Intrusion Detection of a Wireless Sensor Network Over the Air Update Protocol

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***Abstract*—Wireless Sensor Networks (WSN) form interconnections autonomously. They can be used to work together to sense and monitor some phenomena in a unified fashion. However, the software that runs on the sensors might require updating because of changes in requirements, routines, protocols and so on. It is not easy to round up all the deployed sensors in order to reprogramme them. Hence, the capability to reprogramme over the air (OTA) was developed and several specific protocols have been implemented that achieve this purpose. Each protocol has its own suitability depending on the context and scenario. Deluge is one such protocol. The ease of reprogramming opens a backdoor to a potential intruder who can abuse the protocol by injecting a malicious program. The design of Deluge does not cater for the intruder's activity; as a result, it is not possible to detect if the update was a legitimate one or not. The method we propose analyses the timing of update of each of the sensors in the network and computes a 'Intrusion Warning Score' through an algorithmic function to indicate a possible intrusion i.e. a probable illegitimate update.**

I. Introduction

Wireless Sensor Networks (WSN) have become practical within the last two decades. The technology has attracted great attention in recent years due to significant advances in wireless and mobile communication technologies. One of the main driving forces behind the quick evolution of WSN is its cost-worthiness and flexibility in deployment. The sensors, called the nodes or motes, are generally self-powered, wireless, networked sensing devices with inbuilt limited processing hardware. The manager node, which is also called a sink or base station generally has long-lasting power and probably, remain connected to a workstation with greater processing capability. Motes and sinks together dynamically form an autonomous networked environment where all sensor nodes within range and sharing the same radio channel and protocols take part. In such a conventional WSN, data exchange takes place only locally using a autonomous relay mechanism that does not require any routing table to be able to do so. A WSN is ultimately employed for sensing and/or detecting certain physical phenomena, on which basic processing is performed at the individual mote, the processed information is relayed back to a computing device through the sink for further processing. WSNs are generally deployed for long-term monitoring at scales and resolutions that are difficult to manage. They may necessitate reprogramming after deployment to accommodate alteration in the environment, sensing applications, or scientific requirements [1].

Advances in semiconductors and embedded processors initiated the development of sensors with computational capability. Conventionally, sensors were built using micro-electro mechanical systems (MEMS) or CMOS or LED technology, based on the purpose and property to sense. Today, nano-particles are also used for tiny sized sensors. It is now possible to combine a wireless radio transceiver with a microprocessor, memory, and other micro-electro-mechanical sensors into a tiny device. These tiny sensors have advantage of being energy friendly and are deployed in environments with limited power and space. The WSN evolved from the distributed sensor network programme of the DARPA project and is still evolving with newer and smarter ideas such as integrated RFID-enabled WSN with inkjet-printed electronics on paper substrates, distributed WSN to tackle reliability, in-network processing to reduce communication cost [2]. There are other evolving areas like contention and schedule-based energy efficient medium access schemes, cognitive routing methodologies, cross-layer protocols, combining medium access control with routing functionality, security-conscious WSN, deployment of WSN within aircraft to replace wired infrastructure and so on. Today, WSN is developed around an IEEE standard that specifies lower network layers (i.e., MAC layer and physical layer) of a wireless network which focuses on low-cost, low-speed ubiquitous communication between devices [3].

WSNs operate unattended over long period of time that may range from months to years. There is often very little control over the sensors once they are deployed. Changes in the environment and purpose over time affects the operations of the sensors. This necessitates reprogramming of the sensors to suit the evolving requirements and also to enable bug fixes after deployment. The potential scale and types of embedded types of deployments of sensors may make it impossible to collect each sensor, reprogramme it and then redeploy it again. Network code propagation using data dissemination protocols promises a suitable solution to this problem.

The technology has huge potential for future commercial applications. The technology is still evolving with greater promises of being integrated into even larger scale deployment in the form of Internet of Things (IoT) or dusts. It is expected to play a critical role in the computing revolution of cooperating objects and smart embedded devices. However, industry adoption is hampered owing to several factors like difficulty in programming, security issues, integration with other systems and business processes and so on. Historically, security remains as a neglected part in any implementation process, until there is a major breach. One of the main reason why sensor networks has not been widely deployed in industrial systems and safety systems reliably is concerns over security. Reliability and safety critics and academics have continually expressed that the security issues in WSN have not been sufficiently addressed and it is not yet secure enough for mission critical employment. Security is a very important part of system reliability. Before WSN matures to a point that can

be reliably integrated in everyday life, security issues must be adequately addressed.

WSNs have special vulnerabilities that do not exist in wired networks. Security mechanism designed for conventional computing systems often are not appropriate for WSNs. Even the security techniques like the WEP standards for wireless networks cannot be employed in WSN because of memory and computing resource constraints. WSNs are more vulnerable to intrusion attempts and security threats from malicious sources. The limited resources in terms of memory, computational power and energy, make them easier target. The attack targets may range from being on physical sensors, wireless channels, visibility of the network, even to coordination and self-configuration of the network.

Several approaches to address security issues in WSN have been proposed in recent years. They approaches converge on security to ensure reliable data transfer using simple and flexible protocols with high level of confidentiality. Because of the resource constrained nature of the motes, security is a vulnerable area to explore. Lack of suitable computation capability hinders deploying heavy cryptographic measures, wireless nature exposes itself to the adversaries who can easily overcome the barriers to listen to all the traffic and even inject their own packets into the network. When deployed in a hostile environment, the attackers may have physical or logical access or proximity access capability. Threats to security can be directed to individual motes, towards the network traffic or a cluster of motes. A potential adversary may be able to interfere with goals related to security services like authentication, confidentiality, integrity, non-repudiation or even extend to clandestine takeover. In the event of failure from the expected security services i.e. breach of cryptographic measures, an intrusion detection system (IDS) becomes invaluable.

Intrusion is the ability to disrupt or degrade the intended functionality of the network or a part of it; it could be non-intentional or not. An IDS is able to identify malicious break in attempts to a trusted environment. It is directed towards a security mechanism that can detect abnormal behaviour in the network. A suitable IDS can detect attempt of intentional or unintentional break in events from an insider or outsider party. However, an IDS does not prevent the break in, but alerts following some predefined procedures in case of a security breach. Research in WSN security with respect to IDS has lots of potentials for new discovery and implementation. An IDS architectures for static WSNs has been suggested that watches over the communications in the neighbourhood [4]. Such an IDS is not capable to identify a malicious update that has been effected by an adversary in the WSN. We propose a novel intrusion detection algorithm that just requires a minor modification of the OTA update protocol by enabling an Active Message (AM). AM is a single-hop, unreliable packet used for network abstraction in TinyOS. It has a destination address, a type field, provides synchronous acknowledgements [5]. AM enables a centralised view of a network-wide knowledge that is processed and analysed to work out a score function according to an algorithmic formula to raise a red flag which could indicate a possible intrusion.

This work's contributions are two fold. We have analyzed

We have studied how the different algorithm parameters

The rest of this paper is structured in the following way. In Section II, we discuss the security and intrusion primitives that are talked about in the WSN arena. We try to find out what security aspects have not been addressed by the present security researchers and the reasons behind any security deficiencies. In Section III, we explain the main concepts of Deluge and its special security measures that have been implemented on Deluge. We present design of our proposed algorithm in Section **??** and explain how it is connected to the sensor node. In Section **??**, we have explained the experiment methodology and its implementation details. We then present our evaluation of the experiment in Section V. A few difficulties that we ran into throughout the development of this experiment are also commented in this section. Finally, we conclude our arguments in Section VI.

II. Related Work / Literature Review

Security is the prime concern in the path to socialising the WSN technology. Due to its applicability in wide variety of purposes, keeping WSNs secure is a challenging task. WSNs do not have any session or presentation layer. Security techniques designed for MANETs are not readily applicable in WSN for its constraints like small processing capability, low battery life, small memory. various possible attacks on WSNs has been explained by [6], [7]. On the other hand, WSN security design and analysis suggests many techniques to address them. Many security schemes for WSN have been proposed targeting two main approaches—using cryptography and using IDS. Cryptographic approach actively aims to protect privacy, ensure authenticity, data integrity and confidentiality through use of cryptographic keys and algorithms, policies and procedures. While symmetric key cryptographic techniques are more efficient in required resources, they suffer from a shortcoming that the key must be shared for being useful. However, asymmetric key cryptography is free from this limitation with a greater consumption of resources. Anomaly detection, on the other hand, is a passive security measure that monitors the behaviour from a observer's point of view and aims to alert a suitable entity for further actions.

Symmetric key cryptographic techniques are useful when both the secret key and the algorithm remains unknown, which can be difficult due to the fact that the WSN is expected to be deployed in exposed environment. Yet, most security schemes in WSN use the technique due to ease of hardware implementation, small computation, power and memory requirements. [8] recommends Skipjack, MISTY1, and Rijndael to be the most suitable block ciphers for WSNs, based on the combination of required memory, energy efficiency and intended security strength as the benchmark parameters. In terms of operation mode, pairwise links should use Output Feedback and broadcasts should prefer Coded Block Chain (CBC) mode. [9] suggested use of available transceiver chip as resource for hardware based AES encryption in the sensor as it outperforms software implementations of some of the most popular cipher algorithms suitable for WSN. [10] concludes that the lightweight block cipher proposed by [11] achieves good performance, providing energy efficiency as well as suitable security for sensor nodes in a WSN in comparison to AES, Skipjack, Puffin, Salsa, Sosemanuk, RC4. However, cryptanalysis of the technique by [12] shows that it requires large number of rounds to make it significantly resistant against

attacks. [13] found AES to be the most energy-efficient and RC5 to be better than RC6. He also commented that very few security research have been directed towards cryptographic modes of operation in WSN, which might offer interesting insight for certain modes that allow decryption using a decryption block, hence may significantly speed up the execution.

Asymmetric key cryptography tends to be resource intensive, but has the advantage of private key operation. It is very suitable in key exchange, digital signature and likewise. There are various pubic key cryptographic algorithms like Rabin's Scheme, RSA, Ntru-encrypt, Elliptic curve cryptography (ECC), Pairing Based Cryptography (PBC) and so on; few of them has been implemented in software and hardware for WSN [14], [15], [16]. Suitably customised implementations can result in a reduced protocol overhead, less packet transmission and power savings. ECC and PBC based techniques provide better trade-off between key size and security strength than RSA; thus is suggested to be suitable for WSN with advantages like lower computation time, storage space, transmitted data, required energy [17], [18]. However, asymmetric key cryptography cannot be used as general purpose scheme, rather to be used for authenticated session establishment, authentication, signature generation and verification, secret key exchange.

IEEE 802.15.4 specification does not require any security implementation. Yet, it describes the usage of the AES for either encryption (CTR mode) or authentication (CBC mode) or both (CCM-mode). Transport Layer Security (TLS) relies on the connection-oriented TCP protocol as transport mechanism. TLS implementations have been provided in TinyOS; however, Contiki OS still lacks the support. NEED TO CHECK Contiki ASSERTION TinyOS implemented Skipjack algorithm with the CBC mode in TinySec, which has been discarded later on, and support for hardware based AES-128 encryption has been provided using CC2420 chip. [19] discovered a (slightly) faster than brute force way to break the AES.

There are security issues with use of cryptography in WSN due to the nature of the hardware [20]. Encryption significantly increases energy and decreases packet throughput. In many cases, authentication is more desirable than encryption; but encryption is typically the standard method for authentication. Absence of session and presentation layers complicates the design security protocols. Moreover, WSNs do not have gateways or switches that can enable monitoring of the information flow. Hence, in case of failure from cryptographic measures, intrusions need to be detected before or after attackers have succeeded in breaching the WSN.

Usually an IDS detects suspicious behaviour in the WSN. IDS may also provide some of the information like identification and location of the intruder, extent of intrusion and so on. Butun, Morgera, and Sankar authoritatively discussed the constraints and challenges in WSN IDS design [21]. IDSs in WSN have been suggested using distributed and cooperative architecture. Some other IDS also exist that uses a hierarchical and centralised approach. Anomaly based approach works in a distributed manner using support vector machine that minimizes communication overhead while performing in-network anomaly detection propose dby [22]. A standalone rule based approach to detects anomalies at all layers of a network stack in WSN has been suggested [23]. Rule based techniques rely monitoring of group of nodes and routing tables for detection [24]–[27]. Spontaneous watchdog uses the sensor broadcast, density of deployed sensors for its detection [28]. Specification based IDS has been proposed that relies on data clustering and uses standard deviation from the average inter-cluster distance [25]–[27], [29]. Statistical based anomaly detection looks for anomalies in routing pattern [30]. Statistical methods that use hidden Markov model focus on the accuracy of the gathered data, rather than the security of the nodes or the links. [31]. Such a model monitors data arrival process in real time traffic on the nodes, analyses short term dynamic statistics using a multi-level sliding window event storage scheme that works on each node. The detection algorithms performs locally and individual nodes are not aware of the network-wide attacks [32]. Some other statistical based procedure exploits the stability of the neighbourhood information of the WSN nodes depending on average receive power and average packet arrival rate [33]. Game theory based IDS utilise Markov chain for its decision making process can monitor only one of the clusters of the network at a time, which leaves the rest of the network unprotected [34], [35], [36]. Reputation based IDS relies on heuristic ranking algorithms to identify most likely bad nodes in the network. Such IDSs use high scalable cluster-based hierarchical trust management protocol to effectively identifying the selfish and malicious nodes [37].

Software update in a WSN is a vulnerable process from security point of view. While cryptography is an algorithmic tool designed to verify authenticity and ensure security, IDSs monitor anomaly in network behaviour and raises alarm. There are other IDSs that initiate countermeasure process also, in addition to monitoring and raising alarm. Cryptography and monitoring both work in collaboration with each other and are intended to ensuring security and protect against intrusion. Despite these efforts, WSN passes through a vulnerable phase during the software update process due to the fact that the running operating system and application needs to switch from old version to the new ones and there is a significant increase in traffic owing to software update process. There are high number of transmitted packets in the network that uses huge network bandwidth, thereby depletes sessor energy. When a software update in WSN takes place, it replaces the executing embedded operating system and running application as a package. Cryptographic measures and IDS running in the local sensors are deactivated or unavailable, which open up a vulnerable window in time when it is easy for an intruder due to the transition. Therefore, this is a special case from security point of view and must be dealt with specific measures like an additional layer of security measures that must observe the update behaviour.

Several network data dissemination protocols have been implemented in different sensor/embedded systems operating systems. All the OTA software update protocols are targeted at attaining efficiency, throughput and conserve energy. The OTA reprogramming systems, in general, do not provide cryptographic protection for source authentication, integrity verification and likewise. Limitations of various techniques that can be used in WSN reprogramming has been elaborated in [38]. The program binary authentication technique using a hash is not very useful in to resource-constrained sensors. Deluge has been enhanced to handle security that we have elaborately discussed in section III. Deluge uses digital signatures for codes signing and authenticated broadcast scheme. It also

incorporates digitally signed initial advertisement, which in turn authenticates the following messages in a chained fashion much like the CBC methods used in public key cryptography. However, we contend that it is possible for a malicious intruder to replicate an authentic image source and advertise new programme version which the motes cannot repudiate. Even though, Deluge incorporates on-chip hardware based AES-128 encryption, Cryptography cannot completely prevent attacks.Constrained computational capacity and resources make it possible to compromise the cryptographic measures incorporated in the implemented WSN operating systems. The other vulnerability of such epidemic protocol is breach at any one point does the job of weakening the whole network for the attacker. It is possible for him to appear somewhere in the network, pretend to be an authentic source and disappear after successful transfer of the complete image to only one of the motes in the network. The security mechanisms provided by Deluge would be unable to detect the initial breach in such cases and would allow the network to be flooded by a totally new version of the application that performs completely different function [39]. While the reprogramming protocols are essential for the WSNs, they could act as carriers of rapid spread of malicious code in the network. Hence, we propose an analytical tool that can have valuable insight into the propagation characteristics of OTA reprogramming protocol. The tool should be flexible for comparative studies of different protocols.

There is no previous works available that targets to secure update process using an IDS. The security countermeasures available in WSN systems is predominately cryptographic. None of the well-known WSN operating systems have ever incorporated an IDS due to the reality that such an employment would cut down on the resources, especially power. An IDS residing on the sensors is ideally need to be avoided by design.

Hence,we propose an IDS that can primarily be applied on OTA protocol. The technique has been tested successfully on Deluge. We have exploited services from other existing standard protocols a to gather timing information outside the WSN and then process the timing information for intrusion detection. Use of timing analysis approach is a new technique in IDS for WSN. The technique may further be extended for use with broad range of intrusion detection motives specially in WSN and also in MANET. The technique is centrally controlled, resides outside the WSN, gathers processed information from the sensors in WSN. However, an IDS with that broad spectrum is out of scope of this paper. We shall limit ourselves within its application on WSN, specifically on Deluge only. Before one understands how the IDS works and is able to focus on its mechanism, one needs some prior knowledge about Deluge and its security techniques.

ADDITIONAL NOTES TO BE INCORPORATED or DISCARDED

Most of the solutions are context specific and are vulnerable depending on its application. The assumptions made on the corresponding threats may be inconsistent with the problem domain and attempts to address unrealistic problems.

WSN have limitations in computing resources, memory and physical security. Even after stringent security implementation, it cannot overcome security threats and possible security weakness. Sensor nodes use wireless communication, which is particularly easy to eavesdrop on. Similarly, an attacker can easily inject malicious messages into the wireless network.

[40] suggests a distributed approach in which nodes do not have a global view, monitor their neighbourhood and collaborate with their nearest neighbours for their normal operational condition, yet can detect an intrusion against blackhole and selective forwarding attacks. [41] proposes a mechanism based on trust that uses node localisation, density of the WSN, collaborative sensing, cryptographic techniques and focuses on misbehaviour characterisation and behaviour monitoring to build a 'Reputation Table' for each node . However, the mechanism have assumptions about motives of the adversary, symmetric links, nodes are not compromised or faulty at the time of bootstrapping.

[42] proposes a guaranteed interleaved hop-by-hop authentication schemes for detection of injected false data immediately when no more than t nodes are compromised, where t is a system design parameter.

III. Deluge

A. Popular OTA Protocols

Reprogramming of the sensors in a WSN is one of the most important management task. Performing the task manually may work out for a small no of sensors, but this is not a scalable idea. Hence automatic OTA reprogramming of sensors becomes an important issue. While some of the protocols designed for OTA reprogramming deals with a subset of motes, most others necessarily update the whole network at one go resulting into all motes in the WSN running same version of the software. The subset reprogramming allows the same WSN to preferentially perform different tasks, which is a convenience and again increases management overhead. In Trickle, which is a well-known OTA update protocol, the motes periodically advertise their own running code version to the neighbours. When a neighbour listens to an older version, it disseminates the updated code. Trickle addresses single packet dissemination and uses suppression and dynamic adjustment of the broadcast rate to limit transmissions among neighboring nodes. The Trickle algorithm controls the rate of transfer by suppressing a motes own broadcast instead of flooding the network [43]. Another OTA update protocol, Multihop Network Programming (MNP) is an enhancement over Trickle or Deluge in a way that is more efficient in image transfer using 'pipelining' to enable faster data propagation and also in terms of energy. MNP handles the problems that occur from message collision and hidden terminal using a greedy approach of sender selection algorithm to guarantee that at a time, there is at most one programme transmitting source in a neighbourhood. MNP [44]. While the above mentioned reprogramming protocols are either unsuitable or inefficient in a mobile environment, ReMo does not make any assumptions on the location of nodes and suggests an energy efficient, multihop reprogramming protocol for mobile WSNs. ReMo is based on a periodic metadata broadcast paradigm whose probability is dynamically adjusted based on neighbour density and pages are transferred out of order based on availability which in turn depends on high potential of

code availability, not link quality alone [45]. Comparison of code update completion time of different protocols indicates that while Deluge performs moderately, MNP is the fastest among them. Typhoon also reliably delivers large objects to all nodes using a combination of spatially-tuned timers, prompt retransmissions, and frequency diversity and has the benefits of reduced dissemination time and energy consumption by up to three times [46]. MOAP-SW allows a subset of the network to be programmed efficiently [47].

B. Deluge Protocol

Deluge is an efficient and reliable protocol for disseminating large data objects, such as program binaries that are larger than sensor memory [48]. Combining the mechanism with bootloader allows programming the wireless nodes over the air. Deluge has been implemented in TinyOS and later ported on Contiki, bothare prominent WSN open source operating systems. The original protocol was implemented at Barkley by Jonathan Hui. The later version Deluge 2.x was implementation at Johns Hopkins notably by Razvan, who is also credited with secure design of the protocol and author of another OTA protocol Typhoon. Deluge, (which is) an improvement over Trickle, divides the program image into pages that are further split into packets while in transition. Instead of nodes autonomously advertising its own version like Trickle, the nodes periodically advertise the newest pages (only the ones changed from prior version) available to send. Other nodes then request the required pages following a sequential order [48].

Deluge solves several problems in network programming. It deals with larger program image or data objects, mostly much larger than the memory (RAM) available in a sensor. It works on an environment where node density is variable to the extent that includes assymentric links as well. It displays reliable behaviour by correcting packets in environment that is characterised by high packet loss rate. Deluge ensures that all the nodes remain updated with the latest software version. In cases when a node missed several updates and needs to update its state to the very newest version, it can do so without requiring to go through the missed updates. The protocol ensures quick propagation of program codes and requires minimum service interruption.

Deluge displays few prominent characteristics that make it prominent. It transfers complete binary image when it is necessary to do so. It disseminates a program, image from one or more sources to many nodes over multi-hop WSN. The density aware epidemic property achieves reliability in the unpredictable wireless medium. The epidemic protocol works on a state machine principle and follows few local rules that ultimately achieves global behaviour. Deluge allows the sensor to store multiple program images in its flash memory, one of them is identified as golden image which is able to run with minimal support in case of a failure. Deluge can work in conjunction with a isolated bootloader to switch from running image to a newer one. The protocol achieves high performance due to its three-phase handshaking technique, robust support for asymmetric links and density aware mechanism that supresses redundant advertise messages and requests.

To represent large data objects, Deluge splits in into fixed size pages. Pages are basic data transfer objects which are further split into fixed no of packets for wireless transmission. Both pages and packets use 16-bit CRC for integrity and data correctness.

The deluge mechanism is simple yet interesting. Each node periodically advertises its version no and summary of software/data object. Version no is used to differentiate between updates and is chronologically increased for each subsequent updates. Nodes in the neighbourhood can determine from this advertisement if any of its neighbours have an old profile. Nodes listening to such advertisements suppresses their own advertisement if it has the same version of software; however, if it has a newer version then responds with its object profile. This is done in a fashion that can be termed as controlled flood. The nodes with older data object then determines which portion of data it needs updating and requests it from any neighbour it can reach. It works through a three-phase handshaking (advertise-request-updates) protocol which is helpful in a lossy environment to achieve reliability. Node with an old profile requests for the new page and switches to new *receive* mode. However, the neighbouring nodes which require the update can take advantage by receiving the same page without entering into a contention for requesting. The nodes utilise pipelining to increase throughput by working on completed pages before all pages in the image are complete.

A node in *receive* actively requests remaining packets required to complete a page. After making a request, the mote waits for response. However, a node need not be in *receive* mode in order to receive data packets. Packets needed to complete a certain page are saved without any regard to its state. A node in *transmission* broadcasts all requested packets from a given page in round-robin order with an aim of achieving fairness.

C. Security of Deluge

The original Deluge protocol did not consider security of operations. Security of Deluge was mainly suggested by [38] in the form of solution to following problems:

- Authentication of program binary ensures that the transferred program image is from its author and has not been forged. This is usually done by signing and verifying the data stream.
- Verification of data integrity ensures that the binary was not changed during transit and if there was a change then it is detected by the recipient.
- System freshness ensures that older programs cannot overwrite the newer ones.

Since size of the entire program, page and packets are known before a transmission takes place, the program can be split into messages, each message contains a cryptographic hash of the next message and digitally sign the head of hash message. It suggested to use a particular implementation of RSA signature and SHA-1 hashes. However, the RSA signature technique has not been implemented, instead AES-128 based symmetric key has been chosen, as we have mention beforehand. Use of hash function that binds later packets is a kind of digital signature by the base-station, and facilitates authentication [38].

D. Security Vulnerability of Deluge

Deluge security measures are not conclusive to this assertion that it can completely resent security threats. An adversary may employ the suppression to prevent the update propagation, waste network resources, disrupt the normal operation of code dissemination. He may even be able to inject malicious codes to pollute the network and deny intended function.

Advertisements are not authenticated, any node in the WSNs may advertise any message. So an adversary can launch several attacks on Deluge by injecting bogus or modified advertisement packets

IV. Methodology and Overview of System Design

The proposed IDS is external to the WSN, resides on a computing system that is physically connected to the sink. It utilises existing packet transmission protocols to collect related information. The information, which is predominantly identification of the mote i and the time at which the new image updated the mote t_i, is then processed. The IDS analyses the timing of update of each of the sensors in the WSN and computes a 'Surprise Score' or 'Intrusion Warning Score' (IWS) using an algorithmic function to indicate a possible intrusion, i.e., a probable illegitimate update.

A. Methodology

We assume to possess the ability to observe the software update pattern in a fully functional WSN where each node generates and reports the time at which the new software update completes and starts executing. All motes in a WSN has a shared sense of time synchronisation which is accurate to 1 μs and typically is achieved using TSMP protocol [49]. We used deluge protocol implemented in 'Contiki: The Open Source OS for the Internet of Things' for our experiments. We used 'Cooja Network Simulator' distributed with Contiki v2.7 to simulate the software update pattern using Deluge protocol. Different topologies were tested for thoroughness. All tests were conducted in an environment with Contiki installed on Ubuntu 12.04.

All the motes in the WSN were booted at same time running one version of a diagnostic application. The application would necessarily report its time, version number and mote ID on the serial terminal every second. The output from the serial terminal are logged and analysed later. The application in the base station dynamically begins the update process using deluge protocol after it boots and propagates another version of the software. The new version of the software is transmitted to all motes in a fashion as determined by the protocol.

Whenever transfer of the new image is complete for a mote, it replaces its old version of the application and starts executing the new one. The new application would also necessarily print out its time, version number and mote ID on the serial terminal every second. First time we have a mote declaring its version number of the new image is the update time for that mote. We continue running the simulator until all the motes in the WSN are updated to the new version image. All the logs are preserved and the necessary information (first reported update time for each mote) is filtered out from the log. Here necessary information means, the first time each mote reports that it is running new version of the image. The time and mote IDs are filtered out. We sort them based on the time of update. At this instance, we have the information like this:

```
--------------------------------
|  Time (in ms) | Mote ID |
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```

Building the Baseline Data: We have catered for multiple runs to build the baseline data that were compared against intrusion runs later. We have taken data from 20 runs initiated from the sink for each of the topologies tested. The output data from these runs were statistically treated to find out the 'mean' time at which each of the nodes are updated with the new image. Besides the 'mean', the 'standard deviation' was also identified at each of the motes in the WSN. Both 'mean' and 'standard deviation' were used as input to the IDS to calculate the IWS according to the utility function shown in Equation- 1.

Calculating IWS: Similar approach to building baseline data was followed to analyse data for the IWS. Update time of each of the motes during an update run were filtered from the log. The update time were processed along with the 'mean' and 'standard deviation' from baseline data according to the utility function in Equation- 1.

1) Subtract the new update time from the corresponding 'mean' of reference update time for each of the motes to calculate the absolute difference. For example, new update time of updated mote 'n'(new) is subtracted from 'mean' update time found from the baseline data for mote 'n'.
2) The absolute difference is divided by a function of 'standard deviation' to avoid any 'division by zero scenario'. This also smooths the data to avoid unrelated variations.
3) Sum up the the resulting individual scores to find out the total IWS for the update.

The resulting numbers indicated the nature of the update as has been described in Subsection- IV-E. This gives us an approximation of abnormality of the new update pattern. The higher the score, the more dissimilar is the pattern. However, the score does not contain topology awareness, as such a low score must be checked against topological orientation.

B. Threat Model

Directed towards unauthorised program image to infect the entire WSN.

- Node failure
- Node compromise
- Malicious node update
- Popping up of intruder node

C. Assumptions

A single sink in the WSN. The sink is protected and cannot be compromised. All motes in the WSN are static. We have knowledge about the topology [NOT UTILISED]. The software update behaviour in the WSN is transparent to the IDS. The IDS resides externally outside the WSN (not in motes).

- The WSN is of homogeneous nature and works in the same network

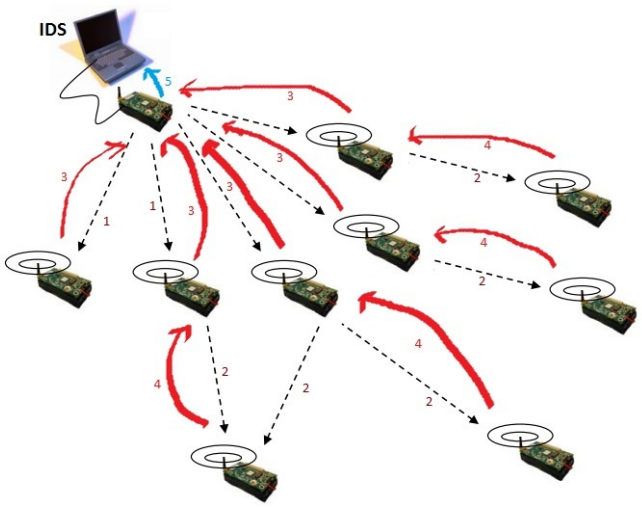


Fig. 1: IDS Modelling

- Each of the motes are connected via wireless to at least another mote
- Whenever possible, there are more than one route to reach each of the motes
- The WSN is static in nature
- Whenever a new image is updated in a mote, it sends a conformation active message to all base stations in the WSN

D. Algorithm

NOT STATED / DISCUSSED IN THIS PAPER

E. System Design

The intrusion detection algorithm suggests some modification of the OTA update protocol by incorporating an Active Message (AM). An AM is a single-hop, unreliable packet used for network abstraction. It has a destination address, a type field, provides synchronus acknowledgements [5]. An AM can be used to carry necessary timing information to the sink once an object has been transferred completely to any mote and the mote reboots with the new image running.

The IDS model has been explained in Figure 1 and 2. The figure has three kinds of components - 1) the motes in the WSN that are subject to legitimate or illegitimate update; 2) the sink which is utilisied to initiate a legitimate update. The sink is protected from all kinds of security breaches whether it is physical or logical. A IDS transport client (ITC) application runs on the sink that works in coordination with the IDS and assists in the intrusion detection; and 3) there is an IDS application that runs on a system with higher computing resources. The device is physically attached to the sink. It houses a network database (NDB).

The motes in the network perform the action of endorsing update time. It initiates an AM with the update time information to the sink. An AM has several fields: destination address, type identifier that indicates the update time information and the protocol, timing information and a checksum value. [DO WE WANT TO INCLUDE THE PATH TAGGING; MAY BE LATER - IT INCREASES RELIABILITY, NOT DIRECTLY IDS ACTIVITY?] [path tagging is good, but in all cases, what's the risk from intruders messing with the reported data?] The packet is transported over the network. When it arrives at the sink, the checksum value is examined by the ITC to ensure that the packet content has not been altered enroute. The ITC then inserts the update time, mote ID and related information to the NDB in the IDS. The IDS maintains an identifier to differentiate among different update times from different runs for the same mote.

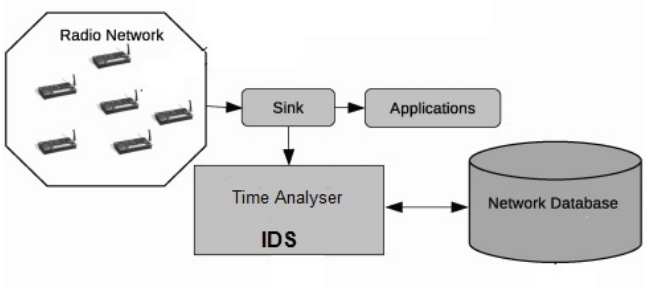


Fig. 2: IDS Framework

The first software update update run in the WSN is considered to be legitimate and the IDS takes this timing information as baseline. It is possible and desirable that the IDS is trained with several other update runs. However, the IDS needs to be manually controlled to enable multiple training runs. Outcome from these runs are statistically treated to build the baseline. Utilising multiple runs are useful and beneficial as it increases accuracy and dependency.

Once the IDS baseline has been built, all subsequent updates are liable to scrutiny by the IDS. The timing analyser module in the IDS inspects the NDB once an update activity has been detected. It determines the changes in the statistics of the update time and calculates IWS based on utility function, as

$$IWS = \sum_{i=0}^{n} \frac{|\mu_i - t_i|}{\sigma_i + 1} \tag{1}$$

where,

i — Identification of the Mote

t_i — Image Update Time at Mote i

μ_i — Mean Update Time at Mote i

σ_i — Standard Deviation of Update Time at Mote i

The IDS considers an increase of IWS upto 10% from the baseline value to be safe and marks as 'GREEN' zone, an increase above 30% to be possible intrusion and is marked as 'RED' zone. However, an increase in 10% — 30% can neither be considered safe, nor an intrusion, hence is marked as 'GREY' that indicates a situation where rules are not known. However, the thresholds are not conclusive and may require some variation based on the density around the sink and scale of deployment.

1) Database Structure: NDB stores the statistics of the update time of all the motes in the WSN for each update applied. NDB consists of three flat tables that work as storage

and also have been designed to improve performance. Records in the In-Network Activity Table (INT) contain following fields:

```
mote_id, timestamp, id_seq,
upd_seq, upd_type, zone_type
```

where, $mote\_id$ is the source node ID, $timestamp$ is the time when the new software image starts executing, id_seq is the number of times an update arrived from same $mote\_id$, upd_seq is the number of time an update has been initiated from the sink. The unique key for INT is $mote\_id$, upd_seq pair. upd_type indicates if the record belonged to a baseline update. For a baseline update type, the $zone_type$ is $zero$, while for others it is updated to indicate if the update related to that particular mote from that particular run was processed as GREEN, GREY or RED.

The Baseline Table (BLT) holds the processed information from the legitimate runs and has the following fields:

```
mote_id, mu, sigma
```

where, $mote\_id$ is the source node ID, mu is the mean time and $sigma$ is the standard deviation for each $mote\_id$ from all legitimate runs.

The Intrusion Activity Table (IAT) filters out necessary information from INT about most recent software update and contributes to the performance of the IDS. The table has two fields:

```
mote_id, timestamp
```

where, $mote\_id$ and $timestamp$ are same as the corresponding fields in INT. Every time a decision on an update has been made and a new update is detected, this table is flashed.

2) Activities in the Network: As part of enhancement into the deluge protocol, the motes are enriched with the prior knowledge of the sink or sinks in the WSN. Whenever an update takes place in a mote, it reboots with the new software running and stores the bootup time in its memory. I NEED TO CONFIRM IF THE TIME IS ALREADY SAVED WITH THE IMAGE AS PART OF DELUGE PROTOCOL IMAGE/GOLDEN IMAGE. The locally stored information is used later in case it requires to recover from packet delivery failure. The information $type$, $mote\_id$, $time\_stamp$,upd_seq are packed along with an additional checksum in an AM packet and forwarded to the sink/sinks. The AM has the following information in the packet:

```
|----------------------------------------|
|Source|---------------------------------|
|  ID  |msgtype|timestamp|upd_seq|checksum||
|------|---------------------------------|
```

Figure: Need to draw a better picture

The AM packet is relayed through the network to the sink.

3) Activities in the Sink: As an AM arrives from the radio network to the sink, the ITC application running on the sink verifies the checksum. If the checksum fails, the packet is discarded and failure recovery is initiated once only in coordination with the IDS. However, if the AM passes checksum, the ITC application extracts the relevant information and populates the INT in the resident host system.

4) Activities in the IDS: An update is typically initiated from the host system where the IDS resided. The IDS constantly monitors the programming port and coordinates with the ITC. They automatically identify the first update as input for baseline training data. It is possible to put the IDS in training mood for extended number of updates. Result from all updates run during the training period are statistically treated to build the baseline. Though the IDS can work theoretically with a single update, it is recommended to have minimum three updates for the training phase while running more training updates is desirable. For our experiments, we have considered 20 runs for each topology.

Once the training phase ends, the IDS calculates mean and standard deviations at each of the motes and stores the information on BLT. It also stores the number of update runs it considered for the BLT. This number contributes two folds: 1) it indicates the reliability of the training data / baseline; and 2) the number is used for statistical processing in case there is a need to increase the training data at a later time or data from an update is identified as acceptable is automatically included in baseline computation and the BLT is updated. Once the BLT has been built, the IDS runs on active mood and all updates are subject to intrusion checks. When an update is initiated in the WSN, data pushed into the INT are filtered and relevant information related to the ongoing update populates the IAT. The IDS waits upto a specific time, which is determined by the maximum time taken to complete a network-wide update during the training phase, before it reports the findings about intrusion possibility. While the procedure described above is quite straight forward, it gets complicated because of the unreliable packet transmission pattern experienced by WSN due to node failure, link failure and node reboot [50], [51]. IDS reports the findings with a provision of updating it later when an expected data from certain mote are not available within reasonable time. In such case, the IDS employs a packet recovery mechanism to obtain necessary information.

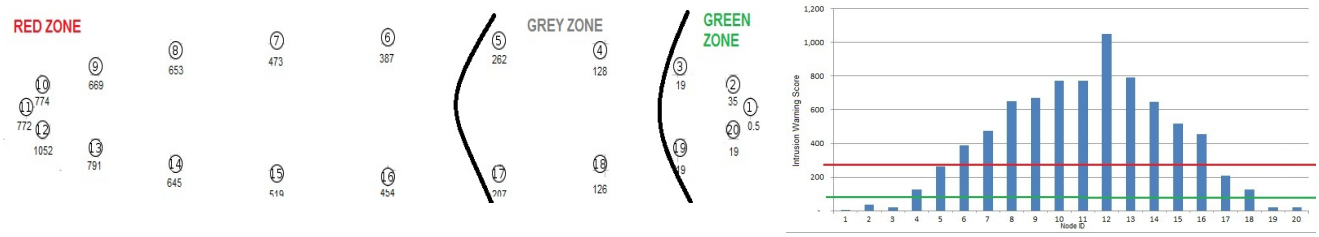
The packet recovery mechanism is initiated when a valid packet is not available form one or more motes within the determined maximum time from the updates during the training phase. Upon receiving signal from the IDS, the ITC initiates AM to the specific requesting a retransmission of the update time and waits further triple time for the required AM packet. If the packet is available, IWS is recomputed and decision is updated accordingly. If the packet is still not available within specified time, the node is marked as compromised or failed and a notification is generated.

V. Evaluation

The proposed IDS system and its technique were evaluated in comprehensive simulations. The simulation environment has been specified in Subsection- IV-A. The raw data were processed using an automation scheme that processed the raw data using a bash script. This semi-processed data were further processed using a programme written in cpp to make them

Node ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
μ	0	5	5	6	22	36	37	43	44	44	44	44	44	45	44	33	24	5	3	5
σ	0	19	19	69	139	213	276	344	377	432	432	432	377	335	273	207	137	68	17	19
IWS	0.5	35	19	128	262	387	473	653	669	774	772	1052	791	645	519	454	207	126	19	19

TABLE I: Mean and Standard Deviations of the motes and IWS of intrusion initiated from different motes. Further explained in Figure- **??**



(a) IWS and Relative position of nodes

(b) Comparison of IWS at different motes

Fig. 3: Relative position and comparison of IWS for intrusion at different motes from data in Table- I

suitable for simple mathematical calculations. Then these data were related and analyses using a spreadsheet programme to produce the IWS.

The effects of the proposed IDS were tested indifferent topologies, namely linear, circular, elliptical, double rings, wide lines/grid, tree and other topologies. While discussing all of these topologies are useful, we shall concentrate our discussion on results and findings from one of the topologies.

A. Data1 + Discussion

We have selected data from elliptical topology for several reasons. The shape of the ellipse has been designed such that motes on either side of minor axis are within each others transmission range and motes on the either side of the major axis are not. Total 20 nodes were deployed with the minor axis approximately 30 mitre. The transmission power level is kept at 100% which has a transmission range of 50 mitre and is able to interfere other transmissions upto 100 mitre apart. The motes are placed at a space of 35 mitre along the circumference of the ellipse. The deployment enables multiple transmission paths to all the motes, achieves redundancy and contributes to reliable image transfer. Extending the minor axis so that motes on either side remain out of transmission range, makes the topology equivalent to a circle, while contracting it is equivalent to a grid or even a linear topology. Overall the simulations ran well with expected results.

We assigned mote ID 1 as the sink and ran 20 updates initiated from the sink. The output data from these runs were processed and statistically treated to find out the 'mean' and 'standard deviation' of the time at which each of the nodes are updated with the new image.

Table- I shows the statistical measurements obtained at different motes and the IWS measured when each of the motes were considered as intrusion point. It can be clearly seen that IWS at the intrusion points differ considerably. The first row in Table- I contain the Node IDs that are headers for the data displayed underneath. The next two rows describe the 'mean' and 'standard deviation' that were established from the 20 legitimate updates initiated from the sink. Each cell in the last row contains the IWS calculated using function shown in Equation- 1 test runs initiated from the node indicated at top of the column. The data shown in the table can best be interpreted with Figure- **??**. Figure- **??** shows the actual relative deployment of the motes with mote ID written at the center of the tiny circle and IWS measured when an intrusion attempt has been initiated from the mote. The figure additionally divides the region in GREEN, GREY and RED zones according to the logic discussed in IV-E4. The graph in Figure- **??** shows the relative measures of the IWS from the motes.

According to the data presented in Table- I, when we analyse baseline data, the motes which are further away from the sink are found to have higher 'mean' and 'standard deviation' in terms of update time. However, 'mean' does not vary to a great extent for relatively small distance difference when multiple paths are present. The availability of more redundant paths make the image transfer more efficient and reliable. Hence, even remaining at considerably different distances from the sink, mote ID 8, 9, 10, 11, 12, 13, 14 and 15 in the elliptical topology have quite similar mean update time. However, 'standard deviation' increases dramatically as the motes are placed further from the sink. The measurement established from the baseline data shows that motes closer to the sink have lower 'standard deviation' which increases sharply with the increase in distance.

On the other hand, the utility function calculated from the Equation- 1 is designed to neutralise the changes in 'mean' and 'standard deviation' which are expected to contribute to a near $zero$ IWS that is further classified as GREEN zone for a legitimate software update. Table- I and Figure- **??** shows defined zones and IWS measured when intrusion was initiated at different motes.

The IWS increases linearly with the increase in distance from the sink. The 'distance' term can be misleading in the context of our discussion and demands further clarification. Euclidean distance between a mote and the sink does not make useful sense as the packets in the network must travel using a

relay mechanism through other motes in the network. Because of the availability of the multiple paths, it is not possible to quantify the exact distance that a packet would travel while transporting form a mote to the sink. However, an estimation of most probable link path based on the connectivity may be considered.

IWS is considerable higher for intrusion at distant motes than ones which are close to the sink. This phenomena is topology which implies connectivity dependent. It is possible that if IWS in a network are organised in a specific order, which could be close to the Figure- **??**, it would represent/resemble the original topology in some fashion. This implication would be more evident once we discuss more topologies in the upcoming paragraphs.

The IWS is also able to detect node failures in the WSN. In case of a node not reporting its its update time is handled by a error recovery procedure put in place by the IDS. However, the recovery procedure fails in such cases resulting into contributing towards the increased IWS that is reported as an intrusion. The IDS structure is such that it has an expected pattern and shape of IWS for an intrusion at some specific point. If the shape is distorted to a great extent, it indicates some unusualness which can be attributed to some other phenomena like node failure or compromise. It might also indicate a different type of attack associated with a physical intrusion. An interpretation form the IDS view of the topology would enable identification of some other types of attacks in WSN like node relocation, node repudiation, node compromise. The node failure or node compromise can take place concurrently with or without intrusion.

B. write here

Discuss other topologies

Insight for secure deployment. which topologies would work better - idea

Insight for a deployment that would ensure better connectivity

Interpretation of the results. Our argument in support of the results.

Explanation of the results to answer the question - so what. Why the result was important. Why does this matter .

Constraints and limitations of the program

Opportunities for future work

What are my specific contributions to the academic society? Do I have some recommendations about it?

VI. Conclusion

Building secure WSN is of paramount importance, yet it is quite difficult. Privacy issues have to be considered depending on application. A good overall solution must integrate many different technologies. Cryptography alone cannot ensure total security mainly due to limited resources in sensors; therefore, a multi-level approach to combine different technique in necessary, which might include designing secure protocol, careful use of key management methods and mechanisms. We propose to investigate such a solution.

Wrap the whole thing up;

Signature _____

Contact Address: 128, Owheo Building
133, Union Street (West)
Dunedin - 9010, New Zealand

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