IMPROVING THE RESILIENCE OF WIRELESS SENSOR NETWORKS AGAINST SECURITY THREATS: A SURVEY AND OPEN RESEARCH ISSUES

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ABSTRACT

Wireless Sensor Network (WSN) technology has gained importance in recent years due to its various benefits, practicability and extensive utilization in diverse applications. The innovation helps to make real-time automation, monitoring, detecting and tracking much easier and more effective than previous technologies. However, as well as their benefits and enormous potential, WSNs are vulnerable to cyber-attacks. This paper is a systematic literature review of the security-related threats and vulnerabilities in WSNs. We review the safety of and threats to each WSN communication layer and then highlight the importance of trust and reputation, and the features related to these, to address the safety vulnerabilities. Finally, we highlight the open research areas which need to be addressed in WSNs to increase their flexibility against security threats.

Keywords: Countermeasures; Reputation; Security; Threats; Trust; Vulnerabilities; Wireless sensor network

1. INTRODUCTION

A Wireless Sensor Network (WSN) is a system composed of devices and actuators to monitor and control any tasks associated with operations in certain environments when connected wirelessly (Yang, 2014). The generic architecture of a WSN is based on sensors placed over a specified field to sense and collect information on a specific task and to communicate back to its base station, often referred to as a data sink. The base station utilizes either public or dedicated communication links connected to a sensor network task manager (Boukerch et al., 2007; Chen et al., 2007b; Khalid et al., 2013; Sarobin & Ganesan, 2016). WSNs possess many benefits, including their low-cost, low-power, robustness, durability, small size, ease of deployment and multi-function ability (Yang & Cao, 2008; Yick et al., 2008; Li & Gong, 2008; Lasol & Pornpromlikit, 2016). Due to their extensive utilization and benefits, these sensors are frequently deployed in places such as deep water, battlefields, forests, airports and extreme temperature environments, which were very difficult to monitor in the past.

Over a period of time, the WSN concept has laid down the foundations for networks of distributed nodes that can communicate wirelessly (Estrin et al., 1999; Byers & Nasser, 2000).

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The Institute of Electrical and Electronic Engineers (IEEE) initially issued the Smart Transducer Networking standard (Lee, 2000); the transducers were soon referred as smart sensors due to the specification of their desired functions (Lewis, 2004), and later the term Wireless Sensor Network was introduced. Subsequently, IEEE set ZigBee as the WSN standard for wireless communication (Kinney, 2003; Egan, 2005; Yang, 2014).

WSNs, like any other communication technology, are vulnerable to security attacks and possess their own security objectives. Security breaches and attacks on WSNs may lead to disastrous events and losses. The widespread application of WSNs makes them a target for attackers and hackers. Hacking into the WSN of government, military, industrial or healthcare organizations may lead to economic collapse, defeat in war, threats to nationwide security and loss of human lives. Consequently, it is extremely important to safeguard and raise the flexibility of WSN security and privacy aspects. This paper presents a literature review of the security issues and attacks on WSNs in order to improve their flexibility. Security attacks have been grouped in terms of physical, data-link, network, transport and application layers. We then move our emphasis to discussion of trust and reputation, and how their application and organization in WSNs could help ease the recognized security concerns. Finally, we highlight the open research issues that need to be addressed to improve the flexibility of WSNs with regard to security issues. The organization of the paper is as follows. Section 2 presents the research methodology adopted, while section 3 explores the different types of vulnerability which impact WSNs. Section 4 discusses in-depth the concept of trust and reputation in WSNs, which is one of the latest and most effective security measures. Section 5 presents the open research issues in relation to increasing WSN resilience, followed by the conclusion and suggestions for future research.

2. METHODOLOGY

A Systematic Literature Review (SLR) is conducted on the specified topic. The protocol for conducting such a review was given by Kitchenham in 2004 and in 2007 (Kitchenham, 2004; Kitchenham & Charters, 2007). According to Kitchenham, the SLR is a systematic procedure of identification, interpretation and evaluation of relevant studies that pertain to a given research topic or area of interest (Kitchenham & Charters, 2007). The SLR is a well-defined and stringent procedure with an unbiased research outlook, which makes it very different to the traditional literature review and helps make a significant contribution to the research and add to the scientific value. The SLR procedure of Portocarrero et al. (2014) and Pa et al. (2015) basically consists of three major steps, namely planning, conducting and reporting. In this case, the research questions, the search plan, and the organizational plan were set during the planning stage. Once the questions had been hypothesized, the search strategies were created. Some of the most well-known and efficient journal search engines, such as Springer, IEEE, ACM, Scopus, ScienceDirect, ProQuest and Google Scholar were selected. Once the initial data gathering and the selection process were complete, the database needed to be further screened and organized. Papers were initially prearranged based on the possibility of answering one or more of the planned research questions. During the screening process for each research question, the papers were further scrutinized by analyzing their organization, topics and subtopics. The organized papers were read and studied very carefully to obtain the understanding and trends in the various aspects of WSNs. The studies clearly show that there has been a drastic rise in the research into and the application of WSNs, due to its huge advantages and usefulness. It has also been observed among researchers that security concerns have at the same time increased; this is because vulnerabilities and threats have increased as the implementation of WSNs has advanced.

3.   SECURITY - DIFFERENT TYPES OF VULNERABILITY IMPACTING WSNS

The WSN field is growing at an enormous speed, which fascinates many stakeholders, including governments, engineers and researchers, but also attackers. WSN wireless communication links are considered to be less secure than wired networks due to their broadcast nature, which can be easily tapped into by cyber enemies (Sarma & Kar, 2006). Attackers can easily interrupt wireless communication and replace valid packets with malicious ones. Without any acceptable safety measures, WSNs are vulnerable to various cyber-attacks. The vulnerabilities and sensor node limitations associated with wireless media pose particular security challenges. Security is normally achieved through a trusted and controlled atmosphere (Undercoffer et al., 2002; Zia & Zomaya, 2006; Ali et al., 2018). Existing security procedures aim to improve the security of WSNs from two aspects, namely security and reliability. Security aims to protect the WSN from outside attacks (Li & Gong, 2008; Lopez et al., 2009; Yu et al., 2012), whereas reliability guarantees the system output based on its specifications. Data packet detection, monitoring, sensing, transmission and event occurrence are some of the known issues with regard to reliability (Willig & Karl, 2005; Hsu et al., 2007; Mahmood et al., 2015).

The diverse set of WSN cyber-attacks can be divided into different categories; from the attackers' perspective, these are normally categorized into internal and external attacks (Yu et al., 2012; Ali et al., 2018). When an attacker is able to access a node by infringement through the cryptographic procedures, this normally occurs through an internal attack. On the other hand, external attacks are carried out through snooping and injecting fractional data into wireless networks. These attacks are further classified into logical network layers (application, transport, network, data link and physical layers) depending upon the type of attack made (Yang, 2014). The number of attacks which targeted the application layer, and the total number of attacks suffered by WSNs, are classified by Li and Gong (2008), López and Zhou (2008), Araujo et al. (2012), Lopez et al. (2010), Ali et al. (2015). Based on the survey carried out for this study, Figure 1 gives a brief overview of the various WSN layers and cyber-attacks involved.

Physical Layer	Data Link Layer	Network Layer	Transport Layer	Application Layer
Sybil				Repudiation Buffer overflow Software tempering Cross-site scripting Canonicalization Brute-force Cookie replay Credential theft Privilege escalation
Traffic-analysis Denial of Service Jamming Eavesdropping		Flooding		
Device tempering	Sink-hole Spoofing Worm-hole		De-synchronization	
	Unfairness Impersonation Resource exhaustion Node outage Collision Traffic manipulation	Black-hole		

Figure 1 Attacks on various WSN layers

Trust and reputation in WSNs will be discussed in the following section. Analysis of the literature is also presented to discuss advances in WSN technology in relation to security concerns in order to improve its resilience.

4.   TRUST AND REPUTATION –IMPROVING THE RESILIENCE OF WSN

Yu et al. (2010) explained that the characteristics of trust are that it is context sensitive, subjective, unidirectional and transitive. Noting this kind of behavior in humans, scholars have also attempted to apply trust to the information technology context, and during the mid-2000s the concepts of trust and reputation were first introduced into the WSN field. Trust is calculated based on the previous experience of a particular node and its degree of belief (Boukerch et al., 2007), whereas reputation is the overall perception of one node among other network nodes (Boukerch et al., 2007).

There are two main trust parameters: trust qualification and trust computation (Pirzada & McDonald, 2004; Ali et al., 2018). Trust qualification defines the numerous levels of trust, while trust calculation describes the means of measuring the trust value between nodes. It is also important to note that Trust and Reputation Management (TRM) is a system which defines the different steps that manage trust. The basic phases in TRM are to collect the facts, update the trust values and activate the creation of choices. The approach adopted in this research paper is twofold: a survey, and diverse proposals on trust and reputation.

4.1.   Brief Survey of Trust and Reputation vital

WSNs have the vital property of being distributed in nature. This is evident in Sorniotti et al.'s (2007) survey. Data processing within a network in a distributed manner makes the communication and data sync considerably simpler. For group detection and self-diagnosis methods, a Sensor Node Failure Recognition (SNFR) scheme was introduced. Ganeriwal et al. (2008) discuss the reputation systems which help to create trust among sensor nodes through the integrated approach of different domains, including economics, data analysis and cryptography. They also discuss the use of Bayesian & beta distribution probability, cryptographic material and public key authentication trust-based frameworks for non-critical sensor networks. Various WSN issues and standards are discussed by Yick et al. (2008). In addition to this, localization, the coverage area of sensors, security and synchronization are some important issues also discussed. An extensive literature on trust and reputation systems is provided by Srinivasan et al. (2009) and Reshmi and Sajitha (2014). Lopez et al., (2010) focused on a WSN trust management system survey, while Khalid et al. (2013) applied the concepts of trust and reputation seen in human behavior in daily life into the WSN field for the purpose of node interactions.

A survey presented by Han et al. (2014) discusses the detection of unusual nodal behavior by focusing on the nature and applications of WSN trust models. Srivastava and Johri (2012) and Reshmi and Sajitha (2014) conducted surveys on WSNs, which are of great importance in the field and highly considered. Both surveys present an expanded overview of indirect and direct methods to measure trust in various trust management structures. Based on the surveys, it is evident that both the notions of Quality of Service (QoS) and social trust parameters are vital for trust.

4.2.   Trust and Reputation Management

Managing the trust of the nodes and modules in a WSN is a process known as Trust and Reputation Management (TRM). Pirzada and McDonald (2004) recommended a trust model composed of trust deviation, qualification, functions and computation. Momani et al., Jsang and Isamil (Momani et al., 2007a; Momani et al., 2007b; Jsang & Ismail, 2002) used the Beta Reputation System (BRS) concept to enhance the trust level in the e-commerce environment.

Momani et al., (2007a) further enhanced their work on trust and reputation management by adopting the recursive Bayesian approach. This research was further investigated by Momani and Challa (2008), who found that a mischievous node may still be considered trusted if it behaves normally during communication. This leads to the introduction of data trust and communication trust to avoid any false data injection into the system. Later, in another study (Momani et al., 2008) compare their work with other models to draw a comparative conclusion.

Chen et al. (2007a) believe that employing tools from different domains such as probability, statistics and mathematical analysis in the trust management framework enhances the security implemented in WSNs. Following their research, they discuss the issue that sensor node trust and reputation is based on an amount of certainty in the values of that particular node. On the other hand, Fernandez-Gago et al. (2007) stress that WSNs in Ad-hoc and P2P lack proper trust management solutions.

To provide faster trust evaluation of clustered WSNs of a grouping nature, a lightweight group for trust computation based on a trust management scheme was proposed by Shaikh et al. (2009). To overcome the problem of using high end resources in implementing a group trust management scheme, an agent based trust calculation scheme was introduced by Reddy and Selmic (2011).

An approach to simplifying the comparison between trust and reputation management systems by building a simulator was introduced by Mármol and Pérez (2009). A particularly scalable cluster-based ordering trust management procedure was also introduced by Bao et al. (2011a; 2011b; 2012) after examining a wide range of trust and reputation management systems.

4.3. Frameworks and Trust Models

Numerous investigators have developed several models based on statistical methods, logical methods, nature inspired methods, fuzzy logic, etc. and various orientations such as individual and clustered distributed to present trust models and frameworks.

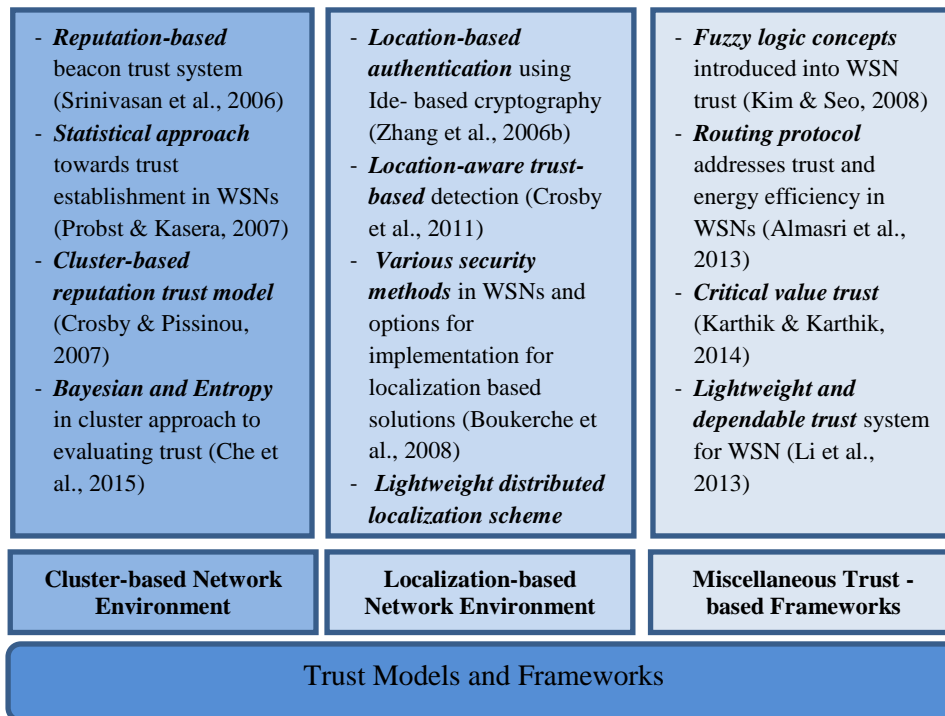| - *Reputation-based* beacon trust system (Srinivasan et al., 2006)
 - *Statistical approach* towards trust establishment in WSNs (Probst & Kasera, 2007)
 - *Cluster-based reputation trust model* (Crosby & Pissinou, 2007)
 - *Bayesian and Entropy* in cluster approach to evaluating trust (Che et al., 2015) | - *Location-based authentication* using Ide- based cryptography (Zhang et al., 2006b)
 - *Location-aware trust-based* detection (Crosby et al., 2011)
 - *Various security methods* in WSNs and options for implementation for localization based solutions (Boukerche et al., 2008)
 - *Lightweight distributed localization scheme* | - *Fuzzy logic concepts* introduced into WSN trust (Kim & Seo, 2008)
 - *Routing protocol* addresses trust and energy efficiency in WSNs (Almasri et al., 2013)
 - *Critical value trust* (Karthik & Karthik, 2014)
 - *Lightweight and dependable trust* system for WSN (Li et al., 2013) |
| **Cluster-based Network Environment** | **Localization-based Network Environment** | **Miscellaneous Trust - based Frameworks** |

Trust Models and Frameworks

Figure 2 Trust models and frameworks overview

A cluster head in a cluster network is selected from the group, which is responsible for communication between the cluster and the base station. The Distributed Reputation-based Beacon Trust System (DRBTS) was proposed and recommended by Srinivasan et al. (2006), while Probst and Kasera (2007) study the trust establishment of WSNs by the application of statistical approaches. The direct and the indirect skills of the nodes are used to assess the confidence interval. Crosby and Pissinou proposed the Cluster-based Reputation and Trust model in (Crosby & Pissinou, 2007). The proposed model supports nodes with a good reputation which build their trust values over time, but disregards those which do not do this. This work was further developed by Shaikh et al. (2009).

Location-based authentication for WSNs using ID-based Cryptography (IBC) was introduced by Zhang et al. (2006), while several localization-based WSN security protocols are considered for application by Boukerche et al. (2008). Crosby et al. (2011) proposed a another location-aware trust-based detection model, which is an extension of their previous work in (Crosby & Pissinou, 2007). The research by Miao et al. (2015) proposes a distributed localization scheme that is lightweight; a localization method of three-step approach is proposed and implemented.

Kim and Seo introduced the fuzzy logic concept into WSN trust in 2008 (Kim & Seo, 2008). In addition, Zhan et al. (2009) introduced the Sensor Trust model to mitigate the problems associated with data integrity for the purpose of hierarchical WSN. Almasri et al.'s (2013) study focused on addressing the question of energy efficiency and proposed a routing protocol which is responsible for WSN trust and energy efficiency, called the Trusted and Energy Efficient Routing Protocol (TERP). Enhancement of the reliability of WSNs based on the critical value of the trust was demonstrated by (Karthik & Karthik, 2014).

The Lightweight and Dependable Trust System (LDTS) for WSNs was proposed by Li et al. (2013). In this model, energy efficiency is increased by removing the feedback of the cluster head. Wang et al. (2014) made the computations modest to reduce the energy consumption of WSNs. Later, a Lightweight Trust Model (LTM) was introduced by Singh et al. (2015), which has a dynamic trust building mechanism. Che et al. (2015) combined Bayesian and Entropy in their cluster approach to evaluating trust.

5.   FINDINGS AND DISCUSSION

Based on the above literature overview and discussion, it is evident that the two main issues considered as key challenges to WSNs are security and reliability. According to Anand et al. (2006), the main tasks in securing WSNs comprise environment complications, topology complications, protected collections, privacy and trust management (Anand et al., 2006). Reliability concerns are associated with sensing/detection, transmission of data, event occurrence and data packets (Willig & Karl, 2005; Hsu et al., 2007; Mahmood et al., 2015). This paper has highlighted the importance of trust and reputation and the features related to them in order to better address security vulnerabilities. The areas that will be addressed by trust and reputation to benefit the overall aim of improving the security and reliability of WSNs are summarized in Table 1.

Table 1 Challenges and open research issues associated with WSN

Research domain	Known open research issues	Description
Security	Topology problems	If targeted nodes are attacked by an attacker then its apparent policy is to compromise both sensors and their keys, which logically reside in high value locations in the routing tree.
	Environment	Classification of cost-effective schemes in order to hide sensor network time; transport messages with periodic breaks; split and add random delay to messages broadcast; forged communication to deceive authentic send times.
	Assessing privacy	Different models and metrics for protocol logical level evidence, privacy and security attributes.
	Threatened cryptographic approaches	Employment of diverse cryptographic approaches for aggregation of messages.
	Ad-hoc network topology	Ad-hoc network topology is vulnerable to cyber-attacks by simplifying different types of link outbreaks, ranging from passive interfering to active snooping.
	Wireless media	Security systems for wired networks are not appropriate for WSNs due to wireless characteristics. The cost of implementing wireless media is also considered as a challenge.
Reliability	Package reliability	Transfer of data from resource-controlled sensor nodes to the sink in an efficient and reliable manner.
	Event reliability	Both in hop-by-hop and end-to-end mode of delivery of packets, receiving node held accountable for reliable transmission of information to the following node or to the destination.
	Link reliability	End-to-end packet loss ratio can be largely reduced through link reliability mechanisms. Some applications, such as intrusion detection applications, surveillance or applications used in battlefields or healthcare, require complete end-to-end reliability.
Trust and reputation	Trust models	Models that support nodes with a good reputation value to gain access to the WSN and disregard those which do not have it. By doing so, unreliable nodes can be avoided from entering the network, thereby enhancing its overall security.
	Risk assessment	Models that base their decisions on the risk of giving access to both cyber and physical realms. The risk assessment methodology consists of risk analysis and risk mitigation, which is more of a proactive approach towards managing security (Govindarasu et al., 2012).
Other challenges	Energy consumption, complexity and data reliability	There are numerous challenges associated with WSNs, mostly associated with the efficient use of energy resources, the complexities involved and data reliability, including data segregation, synchronization and classification.

One of the major security challenges to WSNs is associated with the nature of their error prone wireless links, reliable data transfer from resources to sensor nodes to the unreliable data transfer. These issues can be addressed by utilizing trust and reputation and combining them with an assessment of risk management to improve the resilience of WSNs. Researchers such as Mahmood et al. (2015) have highlighted the importance of trust in WSNs and have classified it into different stages at which it can be utilized. For example, they propose that trust can be applied in packets, at the event dependability level, or by hop-by-hop reliability. In hop-by-hop, the following hop is accountable for ensuring the reliable transmission of information to the destination, whereas in the scenario of end-to-end reliability, it is only the source and destination nodes of the end points which are responsible (Mahmood et al., 2015). However:

a) Trust as a measure can further be utilized to not only ensure reliability in transmission, but also to regulate the joining of nodes to the wireless sensor network. This will ensure an

additional tier in the process of improving security in WSNs and improve their resilience against malicious nodes.

b) Apart from utilizing trust, risk assessment can also be used as a complement to further enhance the security of WSNs. Risk management would enable one to ascertain beforehand the risk to the security of the WSN when it allow a node to join the network. This measure can then be used to assign access level tasks to nodes depending on their level of reliability. This will ensure that critical tasks are handled or assigned only to those nodes which have levels of risk below and of trust above a certain threshold.

Utilizing trust and risk also introduces the challenge of achieving reliable harmonization of measurements, minimization of human intervention in the network, and reliable delivery of a substantial number of measurements (Cinque et al., 2006).

6. CONCLUSION

In the paper, the authors have presented a review of WSN security concerns, with special attention paid to trust and reputation. The research was carried out by making a systematic literature review, which is the most suitable method of conducting a review. Issues related to the type of attacks, the features and vulnerabilities of attacks have been discussed. The notions of trust and reputation in WSNs have been debated and analysed. On the basis of the survey, the study concludes that security and reliability are the two main challenges faced by WSNs. Some shortcomings, challenges and open research issues associated with WSNs are also scrutinised. The paper provides an understanding of trust and reputation in WSNs. In the future, the authors plan to develop a secure, effective and efficient WSN mechanism.

7. ACKNOWLEDGEMENT

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