.

- 2nd-preimage resistance - it is computationally infeasible to find any second input which has the same output as any specified input, i.e, given x, to find a 2nd-preimage $x' \neq x$ such that $h(x') = h(x)$.

- Collision resistance - it is computationally to find any two distinct inputs x, x' which hash to the same output, i.e., such that $h(x) = h(x')$.

We use SHA-256 [18] hash algorithm as a hash algorithm.

3.2 Digital Signatures

A digital signature is a mathematical scheme for demonstrating the authenticity of a digital message. A valid digital signature gives a recipient reason to believe that the message was created by a known sender, such that the sender cannot deny having sent the message (authentication and non-repudiation) and that the message was not altered in transit (integrity). A Digital Signature scheme consists of the following:

1. a plain text message space $\mathcal{M}$ (set of strings over alphabets)

2. a signature space $\mathcal{S}$ (set of possible signatures)

3. a signing key space $\mathcal{K}$ (set of possible keys for signature generation) and a verification space $\mathcal{K}'$ (a set of possible verification keys)

4. an efficient key generation algorithm $\mathsf{Gen} : N \to \mathcal{K} \times \mathcal{K}'$

5. an efficient signing algorithm $\mathsf{Sign} : \mathcal{M} \times \mathcal{K} \to \mathcal{S}$

6. an efficient verification algorithm $\mathsf{Verify} : \mathcal{S} \times \mathcal{M} \to \{\text{true, false}\}$

cite Book for slides

For any secret key $s_k \in \mathcal{K}$ and any $m \in \mathcal{M}$, the message m is signed using key s_k as follows:

$$s = \mathsf{Sign}_{s_k}(m) \tag{3.1}$$

For any s_k let p_k denote public key and for all $m \in \mathcal{M}$ and $s \in \mathcal{S}$, s as follows:

$$\mathsf{Verify}_{p_k}(m,s) = \begin{cases} \textbf{true} \text{ with probability of 1} & if \ \ s = \mathsf{Sign}_{s_k}(m) \\ \textbf{false} \text{ with overwhelming probability} & if \ \ s \neq \mathsf{Sign}_{s_k}(m) \end{cases} \tag{3.2}$$

where the probability space is determine by the $\mathcal{M}, \mathcal{S}, \mathcal{K}, \mathcal{K}'$ and perhaps the signing and verification algorithms. The "overwhelming probability" for the signature scheme determines the probability that the scheme allows for a forgery. Note that the Digital Signature scheme satisfies the following requirements:

- Only the owner of the secret key can generate a valid signature.

- The digital signature is easily verified by other parties.

- The digital signature is not only tied to the signer but also to the message that is being signed.

- Digital signatures cannot be separated from the message and attached to another message.

- Digital signatures do not encrypt the message. However, if necessary, a signed message can be encrypted after it is signed.

The Figure 3.1 from [19], shows the steps for signing and verifying the hashed message. The message is hashed before its being signed to reduce the message size. If
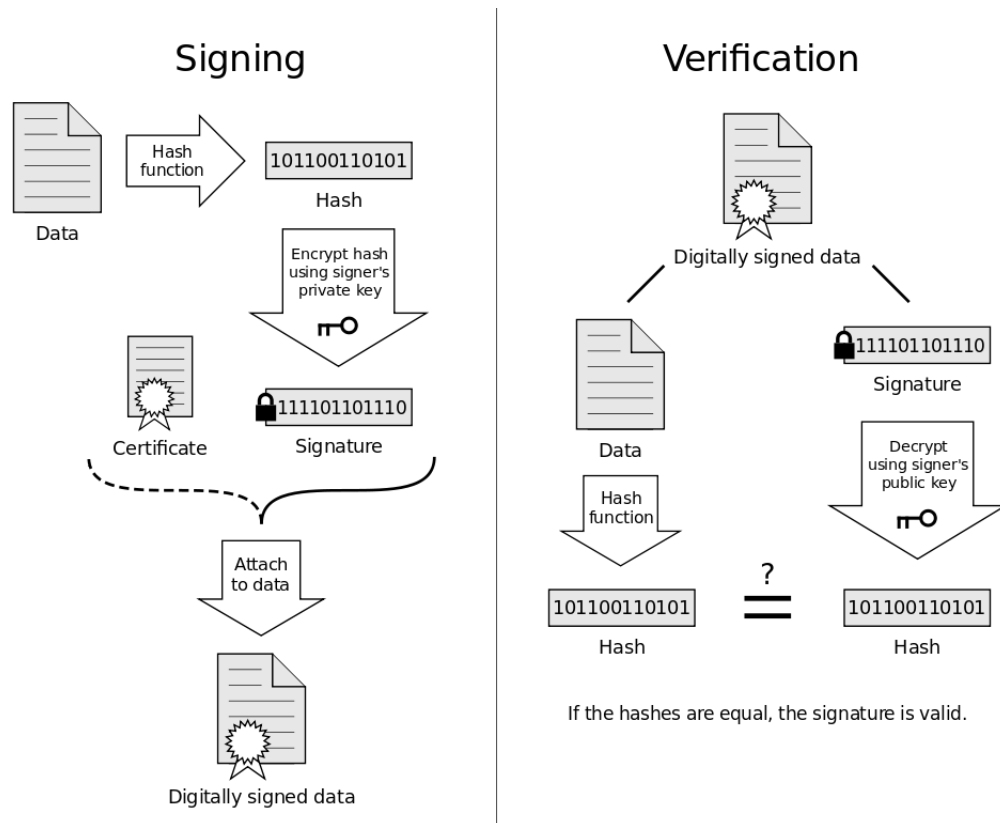

Fig. 3.1.: Signing and verification of digital signatures

the message is not hashed before signing then the signature can be longer than the message which is problematic for the longer messages.

3.3   Tree generation algorithms

3.4   XOR function

3.5   Elliptic curve

4. SECURE HIERARCHICAL IN-NETWORK DATA AGGREGATION

Our work enhances Secure Hierarchical In-Network Data Aggregation (SHIA) protocol of [17] by making it communication efficient, adding new capabilities to the protocol, achieving similar security goals with non-resilient aggregation functions and efficient way of analyzing the protocol. In this chapter, we summarize the important parts of SHIA protocol and relevant terms, to build the foundation to describe our protocol in the following chapters.

SHIA computes aggregate functions (such as *truncated SUM, AVERAGE, COUNT,* $\Phi - QUANTILE$) of the sensed values by the sensor nodes. For example, a network with 5 nodes having the following sensor readings $10, 11, 8, 15, 12$ has the overall all sum of 56, the average of 11.2 and the median ($\Phi = 0.5$) of 11. The goal of the SHIA is to compute the aggregate functions while assuming that partially a network is controlled by an adversary which is attempting to skew the final aggregated result.

4.1 Network Assumptions

We assume a multi hop network with a set $S = \{s1, ..., s_n\}$ of n sensor nodes where all n nodes are alive and reachable. The network is organized in a rooted tree topology. The trusted base station resides outside of the network and has more computation, storage capacity then the sensor nodes in the network. **Note**: SHIA names the base station as the querier and the root of the tree as the base station. The base station knows total number of sensor nodes n in the network and the network topology. It also has the capacity to directly communicate with every sensor node in the network using authenticated broadcast. All the wireless communications between the nodes is peer-to-peer and we do not consider the local wireless broadcast.

Each sensor node has a unique identifier s and shares a unique secret symmetric key K_s with the base station. The keys enable message authentication, and encryption if the data confidentiality is required. All the sensor nodes are capable of doing symmetric key encryption and symmetric key decryption. They are also capable of computing collision resistant cryptographic hash function H (SHA-256) [18].

4.2 Attacker Model

We consider a model with a polynomially bounded adversary of [16], which has a complete control over some of the sensor nodes in the network. Most significantly, the adversary can change the measured values reported by sensor nodes under its control. An adversary can perform a wide variety of attacks. For example, an adversary could report fictitious values (probably completely independent of the measured reported values), instead of the real aggregate values and the base station receives the fictitious aggregated information. Since in many applications the information received by the base station provides a basis for critical decisions, false information could have ruinous consequences. However, we do not want to limit ourselves to just a few specific selected adversarial models. Instead, we assume that the adversary can misbehave in any arbitrary way, and the only limitations we put on the adversary are its computational resources (polynomial in terms of the security parameter) and the fraction of nodes that it can have control over. We focus on **stealthy attacks** [16], where the goal of an adversary is to make the base station accept false aggregation results, which are significantly different from the true results determined by the measured values, while not being detected by the base station. In this setting, denial-of-service (DoS) attacks such as not responding to the queries or always responding with negative acknowledgment at the end of verification phase clearly indicates to the base station that something is wrong in the network and therefore is not a stealthy attack. One of the security goals of SHIA is to detect the stealthy attacks. And one of the

security goals of our work is to detect an adversary who caused the stealthy attacks and remove it from the network to prevent these attacks in the future.

4.3 Resilient and Non-Resilient Aggregate Functions

Wagner [20] uses statistical estimation theory to quantify the effects of direct data injection on various aggregates functions. To understand Wagner's work we define following terms.

Definition 4.3.1 *According to [17], each sensor node s_i has a data value a_i assuming that all the data values are non-negative bounded by real value $a_i \in [0, r]$, where r is the maximum allowed data value. The objective of the* **aggregation process** *is to compute some function f over all the data values, i.e., $f(a_1, \ldots, a_n)$.*

Definition 4.3.2 *According to [17], a* **direct data injection** *attack occurs when an adversary modifies the data readings reported by the nodes under its direct control, under the constraint that only legal readings in $[0, r]$ are reported.*

An **estimator** is an algorithm $f : \mathbb{R}^n \to \mathbb{R}$ where $f(x_1, \ldots, x_n)$ is intended as an estimate of some real valued function of θ. We assume that θ is real valued and that we wish to estimate θ itself. Next, we define $\widehat{\Theta} := f(X_1, \ldots, X_n)$, where $X_1, \ldots, X_n$ are n random variables. We can define the root-mean-square(r.m.s) error (at θ):

$$rms(f) := \mathbb{E}[(\widehat{\Theta} - \theta)^2 | \theta]^{1/2} \tag{4.1}$$

Wagner in [20] defines **resilient estimators and resilient aggregation** as follows. A k-node attack A is an algorithm that is allowed to change up to k of the values $X_1, \ldots, X_n$ before the estimator is applied. In particular, the attack A is specified by a function $\tau_A : \mathbb{R}^n \to \mathbb{R}^n$ with the property that the vectors x and $\tau_A(x)$ never differ at more than k positions. We can define the root mean square(r.m.s) error associated with A by

$$rms^*(f, A) := \mathbb{E}[(\widehat{\Theta}^* - \theta)^2 | \theta]^{1/2} \tag{4.2}$$

where $\widehat{\Theta}^* := f(\tau_A(X_1, \ldots, X_n))$. To explain, $\widehat{\Theta}^*$ is a random variable that represents the aggregate calculated at the base station in the presence of the k-node attack A, and $rms^*(f, A)$ is a measure of inaccuracy of the aggregate after A's intrusion. If $rms^*(f, A) >> rms(f)$, then the attack has succeeded in noticeably affecting the operation of the sensor network. If $rms^*(f, A) \approx rms(f)$, the attack had little or no effect. We define

$$rms^*(f, k) := max\{rms^*(f, A) : A \ is \ a \ k - node \ attack\} \qquad (4.3)$$

so that $rms^*(f, k)$ denotes the r.m.s. error of the most powerful k-node attack possible. Note that $rms^*(f, 0) = rms(f)$. We think of an aggregation function f as an instance of the resilient aggregation paradigm if $rms^*(f, k)$ grows slowly as a function of k.

Definition 4.3.3 *According to [20], an aggregation function f is (k, α)-**resilient** (with respect to a parameterized distribution $p(X_i|\theta)$) if $rms^*(f, k) \leq \alpha \cdot rms(f)$ for the estimator f.*

The intuition is that the (k, α)-resilient functions, for small values of α, are the ones that can be computed meaningfully and securely in the presence of up to k compromised or malicious nodes. His work is summarized in the Table 4.1. According to this quantitative study measuring the effects of direct data injection on various aggregates, concludes that the **aggregates (truncated SUM and AVERAGE) can be resilient** under such attacks.

4.4 Security Goal

Without precise knowledge of application, the direct data injection attacks are indistinguishable from the malicious sensor readings. The goal of SHIA is to design an **optimally secure** aggregation algorithm with only **sublinear edge congestion**.

Definition 4.4.1 *According to [17], an aggregation algorithm is **optimally secure** if, by tampering with the aggregation process, an adversary is unable to induce the*

Aggregate(f)	Security Level
minimum	insecure
maximum	insecure
sum	insecure
average	insecure
count	acceptable
$[l, u]$-truncated average	problematic
5% -trimmed average	better
median	much better

Table 4.1.: Summary of Wagner's work

base station to accept any aggregation result which is not already achievable by direct data injection.

4.5   The SUM Aggregate Algorithm

In this algorithm, the aggregate function f is summation meaning that we want to compute $a_1 + a_2 + \ldots + a_n$, where a_i is the sensed data value of the node i. This algorithm has three main phases:

- Query dissemination - initiates the aggregation process

- Aggregate commit - initiates the commitment tree generation process

- Result checking - initiates the distributed, interactive verification process

4.6   Query dissemination

Prior to this phase, an aggregation trees is created using a tree generation algorithm. We can use any tree generation algorithm as this protocol works on any

aggregation tree structure. For completeness of this protocol, one can use Tiny Aggregation Service (TaG) [9]. TaG uses broadcast message from the base station to initiate a tree generation. Each node selects its parent from whichever node it first receives the tree formation message. One possible aggregation tree for given network graph in Figure 4.1 is shown in Figure 4.2.

Fig. 4.1.: Network graph

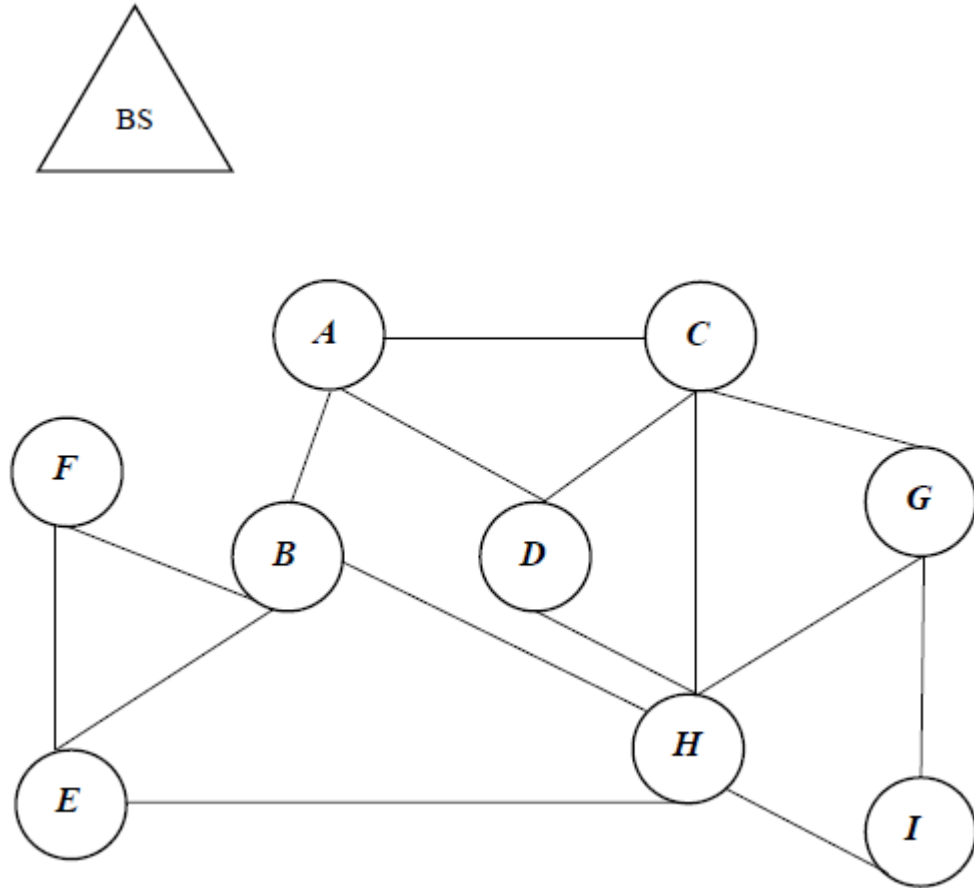To initiate the query dissemination phase, the base station broadcasts the query request message with the query nonce N in the aggregation tree. The query request message contains new query nonce N for each query to prevent replay attacks in the network. It is very important that the same nonce is never re-used by the base station. $SHIA$ uses **hash chain** to generate new nonce for each query. A hash

chain is constructed by repeatedly evaluating a pre-image resistant hash function h on some initial random value, the final value (or "anchor value") is preloaded on the nodes in the network. The base station uses the pre-image of the last used value as the nonce for the next broadcast. For example, if the last known value of the hash chain is $h^i(X)$, then the next broadcast uses $h^{i-1}(X)$ as the nonce; X is the initial random value. When a node receives a new nonce N', it verifies that N' is a precursor to the most recently received (and authenticated) nonce N on the hash chain, i.e., $h^i(N') = N$ for some i bounded by a fixed k of number of hash applications. A hash chain prevents an adversary from predicting the query nonce for future queries as it has to reverse the hash chain computation to get an acceptable pre-image.
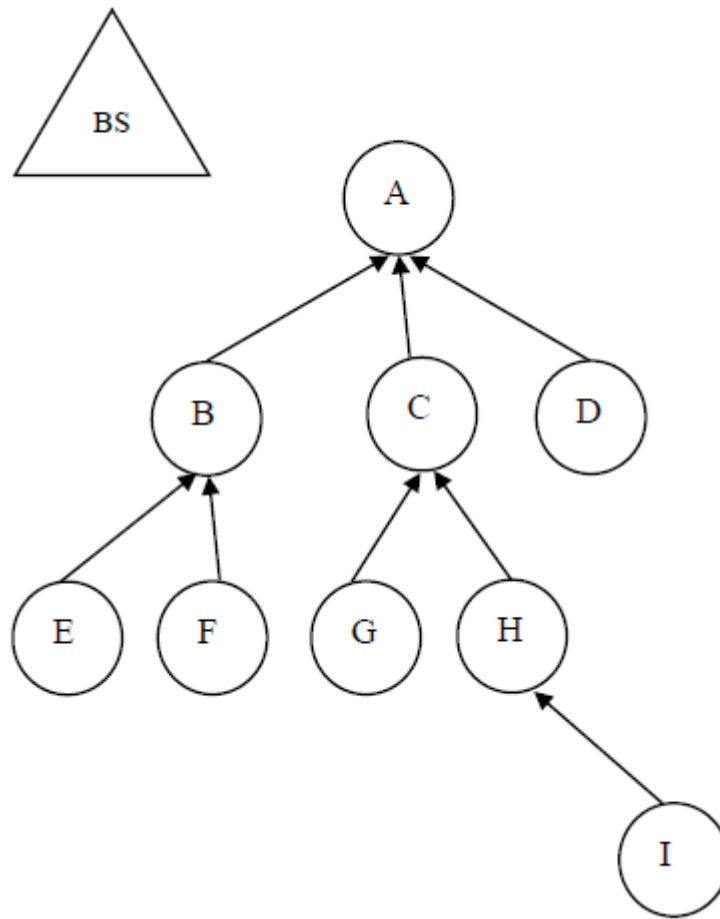

Fig. 4.2.: Aggregation tree for network graph in Figure 4.1

4.7   Aggregate commit

The aggregate commit phase constructs cryptographic commitments to the data values and to the intermediate in-network aggregation operations. These commitments are then passed on to the base station by the root of an aggregation tree. The base station then rebroadcasts the commitments to the sensor network using an authenticated broadcast so that the rest of the sensor nodes in the network can verify that their respective data values have been incorporated into the final aggregate value.

4.7.1   Aggregate commit: Naive Approach

In the naive approach, during aggregation process each sensor node computes a cryptographic hash of all its inputs (including its own data value). The aggregation result along with the hash value called a label, is then passed on to the parent in the aggregation tree. The label is format is described in Definition 4.7.1. Figure 4.3 shows a commitment tree for the aggregation tree shown in Figure 4.2. Conceptually, a commitment tree is a logical tree built on top of an aggregation tree, with additional aggregate information attached to the nodes to help in the result checking phase.

Definition 4.7.1 *[17] A commitment tree is a tree where each vertex has an associated label representing the data that is passed on to its parent. The labels have the following format:*

$$<count,\ value,\ complement,\ commitment>$$

Where count is the number of leaf vertices in the subtree rooted at this vertex; value is the SUM aggregate computed over all the leaves in the subtree; complement is the aggregate over the COMPLEMENT of the data values; and commitment is a cryptographic commitment.

There is one leaf vertex u_s for each sensor node s, which we call the leaf vertex of s. The label of u_s consists of count = 1, value = a_s where a_s is the data value of
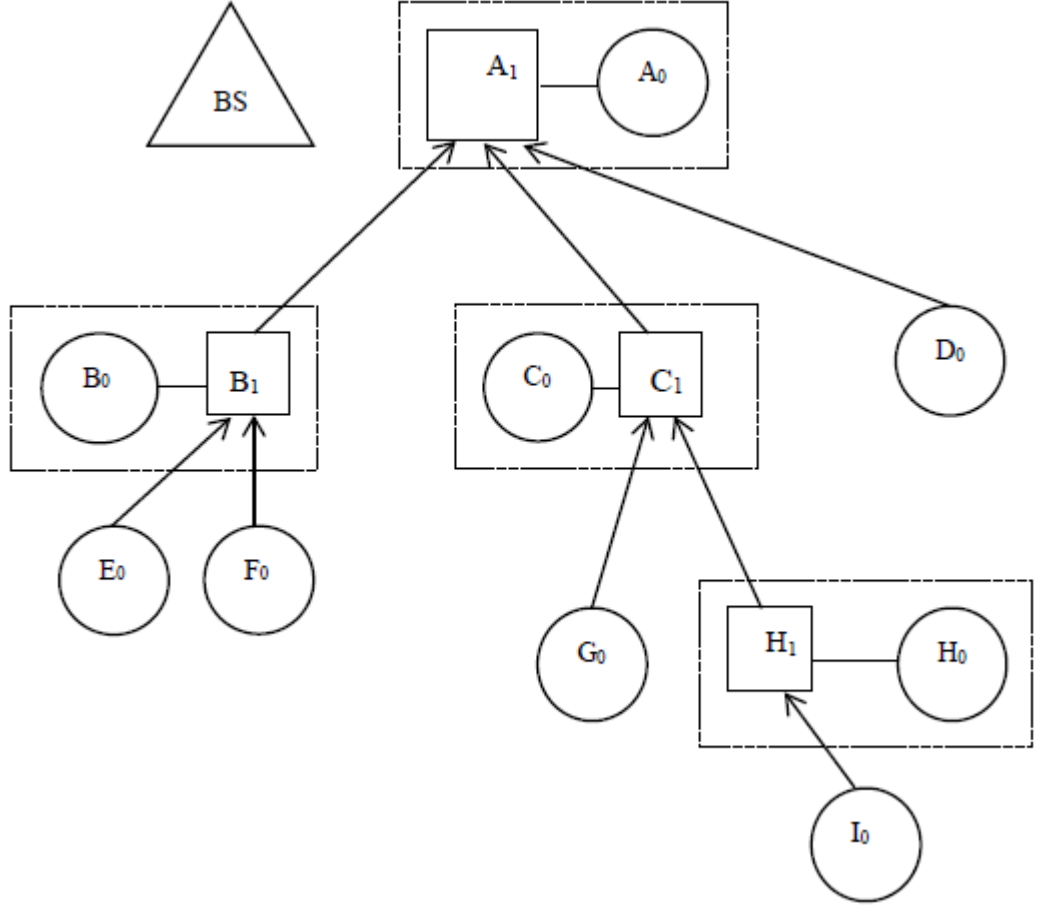
Fig. 4.3.: Naive commitment tree for Figure 4.2. For each sensor node s, s_0 is its leaf vertex, while s_1 is the internal vertex representing the aggregate computation at s (if any). The labels of the vertices on the path of node I to the root are shown from Equation 4.4 to 4.8.

s, complement $= r - a_s$ where r is the upper bound on allowable data values, and commitment is the nodes unique ID.

Internal vertices represent aggregation operations, and have labels that are defined based on their children. Suppose an internal vertex has child vertices with the following labels: u_1, u_2, ... , u_q, where $u_i = <c_i, v_i, \bar{v}_i, h_i>$. Then the vertex has label $<c,$

v, $\bar{v}$, h>, with $c = \sum c_i$, $v = \sum v_i$, $\bar{v} = \sum \bar{v}_i$ and $h = H[N||c||v||\bar{v}||u_1||u_2||\ldots||u_q]$. The labels of the vertices of the commitment tree of Figure 4.3 are shown below.

$$I_0 = < 1, a_I, r - a_I, I > \tag{4.4}$$

$$H_1 = < 2, v_{H_1}, r - v_{H_1}, H[N||2||v_{H_1}||v_{\bar{H}_1}||H_0||I_0] > \tag{4.5}$$

$$B_1 = < 3, v_{B_1}, r - v_{B_1}, H[N||3||v_{B_1}||v_{\bar{B}_1}||B_0||E_0||F_0] > \tag{4.6}$$

$$C_1 = < 4, v_{C_1}, r - v_{C_1}, H[N||4||v_{C_1}||v_{\bar{C}_1}||C_0||G_0||H_1] > \tag{4.7}$$

$$A_1 = < 9, v_{A_1}, r - v_{A_1}, H[N||9||v_{A_1}||v_{\bar{A}_1}||A_0||D_0||B_1||C_1] > \tag{4.8}$$

The word vertices is used for the nodes in the commitment tree and the word node is used for the nodes in the aggregation tree. There is a mapping between the nodes in the aggregation tree and the vertices in the commitment tree, a vertex is a logical element in the commitment tree where as the node is a physical sensor node which does all the communications. The collision resistant hash function makes it impossible for an adversary to change the commitment structure once it is sent to the base station. Our payload format is compact than the label format which is discussed in the next chapter.

4.7.2 Aggregate commit: Improved approach

The aggregation tree is a subgraph of the network graph so it may be randomly unbalanced. This approach tries to separate the structure of the commitment tree from the structure of the aggregation tree. So, the commitment tree can be perfectly balanced.

In the naive approach, each sensor node always computes the aggregate sum of all its inputs which is a greedy approach. SHIA uses delayed aggregation approach, which performs an aggregation operation if and only if it results in a complete, binary commitment tree.

We now describe SHIA's delayed aggregation algorithm for producing balanced commitment trees. In the naive commitment tree, each sensor node passes to its

parent a single message containing the label of the root vertex of its commitment subtree T_s. In the delayed aggregation algorithm, each sensor node passes on the labels of the root vertices of a set of commitment subtrees $F = \{T_1, \ldots, T_q\}$. We call this set a commitment forest, and we enforce the condition that the trees in the forest must be complete binary trees, and no two trees have the same height. These constraints are enforced by continually combining equal-height trees into complete binary trees of greater height.

Definition 4.7.2 *[17] A commitment forest is a set of complete binary commitment trees such that there is at most one commitment tree of any given height.*

The commitment forest is built as follows. Leaf sensor nodes in the aggregation tree originate a single-vertex commitment forest, which they then communicate to their parent sensor nodes. Each internal sensor node s originates a similar single-vertex commitment forest. In addition, s also receives commitment forests from each of its children. Sensor node s keeps track of which root vertices were received from which of its children. It then combines all the forests to form a new forest as follows. Suppose s wishes to combine q commitment forests $F_1, \ldots, F_q$. Note that since all commitment trees are complete binary trees, tree heights can be determined by inspecting the count field of the root vertex. We let the intermediate result be $F = F_1 \cup \ldots \cup F_q$, and repeat the following until no two trees are the same height in F. Let h be the smallest height such that more than one tree in F has height h. Find two commitment trees T_1 and T_2 of height h in F, and merge them into a tree of height $h + 1$ by creating a new vertex that is the parent of both the roots of T_1 and T_2 according to the inductive rule in Definition 4.7.1.

Example 4.7.1 *The commitment-forest generation process for node A of Figure 4.2 is shown here.*
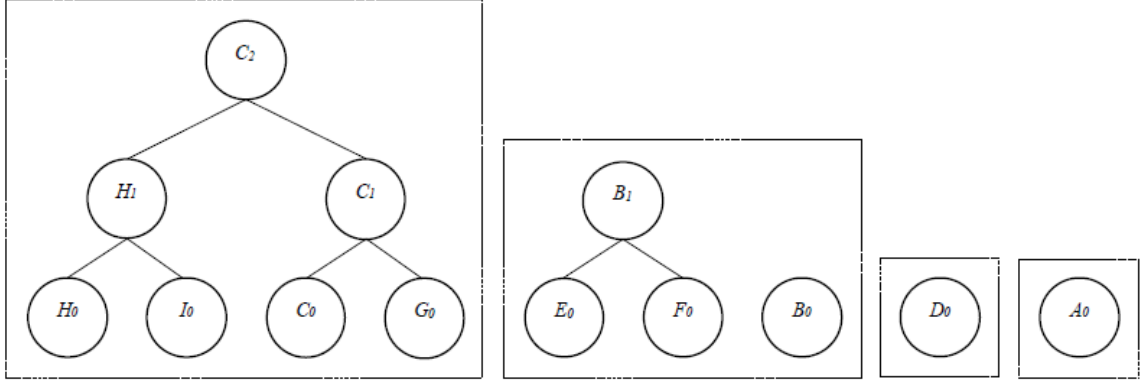
Fig. 4.4.: A receives C_2 from C, (B_1, B_0) from B, D_0 from D and generates A_0. The commitment forest received from a given sensor node is indicated by dashed-line box.

$$A_0 =< 1, a_A, r - a_A, A >$$
$$D_0 =< 1, a_D, r - a_D, D >$$
$$E_0 =< 1, a_E, r - a_E, E > \qquad (4.9)$$
$$B_1 =< 2, v_{B_1}, v_{\bar{B_1}}, H(N||2||v_{B_1}||v_{\bar{B_1}}||B_0||F_0) >$$
$$C_2 =< 4, v_{C_2}, v_{\bar{C_2}}, H(N||4||v_{C_2}||v_{\bar{C_2}}||H_1||C_1) >$$
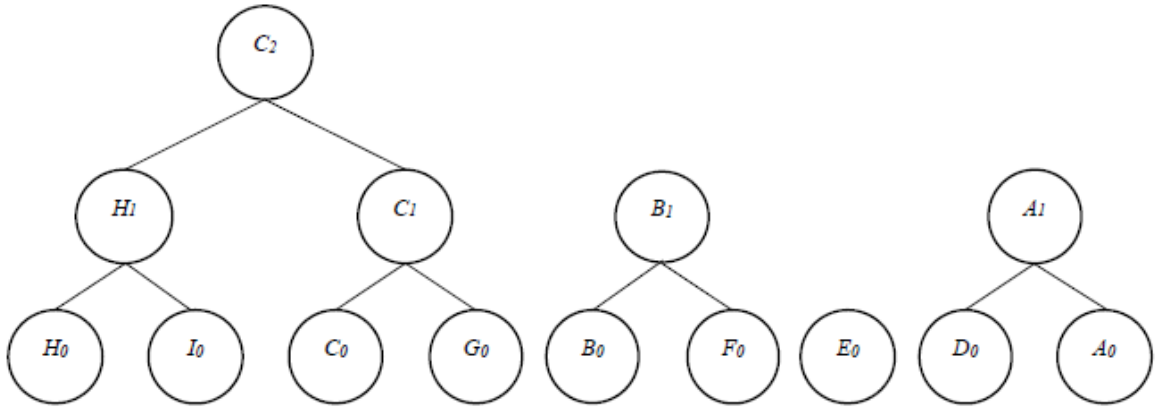
Fig. 4.5.: First Merge: A_1 vertex created by A.

$$A_1 = < 2, v_{A_1}, v_{\bar{A}_1}, H(N||2||v_{A_1}||v_{\bar{A}_1}||A_0||D_0) >$$

$$v_{A_1} = a_A + a_D; v_{\bar{A}_1} = r - a_A + r - a_D$$

(4.10)
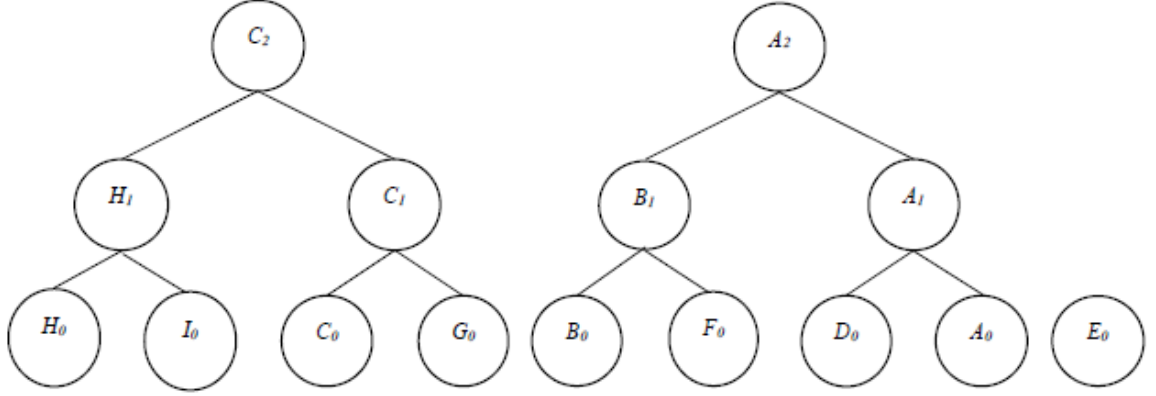
Fig. 4.6.: Second Merge: A_2 vertex created by A.

$$A_2 = < 4, v_{A_2}, v_{\bar{A}_2}, H(N||4||v_{A_2}||v_{\bar{A}_2}||B_1||A_1) >$$

$$v_{A_2} = v_{A_1} + v_{B_1}; v_{\bar{A}_2} = r - v_{A_1} + r - v_{B_1}$$

(4.11)
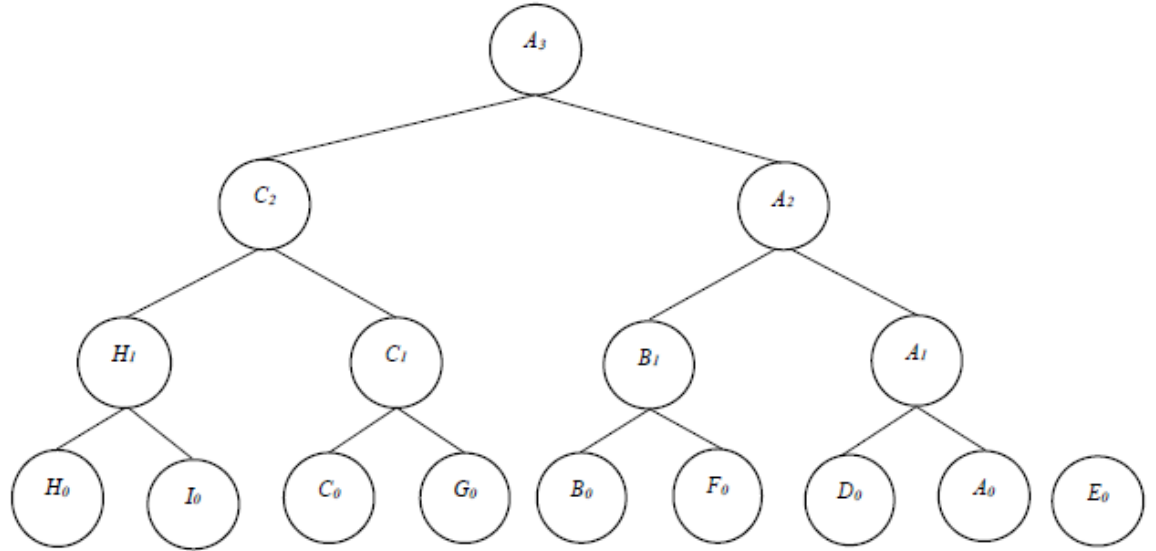
Fig. 4.7.: Third Merge: A_3 vertex created by A.

$$A_3 = < 8, v_{A_3}, v^-_{A_3}, H(N||8||v_{A_3}||v^-_{A_3}||C_2||A_2) >$$

$$v_{A_3} = v_{A_2} + v_{C_2}; v^-_{A_3} = r - v_{A_2} + r - v_{C_2}$$

$$(4.12)$$

4.8 Result checking

SHIA presents novel distributed verification algorithm achieving provably optimal security while maintaining sublinear edge congestion. In our work, we take similar approach and add new capabilities to help find an adversary. Here, we describe the SHIA's result checking phase to build the basis for our work. The purpose of the result checking phase is to enable each sensor node s to independently verify that its data value as was added into the SUM aggregate, and the complement $(r - a_s)$ of its data value was added into the COMPLEMENT aggregate. First, the aggregation results from the aggregation-commit phase are sent by the base station using authenticated broadcast to every sensor node in the network. Each sensor node then individually verifies that its contributions to the respective SUM and COMPLEMENT aggregates were indeed counted. If so, it sends an authentication code to the base station. The authentication code is also aggregated for communication efficiency. When the base station has received all the authentication codes, it is then able to verify that all sensor nodes have checked that their contribution to the aggregate has been correctly counted. The result checking process has the following phases.

Dissemination of final commitment values. Once the base station receives final commitment labels from the root of the commitment forest, it sends each of those commitment labels to the entire network using authenticated broadcast. Authenticated broadcast means that the each sensor node can verify that the message was sent by the base station and no one else.

Dissemination of off-path values. Each vertex must receive all of its off-path values to do the verification. The off-path values are defined as follows.

Definition 4.8.1 *[17] The set of off-path vertices for a vertex u in a tree is the set of all the siblings of each of the vertices on the path from u to the root of the tree that u is in (the path is inclusive of u).*
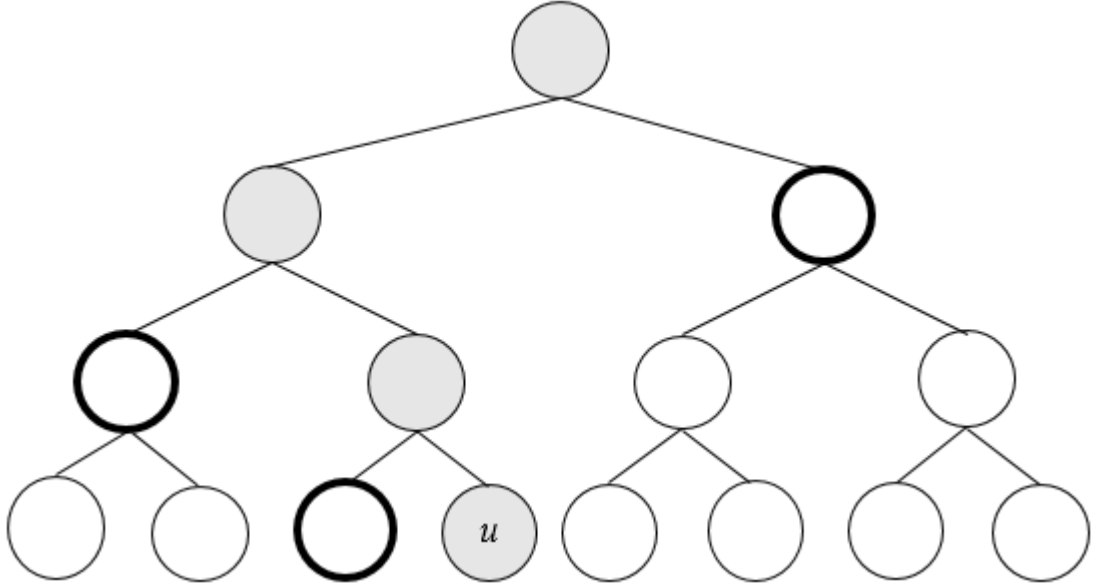

Fig. 4.8.: Off-path vertices from u are highlighted in bold.

Vertex receives its off-path values from its parent. Each internal vertex has two children. For example, an internal vertex k has two children k_1, k_2. k sends the label of k_1 to k_2 and vice versa. k tags the relevant information of its left and right child. Once a vertex receives all of its off-path values it begins a verification phase. **Verification of contribution.** The leaf vertex calculates the root vertex's label using its own label and off-path vertex labels. This allows the leaf to verify that its label was not modified on the path to the root during the aggregation-commit process. Then it compares the the calculated root vertex's label with the label received from the base station via authenticated broadcast. If those two labels match then it proceeds to the next step with ACK message or with NACK message.

Collection of authentication codes. Once each sensor node s does verification of contribution for its leaf vertex v_s it sends the relevant authentication code to the base

station. The authentication code for sensor node s with ACK and NACK message has the following format.

$$MAC_{K_s}(N||ACK) \tag{4.13}$$

$$MAC_{K_s}(N||NACK) \tag{4.14}$$

Where ACK, NACK are unique message identifier for positive acknowledgment and negative acknowledgment respectively, N is the query nonce and K_s is secret key that s shares with the base station. Collection of authentication code starts with the leaf nodes in the aggregation tree. Leaf nodes in the aggregation tree send their authentication codes to their parent. Once the parent node has received the authentication from all of its children it does XOR operation on all the authentication codes including its own authentication code and sends it to its parent in the aggregation tree. Each internal sensor node s in the aggregation tree repeats the process. Finally, the root of an aggregation tree sends a single authentication code to the base station which is an XOR of all the authentication codes of the aggregation tree.

Verification of confirmations. Since the base station knows the key K_s for each sensor node s, it verifies that every sensor node has released its authentication code by computing the XOR of the authentication codes for all the sensor nodes in the network, i.e., $\bigoplus_{i=1}^{n} MAC_{K_i}(N||ACK)$. The base station then compares the computed code with the received code. If the two codes match, then the base station accepts the aggregation result.

Theorem 4.8.1 *[17] Let the final SUM aggregate received by the base station be S. If the base station accepts S, then $S_L \leq S \leq (SL + \mu \cdot r)$ where S_L is the sum of the data values of all the legitimate nodes, μ is the total number of malicious nodes, and r is the upper bound on the range of allowable values on each node.*

The above theorem is proven by SHIA. SHIA achieves security over the truncated SUM which is a resilient aggregator according to Wagner [20]. Our protocol works on SUM which is non-resilient aggregate and achieves the similar security goals.

5. AGGREGATE COMMIT WITH VERIFICATION

The high level idea of the aggregate commit with verification scheme is that all the leaf nodes in the aggregation tree sends the signature of their data-item Defined in 5.2.1, with their signatures signed by themselves. The aggregate node proceeds to the aggregation only after verifying all the received the signatures. The aggregate node also signs its payload in addition to its data-item which is discussed in great detail in the following sections.

5.1 Motivation

In the previous chapter, we saw that SHIA limits the adversary's ability to manipulate the aggregation result with the tightest bound possible. But, SHIA uses truncated sum as an aggregate function which is resilient according to the Wagner [20]. It does not help accurately calculating the sum aggregate. Furthermore, SHIA does not help detecting and revoking the malicious aggregate node from the network. We develop the aggregation protocol which works for any random hierarchical sensor networks with a single or multiple adversaries. The algorithm works on the resilient as well as non-resilient aggregation functions Defined in 4.3.3, without compromising any desired security properties. Our protocol helps identify the malicious aggregate node or nodes in the network who are responsible for it. We want to prevent masquerade attacks in the network to apply this protocol in the voting applications. We want to achieve all these desired security properties by inducing only $O(\delta \log^k n)$ node congestion in the aggregation tree; where n is the number of nodes in the network, δ is the fanout of any node in the aggregation tree, and k is the variable.

5.2 Data-Item

Here, we describe structure of the data-item, how it is different from the label structure of SHIA and rational behind it.

Definition 5.2.1 *A commitment tree is a binary tree where each vertex has an associated data-item representing the data that is passed on to its parent. The data-items have the following format:*

$$< \textbf{\textit{id, count, value, commitment}} >$$

Where *id* is the unique ID of the node; *count* is the number of leaf vertices in the subtree rooted at this vertex; *value* is the SUM aggregate computed over all the leaves in the subtree and *commitment* is a cryptographic commitment.

We remove the *complement* field from the label structure Defined 4.7.1. We think including the complement filed in the label is redundant information. The complement field is used by the base station (the querier according to SHIA), before the result checking phase, to verify $\textbf{SUM} + \textbf{COMPLEMENT} = \textbf{n}\cdot\textbf{r}$; where $\textbf{n}$ is the number of nodes in the network, $\textbf{r}$ is the upper bound on the allowed sensor readings. We can achieve the same upper bound without the complement field. As the querier knows n, r and it gets SUM from the root of the aggregation tree.

If $\textbf{SUM} > \textbf{n} \cdot \textbf{r}$, then the base station knows some node or nodes in the network reported out of range readings.

We include *id* of the node in its data-item. SHIA does not have the ID field in their label structure as they do not do internal verification while creating a commitment tree. In the label format ID of the node is hashed after the first aggregation and virtually gets lost. We do internal verification so it is necessary for any aggregate node to know the ID of all the received data-items in its forest, for the verification of the received signatures.

5.3 Signing the Data-Item

There is one vertex S_0 for each sensor node S, which we call the leaf vertex of S. The data-item for leaf vertex S_0 is defined according to Equation 5.1 and associated signature to it is defined according to Equation 5.2.

$$S_0 \; = \; < S_{id}, 1, S_{value}, H(N||1||S_{value}) > \tag{5.1}$$

$$\mathsf{Sign}_{S_S}(S_0) \tag{5.2}$$

where H is a collision resistant hash function, S_S is the secret key of S, N is the query nonce. In aggregate commit with verification scheme, in addition to sending the data-item, each sensor node sends the signature of the data-item to its parent. The parent node verifies all the received signature and then proceeds to the aggregation.

5.3.1 Security Benefits

- A sensor node has the proof for the sent data-item and can not claim sending the different data-item to its parent in the future.

- Each data-item has an associated signature to it, which helps an aggregate node verify the authenticity of the data-item.

- The parent node has the proof for the received data-item, and can not claim receiving different data-items form its children in the future.

5.4 Signing the Commitment Payload

We define commitment payload based on the commitment forest Defined in 4.7.2.

Definition 5.4.1 *A **commitment payload** is a set of data-items of the root vertices of the trees in the outgoing commitment forest.*

For brevity, we use the term forest, payload instead of commitment forest, commitment payload respectively. In addition to sending all the data-items with their

respective signatures, an aggregate node sends an additional signature to its parent, which is a signature of all the data-items in its payload.

Example 5.4.1 *The aggregation tree shown in Figure 5.1, the payload of sensor node C is show in Figure 5.4. The sensor node C sends all the data-items in its payload*

Fig. 5.1.: Palm aggregation tree

with their signatures to its parent sensor node D. Furthermore, C sends the signature of its payload $Sign_{S_C}(C_0||B_1)$ to D.

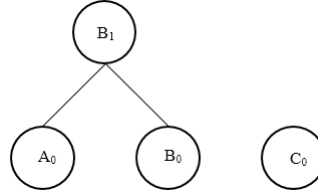Fig. 5.2.: *C*'s commitment commitment-payload

$$B_1 = \ <B_{id}, 2, B_{1value}, H(N||2||B_{1value}||A_0||B_0)>; Sign_{S_B}(B_1)$$
$$C_0 = \ <C_{id}, 1, C_{value}, H(N||1||C_{value})>; Sign_{S_C}(C_0) \qquad (5.3)$$
$$Sign_{S_C}(C_0||B_1)$$

5.4.1 Security Benefits

This additional signature signifies the following:

- An intermediate sensor node has verified all the data-items in its forest before creating its payload.

- From the parent node perspective, it has received all the verified data-items from the signer node and not from anywhere else.

5.5 Re-signing the data-item

If we throw away the old signatures and resign the data-item with current aggregate node then following is true:

- Each parent needs the certificates of only its direct children.

- Each child needs to know the certificate of its parent only.

- Number of signatures remain the same as previous approach.

- Number of certificates needed in the network is $O(n)$; n is the number of nodes in the network.

- We do not need the signature of the payload.

Note that we send signatures while distributing off-path values.

5.6 Commitment Tree Generation

For the given aggregation tree the commitment forest is built as follows. Leaf sensor nodes in the aggregation tree create their leaf vertex by creating data-items and their respective signatures according to Equation 5.1, 5.2 which they send it to their parent as a payload in the aggregation tree. Each internal sensor node I in the aggregation tree also creates their leaf vertex and its signature. In addition, I

receives the payload from each of its children which creates the forest for I. Once I verifies all the received signatures, it merges all the data-items in its forest with same count value to create its payload. Note that we can determine the height of the commitment tree from the count value.

Suppose I have to create its payload by merging i data-items D_1, D_2, ..., D_i in its forest. First, I verifies the received signatures $Sign(D_1)$, $Sign(D_2)$, ..., $Sign(D_i)$. Once verified, I starts merging the data-items as follows. Let c be the smallest count value in I's forest. The sensor node I finds two data-items D_1, D_2 in its forest with the same count value c and merges them into a new data-item with the count of $c+1$ as shown in Figure 5.3.
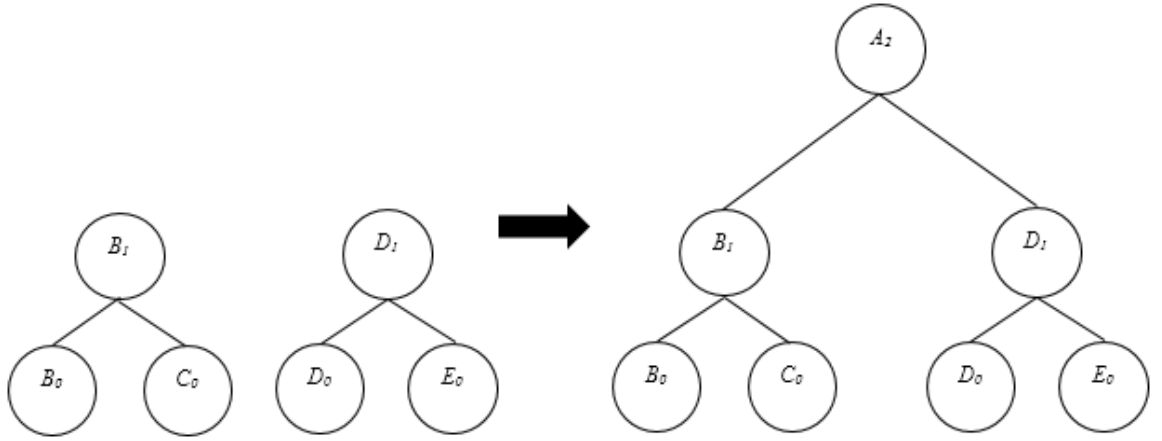

Fig. 5.3.: A has B_1, C_1 in his forest and aggregates those two trees and creates A_2.

It repeats the process until no two data-items in its forest have the same count value. An example of generating the payload by merging the data-items in the forest for the sensor node A in Figure 4.2 is illustrated in the following example.

Example 5.6.1 *The commitment-payload generation process for node A of Figure 4.2 is shown here.*
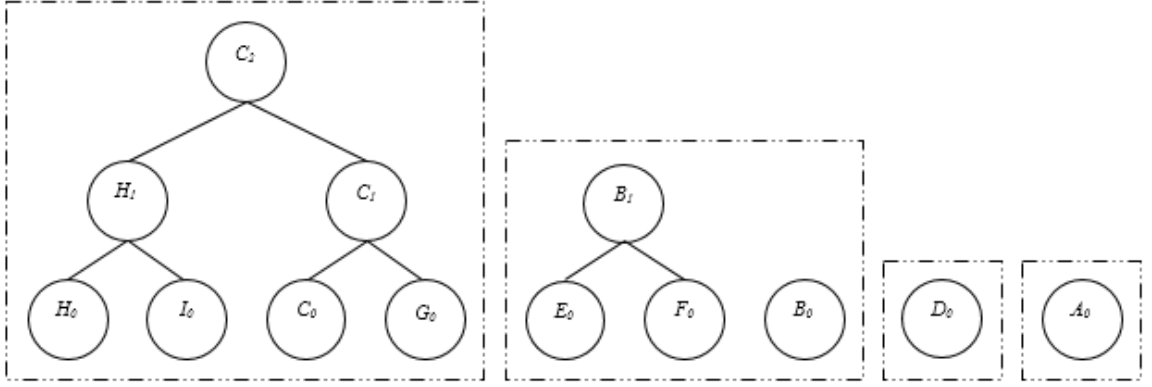
Fig. 5.4.: A receives C_2 from C, (B_1, B_0) from B, D_0 from D and generates A_0. The commitment payload received from a given sensor node is indicated by dashed-line box.

$$A_0 = < A_{id}, 1, A_{value}, H(N||1||A_{value}) >; Sign_{S_A}(A_0)$$
$$D_0 = < D_{id}, 1, D_{value}, H(N||1||D_{value}) >; Sign_{S_D}(D_0)$$
$$B_0 = < B_{id}, 1, B_{value}, H(N||1||B_{value}) >; Sign_{S_B}(B_0)$$
$$B_1 = < B_{id}, 2, B_{value}, H(N||2||B_{value}||E_0||F_0) >; Sign_{S_B}(B_1)$$
$$\textcolor{red}{Sign_{S_B}(B_0||B_1), benefits}$$
$$C_2 = < C_{id}, 4, C_{value}, H(N||4||C_{value})||H_1||C_1) >; Sign_{S_C}(C_2)$$

$$(5.4)$$
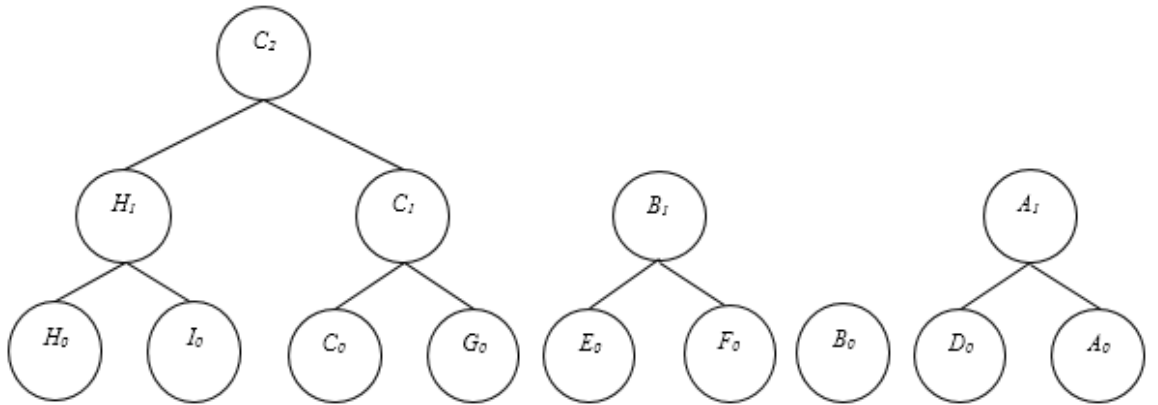
Fig. 5.5.: First Merge: A_1 vertex created by A.

$$A_1 =< A_{id}, 2, A_{1value}, H(N||2||A_{1value}||A_0||D_0) >; Sign_{S_A}(A_1)$$

$$where\ A_{1value} = A_{value} + D_{value}$$

(5.5)

Fig. 5.6.: Second Merge: A_2 vertex created by A.

$$A_2 =< A_{id}, 4, A_{2value}, H(N||4||A_{2value}||B_1||A_1) >; Sign_{S_A}(A_2)$$
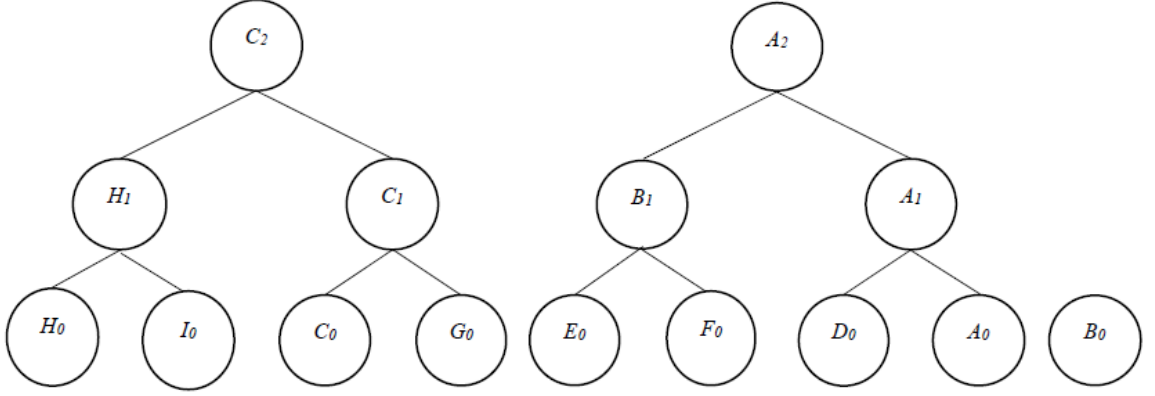
$$where\ A_{2value} = B_{1value} + A_{1value}$$

(5.6)
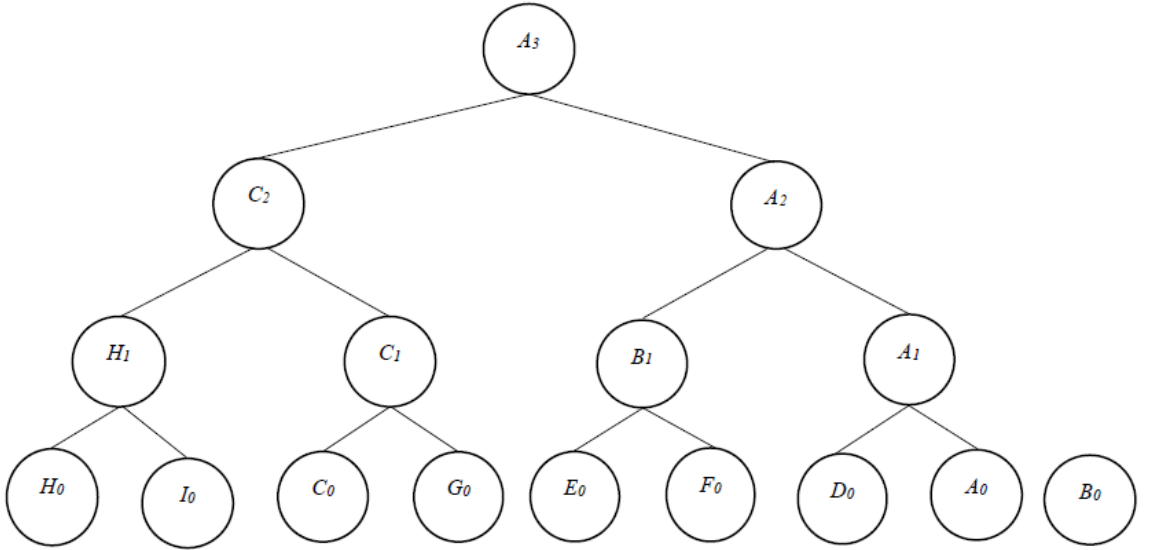
Fig. 5.7.: Third Merge: A_3 vertex created by A.

$$A_3 = < A_{id}, 8, A_{3value}, H(N||8||A_{3value}||C_2||A_2) >; \textbf{Sign}_{S_A}(A_3)$$
$$where \ A_{3value} = A_{2value} + C_{2value}$$

(5.7)

5.7 Bandwidth Analysis

For any given sensor node's forest with n leaf vertices, has at most $\log n$ data-items in its payload. It has at most $(\log n) + 1$ signatures in its payload. The highest possible count value is $\log n$, as all the trees are binary.

An intermediate sensor node S with β descendants in the aggregation tree, has at most $\log(\beta+1)$ data-items with their respective $\log(\beta+1)$ signatures in its payload. S might need to send its payload signature $Sign(S_p)$. At max, S has to send a payload with $\log(\beta+1)$ data-items and $\log(\beta+1)+1$ signatures to its parent in the aggregation tree.

Hence, sending signatures of the data-items causes $O(\log \beta)$ bandwidth overhead for each node in the network, where β is the number of descendants of the sensor node.

5.8 Performance Analysis

In addition to calculating its own data-items, all intermediate sensor nodes with β descendants and ζ direct children need to do the following:

- To calculate and verify $O(\log \beta)$ signatures, creating $O(\log \beta)$ calculation overhead.

- Needs sufficient memory to cache $O(\log \beta)$ certificates.

- Needs enough memory to cache $\Omega(\zeta)$ certificates.

5.9   Applications

The signature based aggregation scheme can be applied to do the **voting** in the network. And voting scheme can be used to solve many sensor network problems. For example, voting can be used to design the distributed algorithm for selecting a cluster head or node revocation system. In the voting scheme, following are the major security concerns:

- The aggregate node needs to know that the vote is coming from the legit voter, no other voter is impersonating the vote of the legit voter.

- Only the intended aggregate node should be able to verify the vote.

- The aggregate node should not be able to tamper with the votes.

- The aggregate node needs the proof that it aggregated the verified votes.

- The voter need the proof for which vote it sent to its aggregator.

For example, the base station wants to know the overall vote-count in the network. To do so, all the leaf nodes send their votes and the signature of their votes to their respective aggregate nodes in the network. The aggregate nodes receive votes with their signatures from all of their children voters. The aggregate nodes verify all the votes and count those votes. Then they forward the count and the signature of that count signed by the aggregate node to their respective parent in the aggregation tree. This process is repeated until the final count and its signature, is sent to the base station by the root of the aggregation tree.

Node power level, **Surveillance Application**

6. CHEATING ANALYSIS

This chapter describes what does it mean to cheat a secure aggregation algorithm. It depicts detailed examples in which an adversary tries different ways of cheating but fails to do so because of the commitment and signatures.

6.1 Introduction

To discuss different ways of cheating first we define the cheating as follows:

Definition 6.1.1 *A sensor node tampering with the data-item to skew the final aggregate data-item without being detected is consider as* **cheating**.

Because of the way an aggregate commit algorithm works, an aggregate node has the highest power to do the cheating as described in Section 2.5. The aggregate node gains more power to cheat as it climbs up in the aggregation tree hierarchy. An aggregate node can cheat at the following phases:

- During commitment tree generation phase

- During dissemination of off-path phase

- At both phases together (the most powerful attack possible)

We can detect a cheating activity with the help of the commitment field in the data-item as shown in Example 6.1.1. But the commitment field is not enough to detect an adversary. And to identify an adversary we need the help from the base station and the signature infrastructure created in the network.
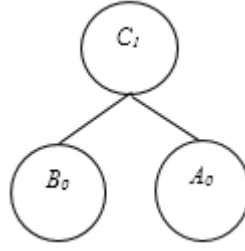
Fig. 6.1.: Smallest possible commitment tree

6.1.1 Assumptions

We make following assumptions for the adversary.

- It can not send an authentication code with NACK message during verification of inclusion phase.

- It does not have the capability to masquerade by reproduce the signatures of any other sensor node.

Without these assumptions, there will be a lot of complainers in the network, creating a lot of traffic in the network. Ultimately, draining the battery levels of the sensor nodes until they die, making some sensor nodes in the network unreachable and potentially causing the denial-of-service attack in the network. Following example shows the different ways an adversary can cheat in the smallest possible commitment tree and how the commitment field in the data-item can help us detect the cheating. And theoretically, all possible commitment trees can be presented as Figure 6.2 for the analysis purpose.

Example 6.1.1 *Let's say the vertices in the commitment tree of Figure 6.2 have the data-items defined as follows.*

$$
\begin{aligned}
A_0 &= <A_{id}, 1, 10, H(N||1||10)> \\
B_0 &= <B_{id}, 1, 20, H(N||1||20)> \\
C_1 &= <C_{id}, 2, 30, H(N||2||30||A_0||B_0)>
\end{aligned}
\tag{6.1}
$$

Note that we did not include the signatures of these data-items in this example for simplification.

- **No cheating**

  C *aggregates* B_0, C_0 *according to the aggregate commit algorithm.*

  dissemination of root data-item

  A, B *receives* C_1 *from the base station using authenticated broadcast.*

  dissemination of offpath values

  A *receives* B_0 *from* C *and vice versa.*

  verification of inclusion

  $$A \ uses(A_0, B_0) \ to \ calculate < 2, 30, H(N||2||30||A_0||B_0) > \ = C_1$$
  $$B \ uses(A_0, B_0) \ to \ calculate < 2, 30, H(N||2||30||A_0||B_0) > \ = C_1$$

  (6.2)

  collection of authentication codes

  A, B *sends their authentication codes with ACK messages.*

- **Cheating by replacing data-items**

  C *replaces* A_0, B_0 *with* A'_0, B'_0 *and then applies aggregate commit algorithm.*

  $$A'_0 = < A_{id}, 1, 100, H(N||1||100) >$$
  $$B'_0 = < B_{id}, 1, 200, H(N||1||200) >$$
  $$C'_1 = < C_{id}, 2, 300, H(N||2||300||A'_0||B'_0) >$$

  (6.3)

  dissemination of root data-item

  A, B *receives* C'_1 *from the base station using authenticated broadcast.*

  dissemination of offpath values

  A *receives* B'_0 *from* C *and vice versa.*

  verification of inclusion

  $$A \ uses \ (A_0, B'_0) \ to \ calculate < 2, 210, H(N||2||210||A_0||B'_0) > \ \neq C'_1$$
  $$B \ uses \ (A'_0, B_0) \ to \ calculate < 2, 120, H(N||2||120||A'_0||B_0) > \ \neq C'_1$$

  (6.4)

  collection of authentication codes

  A, B *send their authentication codes with NACK messages.*

- **Cheating by tampering with a single data-item**

  C replaces A_0 with A'_0 and then applies aggregate commit algorithm.

  $$A'_0 = < A_{id}, 1, 100, H(N||1||10) >$$
  $$C'_1 = < C_{id}, 2, 120, H(N||2||120||A_0||B'_0) >$$

  (6.5)

  dissemination of root data-item

  A, B receives C'_1 from C

  dissemination of offpath values

  A, B receives B'_0, A_0 from C respectively.

  $$B'_0 = < B_{id}, 1, 110, H(N||1||110) >$$
  $$A_0 = < A_{id}, 1, 10, H(N||1||10) >$$

  (6.6)

  verification of inclusion

  A uses (A_0, B'_0) to calculate $< 2, 120, H(N||2||120||A_0||B'_0) > = C'_1$

  B uses (A_0, B_0) to calculate $< 2, 30, H(N||2||30||A_0||B_0) > \neq C'_1$

  (6.7)

  collection of authentication codes

  A, B send their authentication codes with ACK,NACK message respectively.

- **Cheating by tampering with data-items**

  C changes A_0, B_0 to A'_0, B'_0 by changing the value fields and then applies aggregate commit algorithm.

  $$A'_0 = < A_{id}, 1, 100, H(N||1||10) >$$
  $$B'_0 = < B_{id}, 1, 200, H(N||1||20) >$$
  $$C'_1 = < C_{id}, 2, 300, H(N||2||300||A''_0||B_0) >$$
  $$C''_1 = < C_{id}, 2, 300, H(N||2||300||A_0||B''_0) >$$

  (6.8)

  dissemination of root data-item

  A, B receives either C'_1 or C''_1 from the base station using authenticated broadcast based on what C send to base station.

dissemination of offpath values

A, B *receives* B_0'', A_0'' *from* C *respectively.*

$$B_0'' = < B_{id}, 1, 290, H(N||1||20) >$$
$$A_0'' = < A_{id}, 1, 280, H(N||1||10) >$$

(6.9)

verification of inclusion

A *uses* (A_0, B_0'') *to calculate* $< 2, 300, H(N||2||300||A_0||B_0'') > \neq C_1' = C_1''$

B *uses* (A_0'', B_0) *to calculate* $< 2, 300, H(N||2||300||A_0''||B_0) > = C_1' \neq C_1''$

(6.10)

collection of authentication codes

A, B *send their authentication codes with NACK message.*

This example shows how the commitment provides **data-integrity** to the data-items. It makes it nearly impossible for an adversary to tamper with the data-items while creating commitment tree and/or while distributing off-path values. This cheating activity can be detected by the commitment filed in the data-item. Later we will show that the adversary can be detected with the provided signature infrastructure.

6.2   Possible Cheater Analysis

The following example demonstrates that if the base station knows the commitment tree topology and the complainers in the network then it can guess possible adversaries. Then applies interactive protocol described in Algorithm 1 in the next chapter to identify the adversary. The details on how the base station finds complainers in the network are described in the next chapter. For simplicity, we selected the commitment tree where all the vertices are unique. But this analysis holds true for any commitment tree topology.

Example 6.2.1 *The base station creates a set* $c = \{c_1, c_2, \ldots, c_n\}$ *for the complainers based on the protocol described in the Section 7.5. And based on the set c it creates a set* $a = \{a_1, a_2, \ldots, a_n\}$ *of the possible adversaries.*
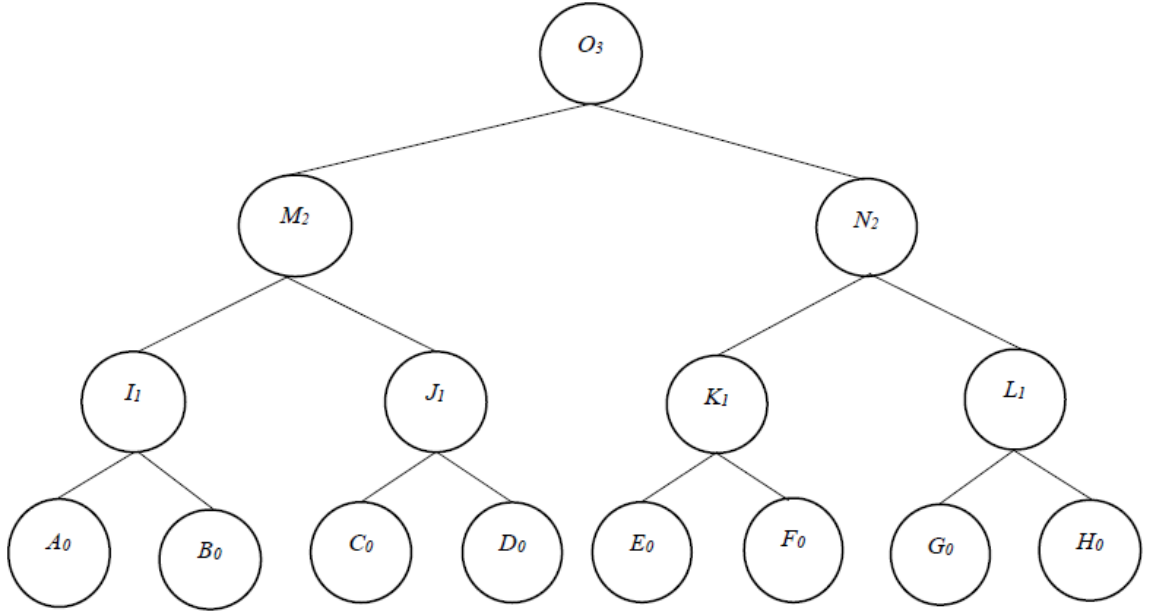
Fig. 6.2.: Smallest possible commitment tree

- If $c = \{A_0\}$ then $a = \{I, (B, I), (B, M), (B, I, M)\}$

- If $c = \{A_0, B_0\}$ then $a = \{I, M, (I, M), (C, D, O)\}$

- If $c = \{A_0, B_0, C_0\}$ then $a = \{(D, O), (I, J), (M, J), (M, J, I)\}$

- If $c = \{A_0, B_0, C_0, D_0\}$ then $a = \{M, O, (I, J), (E, F, G, H, O)\}$

- If $c = \{A_0, B_0, C_0, D_0, E_0\}$ then $a = \{(O, K), (M, K), (J, I, K), (F, G, H, O)\}$

- If $c = \{A_0, B_0, C_0, D_0, E_0, F_0\}$ then $a = \{(O, K), (M, N), (N, O), (J, I, K)\}$

- If $c = \{A_0, C_0\}$ then $a = \{(J, I)\}$

7. VERIFICATION

7.1 dissemination final commitment

7.2 dissemination of off-path values

Two cases:

- With signatures

- Without signatures

7.3 verification of inclusion

7.4 collection of authentication codes

7.5 verification of authentication codes

The authentication codes for sensor node s, with either positive or negative acknowledgment message, are defined as follows:

$$MAC_{K_s}(N \parallel ACK) \tag{7.1}$$

$$MAC_{K_s}(N \parallel NACK) \tag{7.2}$$

K_s is the key that s shares with the base station; ACK, $NACK$ are special messages for positive and negative acknowledgment respectively. The authentication code with ACK message is sent by the sensor node if it verifies its contribution correctly to the root commitment value during the *verification of inclusion* phase and vice versa.

To verify that every sensor node has sent its authentication code with ACK, the base station computes the Δ_{ack} as follows:

$$\Delta_{ack} = \bigoplus_{i=1}^{n} MAC_{K_i}(N \parallel ACK) \tag{7.3}$$

The base station can compute Δ_{ack} as it knows K_s for each sensor node s. Then it compares the computed Δ_{ack} with the received root authentication code Δ_{root} from the root of the aggregation tree. If those two codes match then it accepts the aggregated value or else it proceeds further to find an adversary.

To detect an adversary, the base station needs to identify which nodes in the aggregation tree sent its authentication codes with *NACK* during the verification of inclusion phase. The node who sent authentication code with *NACK* during the verification of inclusion phase is called a *complainer*. We claim that if there is a single complainer in the aggregation tree during the verification of inclusion phase then the base station can find the complainer in linear time. To find a complainer, the base station computes the complainer code c.

$$c := \Delta_{root} \oplus \Delta_{ack} \tag{7.4}$$

Then it computes the complainer code c_i for all node $i = 1, 2, \ldots, n$.

$$c_i := MAC_{K_i}(N \parallel ACK) \oplus MAC_{K_i}(N \parallel NACK) \tag{7.5}$$

Then it compares c with all c_i one at a time. The matching code indicates the complainer node. The base station needs to do $\binom{n}{1}$ calculations according to Equation 7.5 and same number of comparisons to find a complainer in the aggregation tree. Hence, the base station can find a single complainer in linear time.

Example 7.5.1 *If there are four nodes s_1, s_2, s_3, s_4 in an aggregation tree and their authentication codes with ACK, NACK message in the binary format are defined below.*

$MAC_{K_1}(N \parallel ACK) = (1001)_2$; $MAC_{K_1}(N \parallel NACK) = (1101)_2$

$MAC_{K_2}(N \parallel ACK) = (0110)_2$; $MAC_{K_2}(N \parallel NACK) = (1111)_2$

$MAC_{K_3}(N \parallel ACK) = (0101)_2$; $MAC_{K_3}(N \parallel NACK) = (0111)_2$

$MAC_{K_4}(N \parallel ACK) = (0011)_2$; $MAC_{K_4}(N \parallel NACK) = (1110)_2$

$\Delta_{root} = (0100)_2$

$\Delta_{ack} = (1101)_2$

$c_1 = (0100)_2$, $c_2 = (1001)_2$, $c_3 = (0010)_2$, $c_4 = (1101)_2$

$c = (1101)_2$ c is equal to c_4.

So, the base station identifies that the s_4 complained, during verification of inclusion phase.

In general, to find k complainers the base station needs to do $\binom{n}{k}$ calculations and the same number of comparisons to find k complainers.

How XOR is negating the contribution of NACK.

$$\left(\begin{array}{cccc} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ \hline 1 & 0 & 0 & 1 \end{array}\right) \left(\begin{array}{cccc} 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 \\ \hline 1 & 0 & 1 & 1 \end{array}\right)$$

The base station receives the following:

$$\left(\begin{array}{cccc} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \\ \hline 0 & 1 & 0 & 0 \end{array}\right)$$

The base station does the following:

$$\left(\begin{array}{cccc|cccc|cccc|cccc} 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ \hline 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 \end{array}\right)$$

$$\left(\begin{array}{cccc} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ \hline 1 & 1 & 0 & 1 \end{array}\right)$$

And concludes that node 4 is complaining.

7.6 Detect an adversary

Algorithm 1 Pseudo algorithm to detect an adversary

1: BS identifies all the complainer and creates $c = \{c_1, c_2, \ldots, c_n\}$

2: **for all** $N \in c$ **do**

3:     BS asks N to send data-items with its signature, sent during commitment tree generation phase

4: BS identifies possible adversary based on c and creates $a = \{a_1, a_2, \ldots, a_n\}$

5: **for all** $A \in a$ **do**

6:     BS asks A to send data-items with its signature, received and sent by A during commitment tree generation phase

7:     If needed BS asks the parent of A to send data-items with its signature

8: BS determines the adversary based on the verification of signatures

---

Theorem 7.6.1 *Binary commitment tree is optimal in terms of verification as it requires minimum number of off-path values.*

Proof Let us say n is the number of leaves in the given commitment tree.

$$\log_3(n) = y$$

$$3^y = n$$

$$\log_2(3^y) = \log_2(n)$$

$$y * \log_2(3) = \log_2(n)$$

$$\log_3(n) * \log_2(3) = \log_2(n)$$

$$\log_3(n) = \frac{\log_2(n)}{\log_2(3)}$$

$$2 * \log_3(n) = [2/\log_2(3)] * log_2(n) = (1.2618) * log_2(n)$$

$$2 * log_3(n) > log_2(n)$$

For the given binary commitment tree, each leaf vertex needs $\log_2(n)$ off-path values in the verification phase. The total off-path values needed in the given commitment tree is $n \cdot \log_2(n)$.

For the given tertiary commitment tree, each leaf vertex needs $2 \cdot \log_3(n)$ off-path values in the verification phase. The total off-path values needed in given commitment tree is $2 \cdot n \cdot \log_3(n)$.

Hence, in totality the binary commitment tree requires the minimum number of off-path values. ∎

8. NOTES

- Do we hash node's id in the commitment field of its data-item? NO

- Do we send the payload signature in case of Figure 5.4? YES

To do list:

- Cheating: Cheating detection with CT generation.

- Cheating: Cheating detection with off-path distribution.

- Cheating: Cheating detection with both scenarios in place.

- ch-4: Image modifications. Update images with darker borders. Decrease width. Save word as pdf and then crop images

- Review the writing.

- 3. Discuss cheating, distributing off-path.

- ch-6: Why don't you need signatures with off-path?

- ch-4: Advantages of signing the B's payload.

- ch-3: cite book for digital signatures

- ch-6: removing old signatures, and signing those again

- ch-6: equation for number of certificates needed in the network

- Discuss resigning approach and then modify the ch-5 accordingly.

- Meeting: Review cheating chapter, language in ch-4 (often used the word We).

LIST OF REFERENCES

LIST OF REFERENCES

[1] H.-J. Hof, "Applications of sensor networks," in *Algorithms for Sensor and Ad Hoc Networks.* Springer, 2007, pp. 1–20.

[2] D. Li, K. D. Wong, Y. H. Hu, and A. M. Sayeed, "Detection, classification, and tracking of targets," *Signal Processing Magazine, IEEE*, vol. 19, no. 2, pp. 17–29, 2002.

[3] M. Chu, J. Reich, and F. Zhao, "Distributed attention in large scale video sensor networks," in *Intelligent Distributed Surveilliance Systems, IEE.* IET, 2004, pp. 61–65.

[4] J. D. Lundquist, D. R. Cayan, and M. D. Dettinger, "Meteorology and hydrology in yosemite national park: A sensor network application," in *Information Processing in Sensor Networks.* Springer, 2003, pp. 518–528.

[5] K. Lorincz, D. J. Malan, T. R. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland, M. Welsh, and S. Moulton, "Sensor networks for emergency response: challenges and opportunities," *Pervasive Computing, IEEE*, vol. 3, no. 4, pp. 16–23, 2004.

[6] R. Benenson, S. Petti, T. Fraichard, and M. Parent, "Towards urban driverless vehicles," *International Journal of Vehicle Autonomous Systems*, vol. 6, no. 1, pp. 4–23, 2008.

[7] A. Wang and A. Chandrakasan, "Energy-efficient dsps for wireless sensor networks," *Signal Processing Magazine, IEEE*, vol. 19, no. 4, pp. 68–78, 2002.

[8] M. Ettus, "System capacity, latency, and power consumption in multihop-routed ss-cdma wireless networks," in *Radio and Wireless Conference, 1998. RAWCON 98. 1998 IEEE.* IEEE, 1998, pp. 55–58.

[9] S. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "Tag: A tiny aggregation service for ad-hoc sensor networks," *ACM SIGOPS Operating Systems Review*, vol. 36, no. SI, pp. 131–146, 2002.

[10] Payload computing. http://en.wikipedia.org/wiki/Payload_(computing). [Online; accessed January 9, 2015].

[11] S. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "The design of an acquisitional query processor for sensor networks," in *Proceedings of the 2003 ACM SIGMOD international conference on Management of data.* ACM, 2003, pp. 491–502.

[12] D. Wagner and R. Wattenhofer, *Algorithms for sensor and ad hoc networks: advanced lectures.* Springer-Verlag, 2007.

[13] J. L. Hill and D. E. Culler, "Mica: A wireless platform for deeply embedded networks," *Micro, IEEE*, vol. 22, no. 6, pp. 12–24, 2002.

[14] O. Arazi, I. Elhanany, D. Rose, H. Qi, and B. Arazi, "Self-certified public key generation on the intel mote 2 sensor network platform," in *Wireless Mesh Networks, 2006. WiMesh 2006. 2nd IEEE Workshop on.* IEEE, 2006, pp. 118–120.

[15] Y. Yao and J. Gehrke, "The cougar approach to in-network query processing in sensor networks," *ACM Sigmod Record*, vol. 31, no. 3, pp. 9–18, 2002.

[16] B. Przydatek, D. Song, and A. Perrig, "Sia: Secure information aggregation in sensor networks," in *Proceedings of the 1st international conference on Embedded networked sensor systems.* ACM, 2003, pp. 255–265.

[17] H. Chan, A. Perrig, and D. Song, "Secure hierarchical in-network aggregation in sensor networks," in *Proceedings of the 13th ACM conference on Computer and communications security.* ACM, 2006, pp. 278–287.

[18] sha256 standards from nist. http://csrc.nist.gov/groups/STM/cavp/documents/shs/sha256-384-512.pdf. [Online; accessed January 9, 2015].

[19] Digital signature. http://en.wikipedia.org/wiki/Digital_signature#mediaviewer/File:Digital_Signature_diagram.svg. [Online; accessed January 9, 2015].

[20] D. Wagner, "Resilient aggregation in sensor networks," in *Proceedings of the 2nd ACM workshop on Security of ad hoc and sensor networks.* ACM, 2004, pp. 78–87.