How to Secure a Wireless Sensor Network

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Abstract

The security of wireless sensor networks (WSNs) is a complex issue. While security research of WSNs is progressing at a tremendous pace, and many security techniques have been proposed, no comprehensive framework has so far emerged that attempts to tie the bits and pieces together to ease the implementors' adoption of the technologies. We answer the challenge by proposing a guidelines according to which WSN security can be implemented in practice.

1. INTRODUCTION

Security allows WSNs to be used with confidence. Without security, the use of WSN is *any* application domain would result in undesirable consequences. Table 1 serves as an illustration of what might happen to WSNs in the absence of security, categorized according to application domains. However, the implementation of security itself remains much of an art today. Although much progress has been made for the past few years, the field remains fragmented, with contributions dispersed over seemingly disjoint yet actually connected areas, for example key management only makes sure the communicating nodes (one source node and one sink node for ease of discussion) possess the necessary keys, at the same time protecting the confidentiality, integrity and authenticity of the communicated data. To guarantee the sink node receives the data at all within a certain time limit, secure multipath routing is required. Key management and secure multipath routing are but two components of the bigger puzzle that is WSN security.

Our contribution is therefore to provide a step-by-step, layer-by-layer guide to securing a WSN using existing technologies. We do so by picking up the individual puzzles littered over the security research landscape and put them together in a concise and comprehensive framework. Emerging from the framework is a set of guidelines that offer a systematic view of state-of-the-art WSN security. More importantly, our guidelines should make WSN implementators find security more approachable. We know of no existing work that attempts to perform the organization that we have done.

The rest of this paper is organized as follows. Section 2 lays down the principles on top of which our guidelines are built. Section 3 gives the first part of our guidelines from a host-based perspective. Section 4 then presents the second part of our guidelines from a network-based perspective. Section 5 concludes.

2. PRINCIPLES

Security mechanisms are devised based on a set of principles. Among these principles, some are common security strategies, some are direct consequences of the hardware restrictions of sensor nodes. The principles are described here to pave way for the guidelines in the next section:

- 1) **Energy efficiency:** The requirement for energy efficiency suggests that in most cases computation is favored over communication, as communication is three orders of magnitude more expensive than computation [1]. The requirement also suggests that security should never be overdone – on the contrary, tolerance is generally preferred to overaggressive prevention [2].
- 2) **No public-key cryptography:** Public-key algorithms remain prohibitively expensive on sensor nodes both in terms of storage and energy [3]. No security schemes should rely on public-key cryptography.
- 3) **No tamper-resistance:** Since sensor nodes are low-cost hardware that are not built with tamper-resistance in mind, their strength has to lie in their number – a few ‘fallen’ nodes should not bring the entire network down. The network should instead be *resilient* to attacks. The concept of resilience, or equivalently, *redundancy-based defense* is widely cited [2, 4, 5].
- 4) **Multiple layers of defense:** The fact that attacks can occur on different layers of a networking stack (as defined in the Open System Interconnect model) suggests that there should be multiple layers of defense, i.e. a separate defense for each layer [2].

These principles are independent of the specific traits of the application domain, so they are generally applicable.

3. HOST-BASED DEFENSE GUIDELINES

The guidelines are built bottom-up. As with wired networks, an attack on WSNs might start with compromising a node and spread to other nodes. Therefore, we first consider the sensor nodes themselves as standalone devices (host-based defense), then we take communications into account (network-based defense) in the next section.

Since physical tampering cannot be avoided, care must at least be taken to prevent software tampering in the form of malicious code (malcode). Chances are the operating system and/or the applications running in a sensor node are vulnerable to popular exploits such as buffer overflows. There are more

TABLE 1: POTENTIAL SECURITY THREATS, GROUPED ACCORDING TO APPLICATION DOMAINS. SA=SERVICE AVAILABILITY, C=CONFIDENTIALITY, I=INTEGRITY, A=AUTHENTICITY.

Application domain	Potential security threats	Properties violated			
		SA	C	I	A
Military	<ul style="list-style-type: none"> • Denial-of-service attacks by means of jamming and/or confusing the networking protocols. • Eavesdropping of classified information. • Supply of misleading information, e.g. enemy movements in the East where in fact they are in the West. 	×	×	×	×
Disaster detection and relief	<ul style="list-style-type: none"> • Supply of misleading information, e.g. bogus disaster warnings, by pranksters, causing huge financial loss as a result of unnecessary large-scale evacuation and deployment of relief equipments. 				×
Industry	<ul style="list-style-type: none"> • Eavesdropping of commercial secrets by business rivals. • Intentional disruption of manufacturing processes as a result of misleading sensor readings caused by disgruntled employees or business spies. 	×	×	×	
Agriculture	<ul style="list-style-type: none"> • The agricultural department might want to deploy WSNs to ensure that farmers do not overuse pesticides or other hazardous chemicals on their crops, but unscrupulous farmers might tamper with the sensor nodes. 			×	
Environmental monitoring	<ul style="list-style-type: none"> • Suppose government-endorsed environmental sensors are installed near a factory to monitor air/water quality to make sure the factory's emission lies beneath the pollution threshold, however by feeding the sensors with wrong information, the factory allows itself to escape detection and let its polluting emission go unchecked. 			×	
Intelligent buildings	<ul style="list-style-type: none"> • Biometrics-based access control mechanisms are compromisable if the biometric sensors can be bypassed or fooled. • Token-based access control mechanisms are compromisable if the token authentication protocol is insecure. 	×		×	×
Health/medical	<ul style="list-style-type: none"> • Providing wrong physiological measurements of a patient to the carer or doctor, a miscreant may cause potentially fatal diagnosis and treatment to be performed on the patient. 			×	×
Law enforcement	<ul style="list-style-type: none"> • If criminals are able to eavesdrop the databases of the police departments, or to misguide the detection of gunshots, or to disrupt the network, public safety will be affected. 	×	×	×	×
Transportation	<ul style="list-style-type: none"> • There is no order in the city when traffic information can no longer be trusted because they can easily be spoofed. 			×	×
Space exploration	<ul style="list-style-type: none"> • Space agencies invest billions into space exploration projects, it is only logical they want to ensure all commands executed on their space probes are authorized, and all collected data encrypted and authenticated. 	×	×	×	×

risks for operating systems that support dynamic loading of code module over the network [6]. Writing secure code is fortunately an established discipline. There is a vast body of literature on the subject [7]. There are also existing and mature tools for spotting memory errors in programs, so writing secure programs is a non-issue. Mobile code is however problematic. Code-signing, using symmetric keys per Principle 2, alone is insufficient in identifying malicious mobile code since the owner of the signing key might have been compromised. Although techniques are being developed to facilitate the safe execution of untrusted code [8], the overhead involved is non-trivial. The recommendation is thus: mobile code should only be enabled when strictly necessary, per Principle 1, in which case all mobile code should be signed and should carry a proof. The key used for signing the code is determined by the underlying key management scheme, which will be discussed later.

4. NETWORK-BASED DEFENSE GUIDELINES

An attack coming from the network to a sensor node is either aimed at disrupting the operation of the sensor node or getting information from the sensor node. Hence we are mainly looking at two types of protection: protection from denial-of-service (DoS) attacks, and protection of the secrecy of information. Multiple defenses, each for one layer of the networking stack should be implemented, per Principle 4. One layer is discussed at a time:

A. Physical Layer

The physical layer defines the actual methods used to transmit and receive information through the radio interface, for example the frequency, the data rate, the signal modulation and the spread spectrum scheme to use. DoS attacks on the physical

layer are radio jamming. Well-known countermeasures to radio jamming include adaptive antenna systems, spread spectrum modulations, error correcting codes and cryptography. There is not much room to maneuver in antenna systems and error correcting codes because sensor nodes typically use an omnidirectional antenna and Reed-Solomon codes [9–12]. Sectorized antennas as suggested by Noubir [13] are not yet available for sensor nodes. We concentrate on spread spectrum modulations in this section, and will talk about cryptography in Section 4-E.

Ideally the transceiver should support some form of spread spectrum modulation, preferably frequency-hopping spread spectrum (FHSS), instead of direct-sequence spread spectrum (DSSS). FHSS is preferred to DSSS, because DSSS requires more circuitry (higher cost) to implement, is more energy-consuming and more sensitive to environmental effects [14, 15]; on the other hand, the hop rate in a FHSS system is typically much lower than the chip rate in a DSSS system, resulting in lower energy usage [14, 16]. According to Table 2, only one of the most common sensor node transceivers supports DSSS, and among the rest, half of the transceivers support FHSS and the other half do not support spread spectrum at all. We do not recommend DSSS transceivers.

TABLE 2: COMPARISON OF SPREAD SPECTRUM SUPPORT.

Spread spectrum	Transceiver
DSSS	Chipcon CC2400 [17]
FHSS	Chipcon CC1000 [18], Conexant Systems RDSSS9M [15], MaxStream 9XStream [19], Zeevo Bluetooth [20]
No	Infineon TDA 5250 [21], National Semiconductor LMX3162 [22], RFM TR1000 [23], RFM TR1001 [24]

For FHSS transceivers, we recommend quaternary/binary frequency-shift keying (FSK) as the data modulation scheme

of choice [14, 25], and a hop rate between 500 and 1000 hops/s [26]. A maximum hop rate of 1000 hops/s does not hamper the most sophisticated interceptors [12], but per Principle 1, 500–1000 hops/s should be a practical compromise. The exact hop rate should be picked by taking into account the fact that lower hop rate gives larger transmission range, but higher hop rate gives lower response time [16].

For transceivers that do not support spread spectrum, we recommend the *channel surfing* method by Xu et al [27]. Channel surfing is essentially an adaptive form of frequency hopping. Instead of continuously hopping from frequency to frequency, a node only switches to a different, orthogonal frequency $\pm\delta$ away when it discovers the current frequency is being jammed. The value of δ can be determined by experiments, e.g. for Berkeley motes, δ is found to be multiples of 800 kHz [27]. A node can determine if the medium is being jammed if the packet delivery ratio is low but the signal strength of its neighbor is high [28].

B. Data Link Layer

The data link layer defines how data are encoded and decoded, how errors are detected and corrected, the addressing scheme as well as the medium access scheme. The anti-jam strategies in the previous section are mostly effective against ‘dumb’ jammers. According to our latest results in link-layer jamming [29, 30], smart jammers can take advantage of the data link layer to achieve energy-efficient jamming. In the earlier work [29], we show that S-MAC can be jammed energy-efficiently by jamming the control interval of the listen interval alone [29], so we recommend encrypting packets on the data link layer, for example as done in TinySec [31]. An elaborate encryption scheme depends on the key management architecture which will be discussed in Section 4-E. In the latter work [30], we show that even when the packets are encrypted, the temporal arrangement of the packets induced by the nature of the protocol unravel patterns that the jammer can take advantage of. The significance of this result is that to the attackers, compared to radio jamming, link-layer jamming offers better energy efficiency, and compared to DoS attacks on the upper layers, link-layer jamming requires less implementation and no need to know the content of the packets. According to our analysis [30], in the absence of effective countermeasures, TDMA protocols like LMAC [32] have better anti-jam properties, and therefore should be preferred to other protocols like S-MAC [33, 34] and B-MAC [35].

C. Network Layer

The network layer is responsible for routing messages from one node to another node multiple hops away, based on some system-defined parameters such as energy or latency. There are 2 types of routing protocols for WSNs: (1) ID-based protocols, in which packets are routed to the destination designated by the ID specified in the packets themselves; and (2) data-centric protocols [36], in which packets contain attributes that specify what kinds of data are being requested or provided. The

literature considers any action that results in any combination of the following an attack [37]:

- 1) Packets are dropped completely, or selectively forwarded.
- 2) The network is flooded with global broadcasts.
- 3) Some sensor nodes in the network are misguided into believing that nodes that either are multiple hops away, or that do not exist at all are their neighbors. This is called a Sybil attack.
- 4) A significant proportion of the traffic is tunneled from one place in the network to another distant place of the network, depriving other parts of the network that under normal circumstances would have received the traffic themselves. This is called a wormhole attack.
- 5) A significant proportion of the traffic is lured to a particular node or a small group of nodes, depriving other parts of the network that under normal circumstances would have received the traffic themselves. This is called a sinkhole or black hole attack. This attack can be facilitated by the wormhole attack.
- 6) Some routes form loops or detours.

These attacks are sophisticated forms of DoS attacks. Among these attacks, we ignore the last one because we do not see any significant value for the attackers in it – causing loops is not more efficient than just dropping packets; causing detours is an inefficient way of wasting the sensor nodes’ energy.

The first attack is countered using multipath routing [38].

The second attack is countered using authenticated broadcasts, which has to be facilitated by the underlying key management architecture.

Sybil, wormhole and sinkhole attacks require the attacker to forge packets. To prevent this, a key management architecture is required. In particular, Sybil attacks can be countered using random key pre-distribution schemes [39], to be discussed in Section 4-E.

Against wormhole attacks and hence sinkhole attacks, so far there is no resource-lean and energy-efficient countermeasure [40–42], i.e. with or without key management, wormhole and sinkhole attacks are still an open issue [37].

We now describe our recommendation. Consistent with Karlof et al.’s analysis [37], we recommend using data-centric protocols such as multipath directed diffusion [38], or geographic routing protocols [43, 44] in case the nodes are able to determine their own locations, because these protocols include flooding as a robust way of disseminating information. The security of geographic routing protocols depends on the correctness of the location information, as such secure geographic routing requires secure localization, which is discussed in the next section. In conjunction with these protocols, the data link layer should support encryption and authentication, just as we have recommended in the previous section, whereas the key management architecture should support authenticated broadcasts and random key pre-distribution. In general, the above strategy is not effective against wormhole and sinkhole attacks but we believe that the data link layer is easier to DoS-attack than the network layer, so if the security of the network

cannot be helped, the data link layer should at least be made as resistant to DoS attacks as possible.

If there is a need to use ID-based routing, we recommend *endairA* [45], an improved version of *Ariadne* [46], because it is provably secure against an attacker with a single compromised key and a single compromised node. However, it has to be extended to support multipath routing. Furthermore, the corresponding key management architecture has to support node-specific key pre-distribution (i.e. every node has to share one key with every other node in the network), in addition to authenticated broadcasts.

Note that per Principle 2, we do not consider public-key-based secure routing protocols at all [47–50].

D. Application Layer

The application layer manages data. What is most important is the correctness of the collected data. It is common for data to be aggregated, for example, the temperature readings of a particular region of the network to be averaged. However averaging is not a secure aggregation function [51]. A better solution is to use the median of the data. An aggregation function can be, and should always be determined to whether or not be resilient to attacks using Wagner’s technique [51]. However it is important to note that Wagner’s result is only applicable if the aggregator node is in range with all the source nodes, that is if there’s no other intervening aggregator between the aggregator and the source nodes. This scheme is applicable to cluster-based networks where a clusterhead can act as an aggregator for its cluster members.

The communication channel between an aggregator and a home server that is operated by a human user has potentially limited bandwidth, because an aggregator might be a sensor node. To guarantee that if the home server accepts an aggregation result from the aggregator, the reported result is close to the true aggregation value with high probability, Przydatek et al. [52] propose a communication-efficient transaction paradigm called *aggregate-commit-prove*, which in effect provides two layers of defense against data corruption. The first defense is commitment (hence the word ‘commit’ in *aggregate-commit-prove*): the aggregator commits to the aggregated data, by cryptographic means. The second defense is interactive proofs (hence the word ‘prove’): the aggregator proves to the base station the validity of the aggregation result, by statistical means. The aggregator and home server need to share a key with each of the source nodes.

We consider secure localization as an application service, as location is a form of data. As mentioned in the previous section, secure geographic routing depends on secure localization. Lazos et al.’s secure localization scheme [53] works on the assumptions that (1) the locators, i.e. the devices that provide trusted location information to other nodes, are tamper-resistant, and (2) the density of locators is known to every node.

E. Cross-Layer

There are two cross-layer services that are of concern: (1) key management, and (2) intrusion detection and response.

Key management is the process by which cryptographic keys are generated, stored, protected, transferred, loaded, used, and destroyed. At the outset, per Principle 2 and 3, schemes like the pebblenets [54], the terminodes [55, 56] and Luo et al.’s [57] are ruled out. The key management scheme we are recommending is based on Zhu et al.’s LEAP [58], extended according to our earlier analysis of the data link layer, the network layer and the application layer. Before giving the details, it is useful to discuss an important concept of LEAP: *passive participation*. In passive participation, a node that overhears its neighbor’s transmitted data may choose not to transmit its data if its neighbor’s data are the same as its own data, thereby saving energy. To support passive participation, a node has to share a key, called by Zhu et al. the cluster key, with its neighbors. The node also has to establish a one-way key chain [59] and send the commitment of the key chain to its neighbors to allow its neighbors to authenticate its locally broadcast messages. The combination of a cluster key and a one-way key chain is interesting because

- if only the cluster key is used, a compromised neighbor would disclose the cluster key;
- if only the key chain is used, the keys in the key chain would have to be broadcast in the clear, allowing replay attacks to take place;
- but if used together, the cluster key can be used to hide the keys in the key chain from cluster-outsiders, so that the keys do not need to be disclosed according to a schedule as in SPINS, and the keys in the key chain can be used for authentication as usual.

We now present the details. The network can be bootstrapped, and nodes can be added/removed following the protocols of LEAP [58]. We deduce the following keys are needed on each sensor node (for ease of discussion, we give the role of sink nodes / aggregators / locators to the base stations):

- **For link-layer encryption and authentication**, 1 network-wide key.
- **For authenticated broadcasts**, b commitments of b one-way key chains, where b is the number of base stations that are authorized to perform global broadcasts.
- **If the routing protocol is a data-centric protocol and the network is static**, d pairwise keys that are shared with the node’s d neighbors.

If the routing protocol is a data-centric protocol and the network is mobile, a fixed number k of randomly pre-distributed keys.

Note: these d pairwise keys, or k randomly pre-distributed keys are for countering Sybil attacks. Using k randomly pre-distributed keys allows a node to be mobile and yet establish secure connections with new neighbors, although with reduced connectivity.

If the routing protocol is *endairA* (the only ID-based routing protocol we recommend), $n - 1$ keys where n is the total number of nodes in the network.

- **For Przydatek et al.’s secure information aggrega-**

tion [52] (as discussed in the previous section), 1 shared key with the base station and 1 shared key with the home server if the node is a source node.

- **For passive participation**, $d + 1$ cluster keys, d commitments of the one-way key chains of its neighbors, 1 one-way key chain of itself, where d is the number of neighbors.

An energy-efficient key management scheme is built on top of energy-efficient cryptographic primitives, namely block ciphers, message authentication codes (MACs) and hash functions (public-key crypto is excluded per Principle 2). Among these primitives, we are only concerned with block ciphers, because MACs can be constructed from block ciphers [60], and hash functions are relatively cheap [61]. Based on our extensive investigation of the security properties as well as storage- and energy-efficiency of a few carefully selected ciphers [62,63], our recommendation is as shown in Figure 1. The recommended operation mode is OFB for pairwise links, but CBC for group communications.

Fig. 1: Selection of an energy-efficient cipher under the constraints of available memory and required security.

Intrusion detection and response is the process of monitoring anomalies on the network, collecting evidence on whether the anomalies are a result of intrusions and responding with appropriate countermeasures. What should be classified as an anomaly depends strongly on the application. A sensor node can recognize some anomalies as intrusions on its own, e.g. whether it is jammed (Section 4-A), but for some other anomalies like whether it is being targeted with Sybil attacks, it needs to collect evidence from its neighbors (Section 4-C). In view of the possibility that some of the neighbors themselves might be malicious, several reputation-based schemes have been proposed [64–67]. In these schemes, a node rates the reputation of a neighbor based on whether the neighbor is ‘cooperative’. A node’s ability to evaluate cooperativeness is however questionable. For example, the fact that a node receive data from its neighbor does not imply the neighbor is cooperating if the data is false. The node might consult other neighbors on the validity of the data, but depending on what value is measured, the other neighbors may or may not be able to assure the node of the data’s validity, moreover instead of requiring a node to constantly monitor its neighbors’ transmitted data, which is energy-consuming [68], it makes more economic sense from an energy perspective to delegate

the role to a secure aggregator (Section 4-D). Therefore per Principle 1, we do not see reputation-based schemes as playing an essential role in the security of WSNs. Different intrusion responses are applicable to different layers, and are already discussed in the respective layers.

5. CONCLUSION

Practical WSN security is a balancing act that is constantly in search of the highest level of protection that can be squeezed out of the judicious use of limited resources. We have achieved the objective of putting together the individual puzzles that comprise WSN security in the form of a comprehensive set of guidelines. However an integrated design approach should yield better results than what we have done here. For example, we are looking for better integrated secure routing and key management architecture. Until then, our guidelines should serve the need of the time.

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