

# Air Dominance in Sensor Networks: Guarding Sensor Motes using Selective Interference

Matthias Wilhelm, Ivan Martinovic, Jens B. Schmitt, and Vincent Lenders

**Abstract**—Securing wireless sensor networks (WSNs) is a hard problem. In particular, network access control is notoriously difficult to achieve due to the inherent broadcast characteristics of wireless communications: an attacker can easily target any node in its transmission range and affect large parts of a sensor network simultaneously. In this paper, we therefore propose a distributed guardian system to protect a WSN based on physically regulating channel access by means of selective interference. The guardians are deployed alongside a sensor network, inspecting all local traffic, classifying packets based on their content, and destroying any malicious packet while still on the air. In that sense, the system tries to gain “air dominance” over attackers. A key challenge in implementing the guardian system is the resulting real-time requirement in order to classify and destroy packets during transmission. We present a USRP2 software radio based guardian implementation for IEEE 802.15.4 that meets this challenge; using an FPGA-based design we can even check for the content of the very last payload byte of a packet and still prevent its reception by a potential victim mote. Our evaluation shows that the guardians effectively block 99.9 % of unauthorized traffic in 802.15.4 networks in our experiments, without disturbing the legitimate operations of the WSN.

**Index Terms**—Wireless communication, network security, IEEE 802.15.4, wireless sensor networks, RF jamming, selective interference, wireless firewall systems, software-defined radio.

## I. MOTIVATION

Wireless Sensor Networks (WSNs) are extending their application scope from industrial monitoring and location tracking to more personal and assistant technologies, such as in health care [1], assisted living [2], and home energy saving applications [3], [4]. ZigBee-enabled devices such as door locks, occupancy sensors, panic buttons and electrical sockets are already available as low-cost consumer electronics ready to be deployed in users’ residences. Imagine an emergency scenario where a gas leakage detector rises an alarm or a panic button is pressed, and since an occupancy sensor reports an occupied room, the door lock system decides to unlock and provide emergency exits. While such a scenario is a perfect motivation for using WSN technologies, it also provides an attractive playground for an attacker.

In contrast to wired networks where physical control of traffic is inherently given, wireless networks are open by nature. For this reason, both IEEE 802.15.4 (at the link-layer) and ZigBee (at the upper layers) define conventional

security services for frame protection, device authorization, key distribution, and key establishment. However, they also take into account restrictions of battery-powered, performance-limited and low-cost devices and offer tradeoffs between resource requirements and security objectives, depending on the particular application scenario. For example, according to the IEEE 802.15.4 standard, there are three security modes: (i) no security, (ii) access control lists (ACLs) based on a source address, and (iii) secured mode, offering a choice of strong security suites such as 128bit AES-CCM. From a security perspective, only the latter option offers protection in an adversarial setting. Similarly, the ZigBee-2007 specification describes key management and key exchange methods. It specifies three types of keys: (i) master key, used as an initial shared secret to generate link keys, (ii) link key, dynamically generated secret keys shared only between two devices, and (iii) network key, a global secret key shared among all WSN devices. Yet, the master and link keys are optional. Hence, it is realistic to assume that the security of standard ZigBee networks may reside in only a single shared key with the obvious risk that the capture of a single device and extraction of the secret key could jeopardize the security of the whole network. Along these lines, a recently available security analysis toolbox called KillerBee [5] offers a set of attack vectors, such as Over-the-Air (OTA) key sniffing, MAC address manipulation, key extraction from memory, and denial-of-service attacks based on flooding WSNs with memory-consuming association requests.

While it is understandable that securing WSNs includes optimizing various tradeoff “knobs,” we are concerned that this complex task together with the distributed nature of WSNs will result in inconsistent security configurations, misconfigured clients, complex key revocations, and often in a complete resignation from implementing any serious security measure. To overcome these problems, we describe our design objectives as a “wish list” of features that we believe should be part of an effective and practical solution:

- **Central control** for WSN security policy enforcement
- **Outsourcing security costs** from sensor devices
- **Transparency** with respect to existing WSN protocols
- **Generic protection** supporting different communication protocols
- **On-demand security**, i.e., paying security overheads only during attacks.

In wired networks, many of these properties are found within the concept of *network firewalls*. Firewalls are store-and-forward devices located at the edges of networks, controlling the access to the networks they are to protect, effectively

Matthias Wilhelm and Jens B. Schmitt are with the Department of Computer Science, University of Kaiserslautern, Paul-Ehrlich-Str. 36, 67663 Kaiserslautern, Germany. E-mail: {wilhelm, jschmitt}@cs.uni-kl.de

Ivan Martinovic is with the Department of Computer Science, University of Oxford, Parks Road, Oxford OX1 3QD, UK. E-mail: ivan.martinovic@cs.ox.ac.uk

Vincent Lenders is with armasuisse Science and Technology, armasuisse, 3602 Thun, Switzerland. E-mail: vincent.lenders@armasuisse.ch

defining a trust boundary between the inside and outside world by blocking any untrusted traffic from reaching the protected devices. Network administrators are generally very much in favor of firewalls as they enable a central control of policy enforcement. This is, in principle, achieved in a transparent way, without necessitating changes to existing protocols or host configurations. A firewall’s actions are usually specified by generic policies defined by filtering rules. Hence, it is hard to deny that the concept of enforcing security policies by blocking unwanted traffic before it reaches the clients could also be attractive in supporting a practical approach to WSN security. The problem is, however, that in contrast to wireline networks, the broadcast nature of the wireless channel does not provide any physical separation of the traffic and thus setting up a boundary between inside and outside world is much harder to achieve, especially when considering mobile nodes. Consequently, preventing a packet from being received cannot be based on simple and silent dropping at a store-and-forward device but requires a different mechanism.

Recently, the idea of creating intentional radio frequency interference and turning it against an adversary has shown to be a valuable alternative (or addition) to conventional security protocols. Such a “friendly jamming” paradigm has been proposed to, e.g., protect implanted medical devices [6], [7] or block suspicious transmissions in WSNs [8] (more details on related work are given in Section VIII). Yet, these protocols use radio interference either as a proactive countermeasure, i.e., jamming all communication on a certain frequency band, or demand additional higher-layer communication protocols. Hence, the existing approaches violate our design objectives of transparency, generic protection, and on-demand security.

In this work, we describe a guardian system operating at the physical layer that is able to inspect packets (including both packet header and payload) that are already on the air. Then, using a predefined security policy, it classifies a packet in real-time and, in case of policy violations, generates a “surgically” precise interference that introduces bit errors at legitimate receivers such that the malicious packet is discarded. The security policies are centrally defined and enforced ( $\rightarrow$  central control) and wireless sensors are not required to implement complex security mechanisms such as per-device packet filtering [9] ( $\rightarrow$  outsourcing security costs). Since blocked packets are essentially not received by the sensor devices, the WSN is not aware of this countermeasure, i.e., what is correctly received in the network has already been verified ( $\rightarrow$  transparency). And because this protection method is implemented on the physical layer, it is independent of any higher-layer protocols ( $\rightarrow$  generic protection). Finally, the reactive behavior of the guardian system only activates if packets that violate security policies are on the air, which means that there is presently an actual attack against the WSN ( $\rightarrow$  on-demand security). The system is implemented on the widely used software radio platform USRP2, which also facilitates its usage as an open experimental platform. Besides meeting the design goals, we make the following contributions:

- We present an FPGA-based system implementation with an overall reaction delay of  $39\mu\text{s}$ , allowing a per-packet classification based on packet contents, up to the very

last payload byte. The system is very configurable, supporting the definition of access policies in the style of `iptables`.

- Our overall system evaluation shows that even with very limited interference duration ( $26\mu\text{s}$  per packet) and large distances (up to 18 m), the system is able to destroy 99.9 % of malicious packets in our experiments.
- The effectiveness of our protection approach is validated in an IEEE 802.15.4 sensor network using the open-source toolbox KillerBee (as a realistic attacker).

The rest of the paper is structured as follows: In Section II, we describe the key concepts of our guardian system in more detail. A theoretical protection analysis of these concepts directly follows in Section III. Section IV presents the most interesting details of the guardian node implementation. A comprehensive testbed evaluation of critical system aspects is provided in Section V. In Section VI, we illustrate the potential value of the guardian system in several real-world application scenarios. Section VII provides a discussion of limitations, some open issues, and future research opportunities. In Section VIII, we thoroughly review related work and conclude the paper in Section IX.

## II. AIR DOMINANCE CONCEPT

In this section, we outline how the physical layer protection of our guardian system operates in general, and what protection properties are achieved by it.

### A. System Model and Assumptions

We consider a wireless sensor network scenario with three types of devices (see Fig. 1):

- 1) Wireless sensor nodes that perform a distributed sensing application; these nodes are the target of attacks and hence are referred to as *victim* nodes  $v$ .
- 2) *Attacker* nodes  $a$  that attempt to send malicious packets to victim nodes  $v$  to disrupt their intended network operation.
- 3) *Guardian* nodes  $g$  that want to prevent victim nodes  $v$  from receiving malicious packets from attackers  $a$ .

The sensor nodes communicate using IEEE 802.15.4 on the 2.4 GHz band and we assume that all nodes send and receive on the same channel. We further assume that the victim sensor nodes  $v$  act in compliance to the IEEE 802.15.4 standard and that they discard received packets for which the CRC checksum is incorrect. The CRC checksum is a 16 bit field calculated over a packet’s payload and headers. The CRC checksum is erroneous when a packet has at least one symbol error (we do not consider error coding mechanisms such as [10]). We further assume that the victim nodes communicate without header encryption, the guardian nodes can therefore eavesdrop and decode any transmitted packets. This is no limitation of our concept for two reasons: First, header encryption is generally not used in wireless networks because all messages must be received, decrypted, and checked for integrity using all available link keys, which is extremely inefficient; the IEEE 802.15.4 standard only considers *data* confidentiality

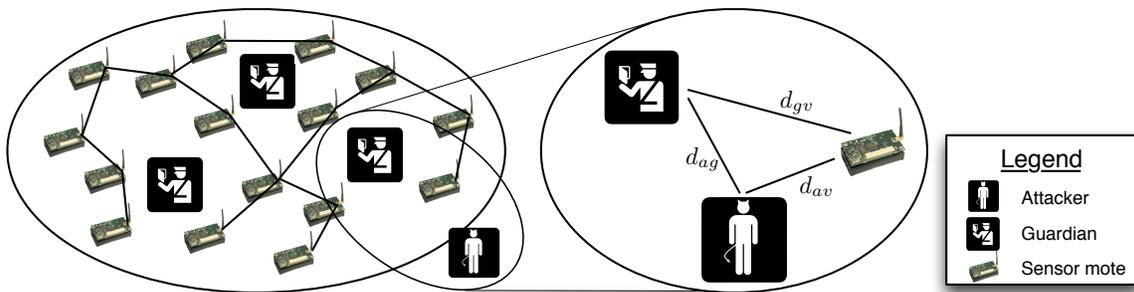


Figure 1: Sensor network deployment with co-located guardian nodes. In our protection analysis (Section III), we use the distances on the right-hand side to show that the maximal attacker distance  $d_{av}$  is drastically reduced by the guardian system.

as a security service [11, §5.5.6]. Second, even if header encryption is used guardians can be given access to the network’s cryptographic material because they are part of the network infrastructure. Then a guardian can decrypt packets during transmission (there are efficient FPGA implementations of AES available [12]) and block them, given the packets are longer than one AES block.

### B. Guardian Operation

Guardian nodes are responsible for blocking unauthorized traffic sent by the attacker nodes to the victim nodes. Each guardian continuously performs the following steps:

- 1) Monitor the RF channel for suspicious transmissions.
- 2) Decide whether a detected packet is allowed or not (before it is fully received by sensor motes).
- 3) If the packet is not allowed, briefly emit interference to destroy the packet.

Packets are destroyed in Step 3) by exploiting the CRC mechanism of IEEE 802.15.4. Since the CRC of packets at victim nodes is erroneous when at least one symbol is wrong, packets that are hit strong enough by interference from a guardian node are discarded by the victim receivers.

To react quickly, the guardians operate autonomously. This means that a packet may be hit by multiple guardians when they detect that a packet that is not allowed. We see in our evaluation ( $\rightarrow$  Section V-D) that this independent operation of the guardian nodes is beneficial, particularly in environments where individual guardians may not reliably overhear all packets. The drawback of this approach is, of course, that we introduce more interference than necessary, which could be problematic for the operation of the sensor network or other wireless networks in the same frequency band. One system design goal for the guardians is therefore to make this interference as “friendly” as possible by using very short periods of interference and using waveforms that are effective at the target sensor nodes but negligibly disturbing for other wireless networking technologies operating in the vicinity. This is important because an unintentional derogation of co-existing networks could prevent a certification of guardian devices or reduce the acceptance of their deployments; we discuss legal aspects in Section VII-B.

### C. Guardian Design Considerations

To be effective the guardians should reliably detect all packets on the air and interfere with all unauthorized ones. At the same time, the interference should be limited in order to minimize possible effects on concurrent communications on the same frequency band. We next analyze the design tradeoffs for the implementation of the guardians’ receive and blocking primitives.

1) *Reflections on Guardian Detection Sensitivity:* In order to correctly detect and demodulate a packet at a receiver, the incoming signal power at the antenna must be greater than the receiver sensitivity. This sensitivity represents the minimum signal power at the antenna that results in a specified packet error performance. The receiver sensitivity is given by  $S = N_T N_F \text{SNR}_{\min}$  [13], where  $N_T$  is the thermal noise,  $N_F$  is the noise figure of the particular receiver and  $\text{SNR}_{\min}$  a modulation-specific threshold for the minimum required signal-to-noise ratio. For IEEE 802.15.4-compliant receivers with O-QPSK modulation on the 2.4 GHz band, optimal coherent detection, and a maximum packet error rate of 1%, the theoretical sensitivity limit is  $S_{\min} = -112.2$  dBm. However the standard only demands a sensitivity of at least  $-85$  dBm, and commercial radio modules exhibit sensitivities ranging between  $-92$  dBm to  $-110$  dBm.<sup>1</sup>

Our analysis in Section III shows that the guardians benefit from a high sensitivity. Next, we discuss several approaches to help increasing the guardian’s detection performance. Lanzisera and Pister [14] show that 6.6 dB are generally sacrificed by design decisions, but 5.8 dB of this can easily be reclaimed with improved receiver implementations. A better sensitivity can also be provided by using low noise components and more efficient demodulating schemes.

The sensitivity of guardian nodes can even be designed to go beyond the theoretical sensitivity limit of  $-112.2$  dBm of regular receivers in sensor nodes. At  $-112.2$  dBm, an ideal IEEE 802.15.4 receiver will exhibit less than 1% packet errors, however, guardian nodes may exploit the fact that it is not necessary to receive all bits in a packet correctly to successfully classify it. Bit errors that occur outside the portion of the packet that matches a rule have no effect on the detection

<sup>1</sup>An online comparison of various commercial receiver implementations with links to the corresponding data sheets is available at [http://en.wikipedia.org/wiki/Comparison\\_of\\_802.15.4\\_radio\\_modules](http://en.wikipedia.org/wiki/Comparison_of_802.15.4_radio_modules)

and may hence be tolerated by guardian nodes. Even bit errors that occur within the portion of the packet of a rule may be tolerated at the cost of occasionally destroying a packet that does not match the specified rule. By tolerating up to 10% BER, the sensitivity can be improved by more than 11 dB [14]. Significant detection improvements are hence realizable. The sensitivity gain of tolerating bit errors is substantial while causing only few false positives. For example, considering a blocking rule that is matched to a 32 bit address field, if we tolerate a 2 bit error (6.25% BER) and assuming a uniform address distribution, the false positive rate remains below 0.00002% while the sensitivity is increased by 10 dB. However, this analysis may be affected by other rules in the active rule set if they consider the same portions of the packet. We assume in this work that modest improvements are possible and leave a detailed analysis of achievable sensitivity gains to future work.

2) *Reflections on Guardian Interference*: To achieve “friendly” interference, the duration of the blocking signals should be as short as possible. In IEEE 802.15.4, one erroneous symbol already leads to a wrong CRC checksum, and the packet at the victim node is discarded. Hence, a guardian who detects an unauthorized packet ideally needs to interfere with that packet for the duration of a single symbol (16  $\mu$ s). We investigate in Section V-C that, under real-world settings, it requires a slightly higher duration of selective guardian interference to effectively block all undesired packets. However, this short interference period is still limited and negligible compared to the signal duration of the packet emitted by the attacker. A wireless sensor network will hence not be significantly impacted since IEEE 802.15.4 nodes perform carrier sensing and should not transmit concurrently with the attacker anyway.

Another aspect of friendly interference relates to the choice of the interference waveform. It is well known that certain waveforms are more effective at causing bit errors than others [15]. The effectiveness of the interference waveform depends on the particular modulation scheme and the filters at the receivers. Advantageously, wireless sensor nodes are generally not designed to suppress in-band interference well. They only low-pass filter the baseband signal and send the output directly to the demodulator [16]. We see in our experimental evaluation in Section V-C that a continuous sine wave, a waveform that is generally known as being ineffective, happens to destroy packets even more effectively in IEEE 802.15.4 with the same power budget than band-limited white noise or modulated signals. Using a very narrowband waveform like this provides the advantage that other technologies like WLAN are able to efficiently suppress this kind of interference [17] and hence remain unaffected by the guardians.

### III. PROTECTION ANALYSIS

In this section, we analyze the nature of protection offered by our system of distributed guardians. For ease of exposition, we deliberately use simple propagation and receiver models to deliver the key insights on the concept (we use log-distance path loss and an SINR-based receiver model). The notation used in this section is summarized in Table I for convenience.

Term	Description
$d_{av}$	Distance between the attacker and the victim
$d_{ag}$	Distance between the attacker and the guardian
$d_{gv}$	Distance between victim and the guardian
$P_a$	Radiated power by the attacker
$P_g$	Radiated (interference) power by the guardian
$S_v, S_g$	Receiver sensitivity of victim and guardian
$\gamma_{\text{SIR}}$	Signal-to-interference threshold for reception
$\alpha$	Path loss coefficient
$L(d)$	Path loss and fading function of distance $d$
$\mathcal{A}_{\text{force}}, \mathcal{A}_{\text{stealth}}$	Attackers using a brute-force or stealthy strategy
$\mathcal{R}_A$	Resulting attack range, performance metric for attackers

Table I: Notation used in the protection analysis.

#### A. Protection Constraints

For a guardian  $g$  to protect a victim node  $v$  from an attacker  $a$ , the guardian must be able to detect the signals from the attacker and interfere with the attacker’s signal at the victim node such that the packet is discarded. This leads to the following two necessary conditions for guardian protection.

*Condition 1 (Detection)*: Let  $P_a$  be the emitted signal power of the attacker and  $L(d_{ag})$  be the path loss and fading between the attacker and the guardian. The guardian is able to detect the malicious signals iff

$$P_a L(d_{ag}) \geq S_g,$$

where  $S_g$  is the sensitivity of the guardian.

*Condition 2 (Destruction)*: Let  $P_a$  be the emitted signal power of the attacker,  $P_g$  be the emitted power of the guardian’s interference signal, and  $L(d_{av})$ ,  $L(d_{gv})$  be the path loss between attacker–victim and guardian–victim, respectively. The guardian is able to destroy the packet at the victim if the signal-to-interference ratio is below a certain threshold

$$\frac{P_a L(d_{av})}{P_g L(d_{gv})} < \gamma_{\text{SIR}},$$

where the threshold  $\gamma_{\text{SIR}}$  is determined by the modulation scheme, the interference waveform and how well the victim node is able to suppress such interference. If the interference waveform is zero-mean white gaussian noise, the threshold  $\gamma_{\text{SIR}}$  is between 0 dB and 3 dB according to the IEEE 802.15.4 standard [11]. More effective waveforms by the guardians leads to higher values of  $\gamma_{\text{SIR}}$ . We evaluated this value for the MICAz platform with several waveforms in Section V-C and find an additional gain of 3–5 dB in jamming effectiveness.

A sensor network remains protected if there exists at least one guardian that fulfills these two conditions for each attacker and victim node pair. In the remaining of this section, we discuss that these conditions are generally easy to fulfill as there exists a large asymmetry between the capability requirements for attackers and guardians.

#### B. Attacker Models

The goal of the attacker is to inject packets of its choice into the protected network. We consider two attacker strategies against the guardians:

*Brute-force attacker  $\mathcal{A}_{\text{force}}$* : the attacker tries to overcome the guardian’s interference by using a large transmission power  $P_a$ :

$$\frac{P_a L(d_{av})}{P_g L(d_{gv})} > \gamma_{\text{SIR}}.$$

*Stealthy attacker*  $\mathcal{A}_{stealth}$ : the attacker tries to choose a small transmission power  $P_a$  such that the injected packet is received only by the victim but is not detected by the guardian. The attack is successful iff

$$P_a L(d_{av}) \geq S_v \quad \text{and} \quad P_a L(d_{ag}) < S_g.$$

While the first strategy is easy to implement, it also leads to a steeply increased energy cost of the attacker (an analysis for 802.15.4 is given in Proposition 8). The second strategy is more challenging to implement in practice as very fine-grained power control and a clever positioning of the attacker is required to perform the attack successfully.

### C. Attacker–Guardian Asymmetry

To illustrate the asymmetry between an attacker attempting to inject malicious packets and the guardian protecting the victim nodes, we consider a log-normal path loss model  $L(d) = L_0 d^{-\alpha}$ , with reference path loss  $L_0$ , distance  $d$ , and path loss coefficient  $\alpha$ . We use the following metric to capture the asymmetry between an attacker and a guardian:

**Definition 1** (Attack Range). The (worst-case<sup>2</sup>) attack range  $\mathcal{R}$  is the maximum distance  $d_{av}$  between attacker  $a$  and victim node  $v$  such that an attack still succeeds.

An attacker wants the attack range to be as large as possible such that it may launch the attack from arbitrary locations and still remain undetected in the physical world. A large attack range further makes an attacker powerful as it can attack more nodes from a single location. From the perspective of the network, a small attack range is desired as it forces an attacker to expose itself in the physical world and minimizes the number of victim nodes that an attacker may attack simultaneously. If the attacker is constrained in terms of reachable locations, e.g., when the attacker can only attack from outside a building, the number of sensor nodes in its attack range may also be zero for all reachable attack positions, effectively thwarting the attack.

**Example 2.** Without a guardian, the attack range  $\mathcal{R}_{\mathcal{A}_{force}}$  of an attacker  $\mathcal{A}_{force}$  using a powerful COTS transmitter ( $P_a = 20$  dBm) and MICAz victims ( $S_v = -94$  dBm) under the log-normal model with path loss parameters specified in the IEEE 802.15.4 standard [11, Annex E.5.3]<sup>3</sup> is  $\mathcal{R} = 384.51$  m.

The effect of an active guardian is to considerably reduce the attack range. We derive bounds on the attack range for both attacker models  $\mathcal{A}_{stealth}$  and  $\mathcal{A}_{force}$  in the following.

**Proposition 3.** *The attack range  $\mathcal{R}_{\mathcal{A}_{stealth}}$  of attacker  $\mathcal{A}_{stealth}$  is bounded by  $d_{vg}/\left(\sqrt[\alpha]{S_v/S_g} - 1\right)$  if a guardian is present.*

*Proof:* To prevent detection, the attacker must satisfy two conditions simultaneously: its received signal power at the

<sup>2</sup>This notion of attack range is under worst-case assumptions where attacker, victim, and guardian are on one line with the victim in the middle, maximizing the distance between attacker and guardian  $d_{ag}$  for a given attacker–victim distance  $d_{av}$ .

<sup>3</sup>We converted the parameters given in the standard to our non-logarithmic model: reference distance  $d_0 = 8$  m,  $\alpha = 3.3$ , path loss at  $d_0$  is  $L_0 = d_0^\alpha 10^{58.5/10}$ . Later derivations use distance ratios and are thus independent of the choice of  $L_0$ .

victim must be above the sensitivity level of the victim and below the sensitivity of the guardian:

$$P_a d_{av}^{-\alpha} \geq S_v \quad (1)$$

$$P_a d_{ag}^{-\alpha} < S_g \quad (2)$$

Following (1) and (2), the attacker must choose a power  $P_a$  that satisfies  $d_{av}^\alpha S_v \leq P_a < d_{ag}^\alpha S_g$ . Thus, such a  $P_a$  only exists iff  $d_{av}^\alpha S_v < d_{ag}^\alpha S_g$ . Using this condition and the relation  $d_{ag} \leq d_{av} + d_{gv}$  (by triangle inequality), we find that the attacker  $\mathcal{A}_{stealth}$  can only remain undetected if its distance to  $v$  satisfies

$$d_{av} < \frac{d_{vg}}{\sqrt[\alpha]{S_v/S_g} - 1}. \quad (3)$$

The bound is independent of the attacker’s transmit power. ■

The asymmetry with the attacker model  $\mathcal{A}_{stealth}$  is provided by the sensitivity ratio  $S_v/S_g$  (as discussed in Section II-C1): the higher this ratio, the smaller is the attack range  $\mathcal{R}_{\mathcal{A}_{stealth}}$ . Additionally, this range only applies if the attacker maximizes its distance to the guardian, such that it has to find a position where the attack is feasible first. The following example applies typical values to illustrate how the attack range is considerably reduced compared to Example 2 where no guardian is present.

**Example 4.** In Section VI-B, we present an indoor application scenario with MICAz sensor motes and a KillerBee attacker. Assuming a near-optimal receiver at the guardian with a sensitivity of  $-110$  dBm ( $-112.2$  dBm is the theoretical sensitivity limit of an ideal 802.15.4 receiver), tolerating a limited number of bit errors and hence a non-zero false positive rate with a conservative improvement of 6 dB to keep the false positive rates low (say less than 0.001 %), the sensitivity of the guardian becomes  $S_g = -116$  dBm, resulting in a ratio  $S_v/S_g$  of 22 dB. With a maximal protection distance  $d_{gv} = 10$  m and  $\alpha = 3.3$ , the attack range decreases to  $\mathcal{R}_{\mathcal{A}_{stealth}} = 2.75$  m, which is a reduction by a factor of 140 compared to the case where no guardian is present.

**Proposition 5.** *The attack range  $\mathcal{R}_{\mathcal{A}_{force}}$  for attacker model  $\mathcal{A}_{force}$  is bounded by  $\sqrt[\alpha]{P_a/(\gamma_{SIR} P_g)} d_{gv}$ .*

*Proof:* If the attack signal is detected, a brute-force attacker has still the opportunity to overcome the interference signal if

$$\frac{P_a d_{av}^{-\alpha}}{P_g d_{gv}^{-\alpha}} \geq \gamma_{SIR}.$$

Consequently, the attacker must choose its distance such that

$$d_{av} \leq \sqrt[\alpha]{\frac{P_a}{\gamma_{SIR} P_g}} d_{gv}. \quad (4)$$

The attacker is assumed to be power-limited, such that this bound exists. ■

**Example 6.** In Section VI-C, a sensor network with several MICAz motes captured by an attacker is considered, which our guardian system effectively disconnects from the network. MICAz motes (like many other COTS transmitters) have a maximum output power of  $P_a = 0$  dBm, the transmit power of a guardian node is  $P_g = 20$  dBm, and the interference waveform being used is assumed as  $\gamma_{SIR} \approx 3$  dB. With a

maximal protection distance  $d_{gv} = 10\text{m}$ , the attack range  $\mathcal{R}_{\mathcal{A}_{\text{force}}}$  of the brute-force attacker is brought down to  $0.70\text{m}$ .

Last but not least, a brute-force attacker also has to pay a price in terms of energy investment to successfully mount its attack.

**Definition 7** (Energy cost). The energy cost of an attacker  $\mathcal{A}_{\text{force}}$  is the ratio of the energy required by the attacker to send a packet over the energy required by the guardian to block the packet.

**Proposition 8.** *The energy cost is*

$$\frac{P_a d_{av}^{-\alpha} \ell \cdot 32 \mu\text{s}}{P_g d_{gv}^{-\alpha} t_{\text{interfere}}}, \quad (5)$$

where  $\ell$  denotes the packet length in bytes and  $t_{\text{interfere}}$  the duration of the interference signal from the guardian.

**Example 9.** If, for ease of exposition, we assume that the attacker and the guardian emit at the same power and are at the same distance from the victim, the (received) power ratio  $P_a d_{av}^{-\alpha} / P_g d_{gv}^{-\alpha}$  is equal to one. Considering a typical IEEE 802.15.4 packet size of 32 bytes and a necessary interference duration of  $t_{\text{interfere}} = 16 \mu\text{s}$  to destroy one symbol, the energy cost is 64. In other words, the guardian needs to invest 64 times less transmit energy to destroy a packet than the attacker needs to invest to transmit the packet to the victim.

This observation shows again an asymmetry in the required energy between an attacker and a guardian. While an attacker might in some cases still be able to slip through the protection of the guardians, the effort required to do so is considerably higher than the effort required by the guardians. This asymmetry is precisely what we refer to as *air dominance*, where guardians are able to effectively and efficiently control and block undesired transmissions from attackers before they can reach the network.

#### IV. GUARDIAN IMPLEMENTATION

After introducing the concept, we describe the implementation of our system that performs the detection, classification, and destruction of malicious packets. The system design is driven by the need for low-latency operation, as the reaction time of the system must be smaller than the duration of a packet to both classify and destroy it. And because the classification is based on packet content, the allowed reaction time should be only a fraction of a packet's duration, i.e., in the order of tens of microseconds.

We implement the guardian nodes on the USRP2 software-defined radio (SDR) platform. The SDR paradigm allows full physical layer access by the guardian; in contrast, off-the-shelf receivers do not allow low-latency access to detected symbols, nor do they offer freedom in choosing the transmitted interference waveform. However, these factors are crucial to enable a deep look into packets and to use the most effective interference waveform with a given power budget. For example, related reactive jamming systems implemented on sensor motes [8], [18], [19] do not allow to classify based on content and to destroy packets during transmission. Still, an implementation on the USRP2 is not straightforward because

the time to classify and intercept a packet is below  $500 \mu\text{s}$ , which forces tight timing constraints on the system. In the common host-based architecture for software radio using GNU Radio, where digital samples are forwarded to a host via Ethernet and signal processing is performed on the host CPU, large and non-deterministic latencies prevent to meet real-time requirements [20]. In our implementation, we fulfill the requirements of real-time detection and subsequent destruction of a packet on the air; we design the guardian as a stand-alone system, completely implemented on the USRP2's FPGA and on-board micro-controller (our previous work is based on the same framework [21], [22]). The system is optimized for speed to reach reaction times of tens of microseconds to allow access to the full payload and still reliably destroy the packet. The system components are depicted in Fig. 2, the workflow of the system is (from left to right): (i) detecting and demodulating relevant transmissions, (ii) forming decisions based on the packet content, and (iii) interfering with malicious packets. The system currently supports the 2.4 GHz PHY of IEEE 802.15.4. Next, we provide a brief description of each functional component.

##### A. Detection Subsystem

This subsystem continuously scans the RF medium to detect any packet that might be received by the network and receives and delivers the packet's content to the subsequent decision subsystem. It consists of a receiver optimized for speed that synchronizes to packets and demodulates the contained bytes, and a framer that interprets the bytes according to the IEEE 802.15.4 standard, providing access to header fields and payload bytes.

**802.15.4 receiver.** We implemented an IEEE 802.15.4 receiver using coherent O-QPSK demodulation and a correlating direct sequence de-spreader to recover symbols in FPGA logic. The de-spreader removes the direct sequence spreading code used in the 2.4 GHz PHY. The receiver directly operates on the stream of complex (I/Q) samples coming from the USRP2's analog-to-digital converter: it first synchronizes with the incoming preamble, then detects each detected symbol (4 bit of information), and finally delivers it to the framer. The FPGA implementation ensures that the detection latency is limited, we measured a delay in the receiver below  $4 \mu\text{s}$  from the presence of the signal on the channel to the time it is available for interpretation by the rule checker.

**Packet framing.** This component interprets the received symbols according to the IEEE 802.15.4 packet definition, granting access to header fields and payload. IEEE 802.15.4 supports several address modes that use varying header layouts that must be supported by the framer. This component also notifies the rule checker that a new packet was detected via interrupts and provides a memory mapping that can be queried to gain access to header fields and payload bytes.

##### B. Decision Subsystem

The decision system is triggered via interrupts by the packet framer when a pre-defined point in the packet is reached (e.g., when the full link layer header is available) to trigger the

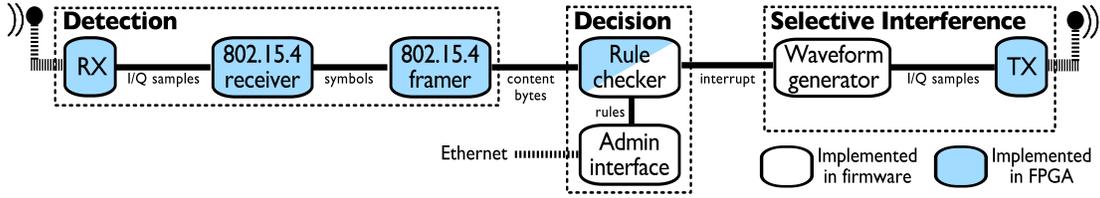


Figure 2: Component diagram of the guardian implementation. We consider two different rule checker implementations (firmware/FPGA).

decision process on whether the packet should be blocked or not. The current implementation supports decisions based on packet content and received signal strength. However, spoofing or replay attacks are challenging to detect based on these features alone. Additional possibilities to classify packets, such as more robust physical layer features (angle of arrival, device fingerprints, etc.) are part of our future work, and are discussed further in Section VII-A.

**Rule checker.** The rule checker classifies incoming packets according to a pre-defined policy. It is the critical component for real-time operation because the overall reaction time mainly depends on its execution time. Therefore we have implemented and evaluated two different versions: (i) firmware code written in C and running on the USRP2’s (soft-) micro-controller, which offers runtime reconfigurability but is comparatively slow, and (ii) an implementation in FPGA logic that reduces the reaction time, but the security policy must be specified at compile time. In both implementations, the rule checker notifies the interference subsystem with an interrupt that a short burst of interference must presently be generated to destroy the malicious packet.

**Rule system.** The firmware-based rule checker allows to define content-based rules in the style of `iptables`, defining rule chains that consist of one or more rules, each with zero or more matches (such as source or destination address). We implemented a command line tool (`gtables`), which generates a data structure that can be directly interpreted by the firmware rule checker. An example is the following rule definition with two matches (preventing the reception of all control packets going to the broadcast address in PAN `0x22`):

```
gtables -A -m dst --pan 0x22 --addr 0xFFFF
        -m type --ctrl -j DROP
```

This mechanism allows to define complex access policies and deploy them on the distributed guardians. The FPGA rule checker uses hardware gates to compare detected packet bytes to a table of predefined values in parallel, such that the execution time is considerably reduced.

**Administration interface.** We use the USRP2’s Ethernet interface to update the active rule set of the firmware implementation, set operation parameters (center frequency, transmission power), and collect system statistics, from a central point of administration. The USRP2 supports the IP protocol over Ethernet, such that all guardians can be connected over existing networks and configured remotely by a single administrator.

### C. Selective Interference Subsystem

When a packet is classified as malicious, the guardian takes action and prevents the reception of the packet by its protected sensor nodes.

**TX waveform generator.** As described in Section 2, the efficiency of intentional interference depends on the waveform that is transmitted, captured in the detection threshold  $\gamma_{\text{SIR}}$ . With a software-defined radio, arbitrary waveforms can be specified using a sequence of I/Q samples, which completely defines a transmitted signal. Our guardian implementation supports continuous wave (CW), noise, and arbitrary IEEE 802.15.4-modulated symbols as interference waveforms.

**Transmission.** The I/Q samples are finally sent to a digital-to-analog converter (DAC), modulated onto a carrier in the 2.4 GHz band, and amplified up to a maximum output power of 20 dBm (100 mW). External antennas and amplifiers can be used to boost the effectively radiated power further.

## V. GUARDIAN EVALUATION

We are interested in the real-time performance characteristics of the guardian, especially with regard to the system challenges of low-latency and reliable packet dropping at the receiver. We evaluate how well the different subsystems of the guardian cooperate to achieve a selective blocking of malicious packets. The relevant time parameters of the guardian operation (depicted in Fig. 3) are described first and then evaluated in the following subsections.

- The IEEE 802.15.4 receiver scans the wireless channel for relevant signals. Once a packet is discovered, the system starts demodulating the incoming signal, interpreting the bits as header fields according to the standard. The rule checker starts after receiving the packet bytes of interest, i.e., after the time duration denoted as  $t_{\text{listen}}$ . This duration depends on how deep the packet is inspected. For example, a typical duration for the physical and link layer headers of IEEE 802.15.4 is  $t_{\text{listen}} = 480 \mu\text{s}$ .
- After the features required by the rule checker are available to the guardian, the rule checker begins to classify the packet according to its active rule set. For the firmware-based rule checker, this set is traversed in sequential order. Thus, the required time (denoted as  $t_{\text{decide}}$ ) depends both on the number of rules as well as the number of matches in each rule. For the FPGA-based checker, several rules are checked in parallel; we measured delays below  $10 \mu\text{s}$ .
- In case the verdict of the rule checker is to destroy the packet, the hardware initiates the interference process by preparing a waveform and starting its transmission.

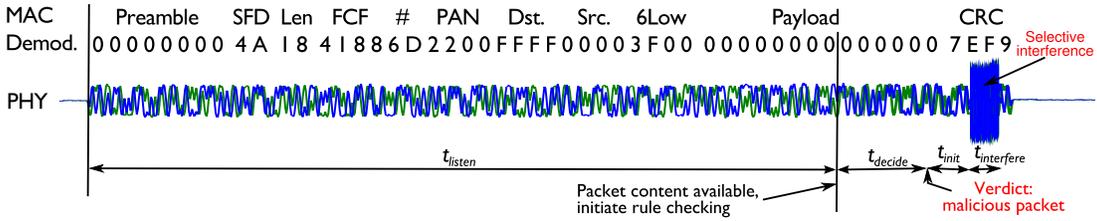


Figure 3: Guardian in operation: first, the packet’s signal is demodulated to access its content for classification. The guardian must wait for the payload bytes to arrive ( $t_{listen}$ ) before the rule checker can start. When the packet is declared malicious (after  $t_{decide}$ ), the transmission of interference is prepared ( $t_{init}$ ), and the packet destroyed ( $t_{interfere}$ ).

We measured this delay ( $t_{init}$ ) to be small ( $2\text{--}3\ \mu\text{s}$ ) and deterministic, so that it is not a limiting factor in the reaction time performance.

- Finally, an interfering signal is applied to the wireless channel, with a duration of  $t_{interfere}$ . The signal must be sufficiently long to reliably destroy the packet at the receiver, but should also be as short as possible to limit the interference with co-existing networks.
- The overall system reaction time is denoted as  $t_{react}$ , which is defined as the time from the start of classification to the end of the interference, i.e.,  $t_{react} = t_{decide} + t_{init} + t_{interfere}$ .

We proceed by first evaluating each system component described in the previous section to determine its time parameters, and then evaluate the overall system performance.

#### A. Detection Accuracy

This part of the evaluation is concerned with the speed and precision of the packet detection subsystem. A correct operation is crucial because only detected packets are classified (and destroyed if necessary). We evaluate the guardian’s ability to detect packets correctly while varying the distance between attacker and guardian ( $d_{ag}$ ). Due to path loss, the signal strength gradually reduces, making it harder to distinguish signal from noise. As reference, we compare the performance of a standard-compliant MICAz receiver in this experiment to observe if the sensitivity of the guardian is better than that of the motes in the protected network.

**Experimental methodology:** The receiver under test (either guardian or MICAz mote) is placed at a fixed position at one end of the experimentation area, a 3 m wide hallway. This indoor scenario is a challenging test for the receiver because multipath effects and inter-symbol-interference (ISI) increase the difficulty to detect signals correctly. The guardian runs on a USRP2 with an XCVR2450 transceiver and omni-directional antennas (3 dBi gain). The attacker is a MICAz mote with its default antenna, using its maximum output power (0 dBm) to transmit 100 packets/s (which contain 48 symbols and have a duration of  $768\ \mu\text{s}$ ) for 10 s.

Starting from a 1 m attacker–receiver distance, we then move the attacker to a set of measurement positions with distances  $d_{ag} = 1, \dots, 30$  m. For each position, the attacker transmits 1000 broadcast packets. The receiver (guardian or MICAz) counts the successfully detected packets (confirmed by a CRC check) for the packet reception ratio.

Blocking rule	Byte offset	Max. $t_{react}$	Firmware	FPGA
Start-of-Frame Delim.	5	864 $\mu\text{s}$	✓	✓
Frame Control Field	7–8	768 $\mu\text{s}$	✓	✓
Source Address	14–15	544 $\mu\text{s}$	✓	✓
Payload byte #16	27	160 $\mu\text{s}$	✓	✓
Last payload byte	30	64 $\mu\text{s}$	×	✓

Table II: Impact of overall reaction delay on feasible blocking rules. The symbol ✓ indicates that the guardian can use the respective blocking rule and still destroy the packet.

**Results:** The detection results are shown in Fig. 4b. The COTS receiver performs well in this experiment, with a detection radius of approximately 20 meters. With 12 out of 20000 packets in this range, only a limited number of packets was not received successfully. Our FPGA-based receiver implementation has an increased reception radius (up to 25 m), indicating a higher sensitivity compared to the MICAz mote. However, the performance for longer distances deteriorates slightly because the receiver is sensitive to multipath fading effects, causing a fraction of packets to be missed in some locations. We mitigate this effect by using a second guardian. In this setup, the number of missed packets is again reduced. Overall, the system fulfills the goal of a better receiver sensitivity discussed in Section 2, such that the guardians are suitable to protect sensor nodes from a distance.

#### B. Reaction Delay

By reaction delay  $t_{react}$ , we refer to the time from receiving the content bytes of interest until the interference is finished. This delay affects how deep the guardian can look into a packet, because the interference must overlap with it. It is mainly dependent on the execution time  $t_{decide}$  of the guardian rule checker to decide whether the packet should be destroyed. An overly slow decision process may shift the selective interference behind the end of the packet. We put both firmware and FPGA-based rule checker to the test.

**Experimental methodology.** The measurements are taken using the FPGA’s 100 MHz internal clock to record timestamps, which allows us to reach a timing precision of 10 ns. The rule evaluation is timed from the instant a hardware interrupt signals the detection of an IEEE 802.15.4 header by the framer to the instant the rule system returns a verdict on how to treat the packet. In the firmware-based rule system, this is the return of the C function call that activates the rule checker. For the FPGA-based rule checker, the timestamp is taken when the rule checker interrupt to start the interference arrives in the firmware.

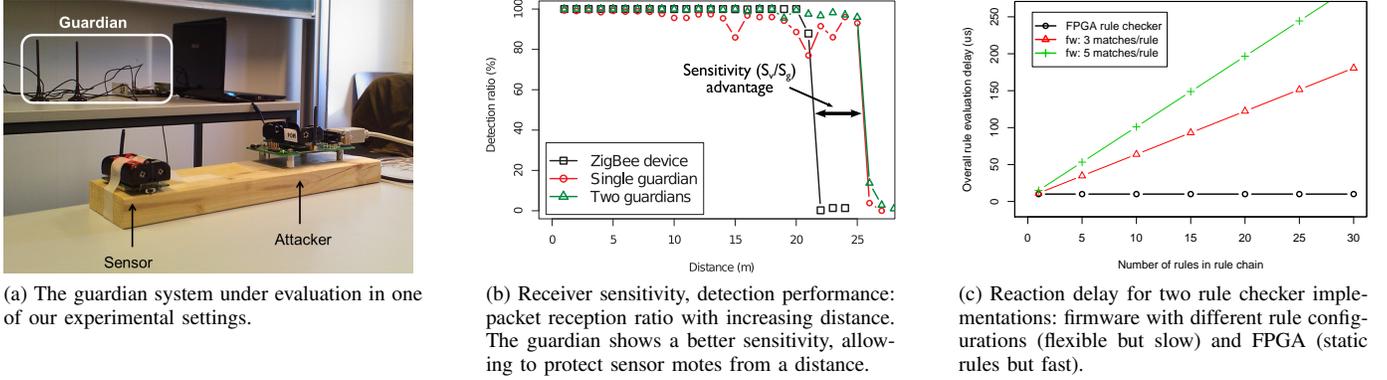


Figure 4: Guardian performance evaluation: experimental setting, detection performance, and rule checking delay.

We vary the number of rules in the chain, and the number of matches in each rule (each match is a C function that reads data from the framer and compares these values to constants stored in the chain). The rules are chosen such that none of them matches the packet, hence we measure the worst-case run time where the chain is traversed completely. As the rules are evaluated in parallel in the FPGA-based implementation, increasing the rule set size affects the FPGA resource usage and not the timing.

**Firmware-based rule checker results.** The compound execution times depicted in Fig. 4c show that the reaction delay is depending on the rule set used. The reason is that our implementation follows the general design of `iptables` using linked lists with variable size, such that a small overhead occurs for the evaluation of each rule chain, rule, and the matches contained in a rule to traverse the list. As the used micro-controller only supports a single thread, the required execution time is deterministic but increasing with each rule.

To break the delays into components, we analyzed the rule checker implementation in depth. First, a constant time of  $4.03\ \mu\text{s}$  is needed to enter the interrupt handler, jump into the rule checker and back, and trigger the interference process. This cost is independent of the chain’s contents and is paid for each detected packet. To evaluate one rule in the chain, the guardian needs  $0.26\ \mu\text{s}$  for evaluation (mainly the time to traverse the chain). Evaluating the time needed for individual rule, each match needs  $0.34\ \mu\text{s}$  to start the execution of the associated test function. The overall running time of a match function depends on the logic of the match itself. Considering the address match, a match with representative complexity, the execution takes  $1.86\ \mu\text{s}$  before the function returns. All matches in a rule are checked sequentially, such that the execution times add up. For example, the execution of one rule with 3 matches accounts to  $5.58\ \mu\text{s}$ . So, when considering a chain with 20 rules of 3 matches each, the guardian requires  $116\ \mu\text{s}$  or approximately 4 payload bytes to react in the worst case (when all rules are traversed).

**FPGA-based rule checker results.** To allow more deterministic decision delays and to support a deeper look into the packet, we also implemented a rule checker implemented in FPGA logic that is less flexible but provides faster reaction times. Using this approach we are able to cut the latency

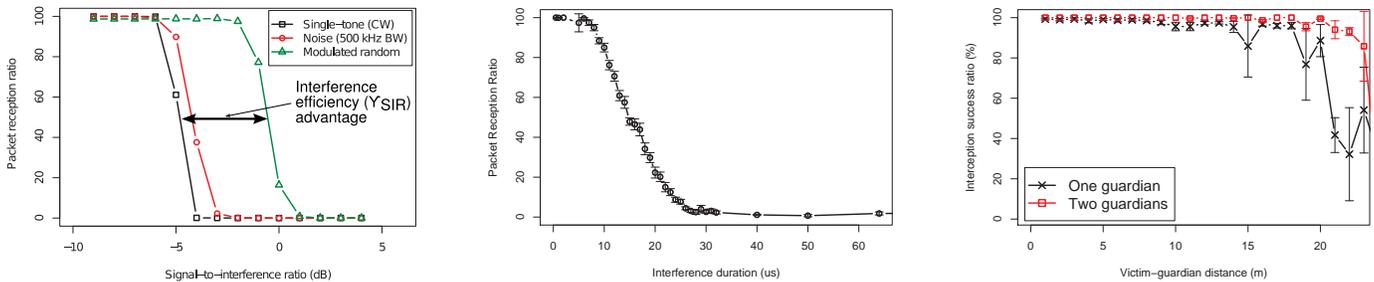
down to a limited number of FPGA clock cycles, i.e., below one microsecond up to  $10\ \mu\text{s}$ . This enables us to achieve an overall reaction time of  $t_{\text{react}} = 39\ \mu\text{s}$ , even with complex rule sets. This means that the guardian can base its decision on the complete payload and still hit the CRC bytes at the end of the packet to cause a packet drop.

### C. Interference Waveforms and Duration

We are interested in the optimal waveform that offers a high chance to intercept a packet (by providing a beneficial  $\gamma_{\text{SIR}}$ ), and the minimum interference duration that introduces bit errors into the packet with high probability.

**Interference waveform.** We tested three candidate waveforms for their ability to prevent a packet reception: a continuous wave (CW) positioned at the center frequency of the channel, white noise with a bandwidth of 500 kHz around the center frequency, and random symbols spread and modulated as specified in IEEE 802.15.4. We evaluated their performance according to the required transmit power to achieve a packet reception ratio of 0%. The results are shown in Fig. 5a: the continuous wave offers the most energy-efficient way to interfere with reception against the sensor platform we use, with the additional benefits that it is easy to generate on the SDR and that co-existing technologies such as WLAN filter out this type of interference relatively well, hence their operation is not disturbed by the guardian.

**Minimum interference duration.** Using the CW waveform, we evaluated the minimum interference duration on the channel to reliably destroy a packet. Guardian and victim are placed in close vicinity such that the guardian’s interference is stronger than the signal of each packet (see Fig. 4a). The results in Fig. 5b show that an interference duration of  $26\ \mu\text{s}$  is sufficient to destroy a packet. This result has two implications: first, the energy cost of the attacker is high; while the attacker must transmit a complete packet to be successful (e.g.,  $1024\ \mu\text{s}$  for a 32 byte packet), the guardian invests 40 times less energy to successfully prevent the reception. Second, the interference duty cycle of the guardian is very low, minimizing the effect on co-existing networks. In the experiments in the next section (100 attack packets/s), the guardian only transmits for less than one millisecond each second. We discuss the



(a) Comparison of the packet reception ratio for three interference waveforms: efficient waveforms increase the detection threshold  $\gamma_{SIR}$  and thus require less transmit power for blocking.

(b) Minimum interference duration for IEEE 802.15.4 radios, interfering with  $26 \mu\text{s}$  of a packet transmission is sufficient to trigger packet drops at the receiver reliably.

(c) The system's overall protection performance with close-proximity attacker (the attack always succeeds without guardians): detecting, classifying, and destroying the attacker's packets.

Figure 5: Performance evaluation: interference waveforms, minimum interference duration, and overall system performance.

issue of interference further in Section VII-B. The presented experiments are based on preliminary results published in [21].

#### D. Protection Performance

The most important aspect of our system is to effectively block malicious packets at the sensor motes. We consider the performance of the overall system here, i.e., both detection and selective interference are used in combination.

**Experimental methodology.** We place one or two guardian(s) at one end of the hallway, with the same measurement positions as in the detection experiments, i.e.,  $d_{ag} = 1, \dots, 30\text{m}$ . Attacker and victim (both MICAz) are moved together with a constant distance of one meter ( $d_{av} = 1\text{m}$ ), providing the attacker with excellent conditions. For each position, the attacker sends 100 packets/s back-to-back with 0dBm output power. Under this attack rate, the guardian must also prove that the transmission operation does not affect its subsequent detection performance and that its turnaround time is small enough to support high frequency attacks.

We repeat this attack 10 times for each distance, slightly moving the attacker each time, to lower the effects of multipath fading on the experimental results. We use the firmware-based rule system; the rule used is to search for all broadcast packets originating in the current PAN:

```
gtables -A -m dst --addr 0xFFFF --pan 0x22
-j DROP
```

All packets sent by the attacker match this specification, thus the guardian has to interfere with all attacker packets.

**Results.** A single guardian successfully prevents a packet reception in 98–99% for distances up to 15m, despite the close proximity of attacker and victim (see Fig. 5c). The outcome of this experiment is similar to the detection experiment, suggesting that the system performance is mainly influenced by the guardian's receiver implementation. Similar to the detection case, two guardians located at the same position effectively counter the issue of 1–2% packet misses, and achieve a combined 99.9% protection rate up 18m. The two guardians only missed 19 out of 18000 packets up to this distance.

#### E. Summary

The guardian implementation allows real-time detection of malicious packets with a high accuracy during their transmis-

Parameter	Description	Firmware	FPGA
$t_{\text{decide}}$	Rule checker execution time (var.)	116 $\mu\text{s}$	10 $\mu\text{s}$
$t_{\text{init}}$	Duration decision–start transmitting	3 $\mu\text{s}$	3 $\mu\text{s}$
$t_{\text{interfere}}$	Interference duration for packet drop	26 $\mu\text{s}$	26 $\mu\text{s}$
$t_{\text{react}}$	<b>Overall reaction delay</b>	<b>145 <math>\mu\text{s}</math></b>	<b>39 <math>\mu\text{s}</math></b>

Table III: Time parameters of our guardian implementation, indicating that packets can still be destroyed after observing a large part of their contents.

sion and a reliable destruction before the packet may arrive at a receiver. The results are summarized in Tables II and III. The system is able to classify and destroy 99.9% of the packets, even if the classification depends on the last byte in the payload, because the reaction time of the system (39  $\mu\text{s}$ ) is shorter than the duration of the CRC field (64  $\mu\text{s}$ ).

## VI. APPLICATIONS

This section demonstrates the ability of our guardian system to control wireless channel access in order to protect IEEE 802.15.4 wireless sensor networks from message injection attacks. To evaluate the effectiveness of our guardian system, we set up different use cases in our lab and implement real-world attacks using open-source attack tools from the KillerBee suite [5].

#### A. Experimental Setup

**Radio network environment.** The experiments are conducted in a fairly typical office environment, located on the second floor of our university building. The IEEE 802.15.4/ZigBee network consists of heterogeneous devices operating on the 2.4GHz frequency band. The WSN includes the following devices (a floor plan with the positions of deployed devices is shown in Fig. 6): (i) one PAN coordinator using the Atmel AVR Wireless Service Suite under Windows XP on a 2.0GHz machine with an Atmel RZ USB transceiver, (ii) two Atmel AVR RAVEN boards equipped with a picoPower AVR processor, and (iii) six Crossbow MICAz devices running TinyOS.

**Attacker configuration.** The attacker is equipped with an 802.15.4-compliant ZigBee transceiver flashed with the KillerBee firmware. It can launch a variety of automated attack vectors against ZigBee networks. Particularly interesting

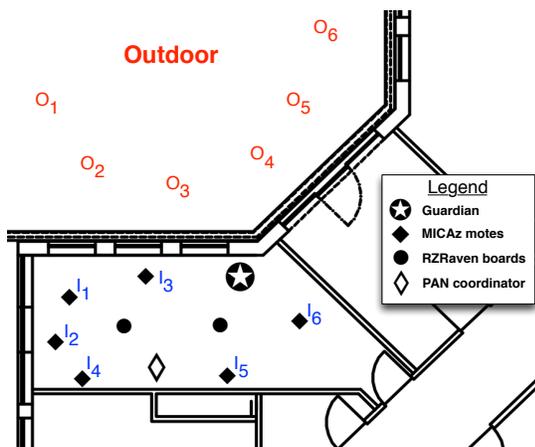


Figure 6: Floor plan and experimental setup. The experiments are conducted in a university lab on the second floor, with several WLAN access points working in the same frequency band. Outside positions are located on the roof of the building.

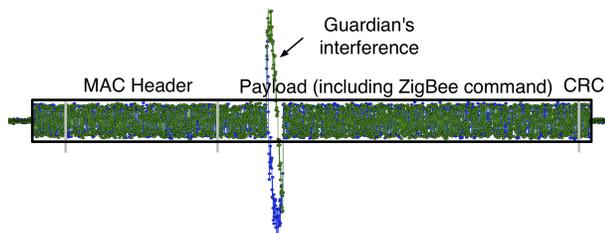


Figure 7: Preventing an unprotected OTA firmware upgrade with selective interference (measured physical layer baseband trace).

are attacks which abuse legitimate protocol operations like launching resource-depletion (DoS) attacks or the intercepting and manipulating over-the-air (OTA) configurations (including firmware upgrades and key exchanges).

**Guardian configuration.** Depending on the respective scenario, we change the type of antenna (either omni-directional or sector) and its orientation (inside/outside). We use COTS 2.4 GHz antennas, with standard specifications.<sup>4</sup>

### B. Protecting from Unauthorized Messages

1) *Controlling Over-the-Air Updates:* In this experiment, an attacker tries to modify the firmware of a ZigBee device with an Over-The-Air (OTA) configuration update. The off-the-shelf OTA update functionality of the RZ RAVEN boards does not require any authentication. The only requirement is that the node initiating the update is associated to the PAN. The attack is implemented using KillerBee: with the `zbreplay` tool and a spoofed address of the PAN coordinator, an arbitrary firmware is uploaded to the RZ RAVEN devices. To avoid such vulnerabilities, the guardian blacklists all OTA configuration traffic. In order to enforce such a policy, the guardian have to

<sup>4</sup>Detailed antenna specifications of the antennas used:

- Omni-directional antenna: length: 12 cm, gain: 5 dBi.
- Directional (sector) antenna: length: 16 cm, beam width horizontal: 69.6°, vertical: 64°, max. gain: 8 dBi. A data sheet is available at [http://www.wimo.com/download/18560\\_8.pdf](http://www.wimo.com/download/18560_8.pdf)

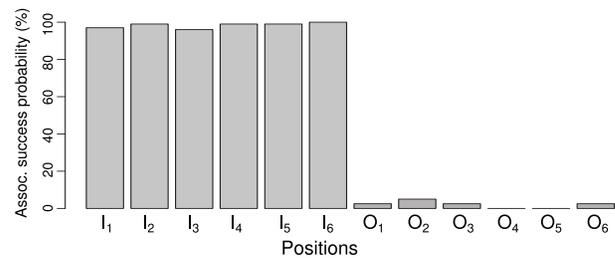


Figure 8: Resource-depletion attack by flooding the network with association requests. Outside attackers are effectively blocked, while indoor operations are not affected.

perform a payload inspection because the information about packets carrying OTA configuration commands can only be found in higher layers of the ZigBee protocol stack. More specifically, it checks for data frames with a certain network layer control field (0x0008), and a certain ZigBee application support layer command type (0x01) in the payload of the packet, resulting in the following rule:

```
gtables -A -m dst --pan 0xACAC -m nw_ctrl
0x0008 -m asl_cmd 0x01 -j DROP
```

Fig. 7 shows the baseband trace of an OTA firmware upgrade packet while it is being blocked by the guardian. A short, yet precise selective interfering signal hits the middle of the packet and renders it unusable. Hence, the attacker is no longer able to modify the firmware of the RZ RAVEN nodes in the vicinity.

2) *Mitigating Resource-Depletion Attacks:* Next, the KillerBee toolbox is used to launch a resource depletion attack on the ZigBee devices. The attack is executed by KillerBee's `zbflood` tool, which floods the PAN coordinator with association requests (IEEE 802.15.4 control frames). Under normal conditions, we verified that this causes our PAN coordinator to crash repeatedly. To make the coordinator operational again, the node must be reset manually after each crash.

To mitigate this attack, assuming that the attacker is located outside the room, we deploy the following guardian rule:

```
gtables -A -m type --control -m dst --pan
0xACAC -m RSS --above -80 -j DROP
```

The guardian's policy is to destroy all association requests (IEEE 802.15.4 control frame type 0xC823) sent to the network ID 0xACAC, and transmitted from outside. The idea of this policy is to allow associations from inside the room, but not from outside (assuming access to the room is physically secured). To that end, we define outside as an area covered by the sector antenna and a signal threshold exceeding  $-80$  dBm.<sup>5</sup> The guardian's response is to generate interference using its omni-directional antenna. We are interested in the successful association request rates from inside (sent by legitimate sensors) vs. outside positions (sent by KillerBee). The tested positions are marked in Fig. 6 as  $I_1, \dots, I_6$  for inside, and  $O_1, \dots, O_6$  for outside positions. As can be observed in Fig. 8, the guardian allows association requests from inside positions

<sup>5</sup>Admittedly, this definition of outside is not particularly robust, but can be improved by more sophisticated signal features (see the discussion in Section VII-A1). The assumption is the guardians are placed at the border between inside and outside and the attacker's effective power must be at least  $-80$  dBm at the guardian's position to reach the sensor motes located behind it.

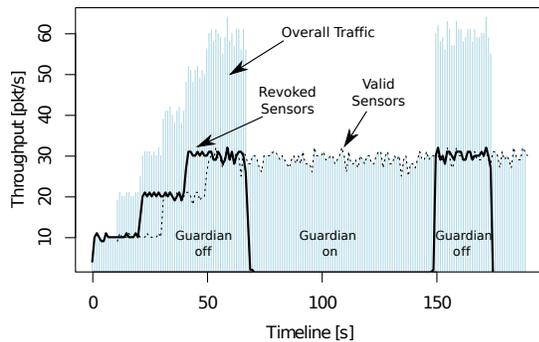


Figure 9: Instant node revocation: 6 MICAz motes are consecutively turned on and start transmitting. After 70 seconds, the guardian is turned on to selectively block traffic transmitted from revoked devices (3 motes).

with a probability of over 95%. However, for senders closer to the sector antenna, the guardian occasionally blocks ( $\rightarrow$  positions  $I_1$  and  $I_3$ ). This is an artifact of the simple location detection scheme used. Nevertheless, the attacker’s flooding rate from outdoor positions is severely limited and this rate is no longer sufficient to make the PAN coordinator crash from any outdoor position.

### C. Instant Node Revocation

The next attack scenario considers node capture and replication attacks in WSNs [23], [24]. While this problem is mainly treated as a key management issue in the literature [25], [26], we show that compromised sensor motes can also be removed on the physical layer once they are identified. We refer to this as *instant* revocation because once the blocking rules are committed to the guardian, the motes’ channel access is instantaneously blocked and they are thus disconnected from the network; it is not necessary to reliably distribute a revocation command in the (possibly Byzantine) network. From the guardian’s perspective, the channel control policy is to detect packets from revoked nodes by their source addresses (sensors  $0x1111$  ( $I_1$ ),  $0x1112$  ( $I_3$ ),  $0x1115$  ( $I_5$ )) and network ID ( $0xACAC$ ) and to destroy those packets:

```
gtables -A -m src --addr 0x1111 --pan
        0xACAC -j DROP
gtables -A -m src --addr 0x1112 --pan
        0xACAC -j DROP
gtables -A -m src --addr 0x1115 --pan
        0xACAC -j DROP
```

In this experiment, six MICAz motes consecutively start transmitting with 10 packets/s. After 70 seconds, three nodes are revoked for 90 seconds, then allowed again for 20 seconds, and finally revoked for the rest of the experiment. We are interested in packets from revoked nodes able to reach the network (false negatives) and the impact of the guardian on the legitimate traffic (false positives).

The results are shown in Fig. 9. The stepwise traffic increase is due to the consecutive start of the transmissions. The black solid line is the cumulative traffic of the nodes to be revoked, the dashed line shows the traffic of legitimate

nodes, and the overall traffic is depicted by the bars in the background. As can be seen, the guardian immediately reacts by completely blocking the traffic from the revoked nodes. During the revocation phases, the amount of legitimate traffic equals the overall traffic, so there are no false positives. The number of false negatives is one packet at the beginning and at the end of revocation phases (due to the transition of the guardian’s rule re-configuration).

## VII. DISCUSSION

In this section, we provide a discussion on how to lift limitations of our guardian implementation, some non-technical aspects of its use, and future work opportunities.

### A. Lifting Limitations

We first discuss functional extensions to support rules based on physical features and multi-channel operation to enable additional applications.

1) *Going Beyond Content*: The current system implementation supports classification based on the content of the packet, such that certain types of attacks (spoofing and replay attacks) are hard to single out. However, the packet content is not the only feature extractable from incoming packets: the physical characteristics of a signal are influenced by RF propagation phenomena and transmitter characteristics. We already exploited such signal “meta-data” in the DoS application scenario (Section VI-B2) by giving the rule system access to the received signal strength, thwarting a DoS attack that used replayed packets. Still there is a wide range of additional physical features that can increase the attack detection options of our guardian system. We briefly introduce a selection of features considered in the literature.

**Energy-based positioning:** Several methods to infer a sender’s position are proposed in the literature. The use of power level information such as RSS is used to position devices precisely [27], even to localize them in large scenarios [28]. This enables location-aware applications such as *geo-fencing* [29]. The guardians could then benefit from rules that use the sender location in their decision and detect spoofing attacks [30].

**Direction-based positioning:** With antenna configurations such as directional antennas or antenna arrays, guardians can also gain capabilities of position-based classification; a simple example use is shown in Section VI-B2. These methods use the direction of arrival to infer the position of a transmitter. Angle of arrival information has already been shown to be valuable for securing WLANs [31].

**Link signatures:** A more complex method using physical layer information to position devices is the use of link signatures [32]. This method is able to discern the position of two devices with a large probability using spectral information and may be used to prevent spoofing and replay attacks.

**Device identification:** This analysis method enables to uniquely identify transmitting devices [33]. For example, the concept of device fingerprints [34] uses imperfections in the TX chain of transmitters to associate packets to the transceiver hardware used. These features are stable and unique enough

to identify devices even from the same production line. This technique can be used to whitelist trusted devices, blocking adversaries that cannot mimic the physical layer behavior of the devices.<sup>6</sup>

2) *Protecting Multiple Channels in Parallel*: Currently, the guardian implementation supports the protection of a single IEEE 802.15.4 channel. However, it can be extended to support the monitoring of multiple channels in parallel, by replicating the relevant subsystems in the FPGA for each channel. This only alters the amount of resources used, not the timing behavior because of the inherent parallelism of the FPGA architecture. Recent results show that this approach is feasible by demonstrating that four IEEE 802.15.4 channels can be received concurrently on the USRP2 platform [36].

### B. Non-technical Aspects

**Legal Aspects.** The intentional generation of interference may raise the concern whether our guardians can be operated legally. In general, this question is not simple to answer because the rules governing spectrum access vary across countries and frequency bands. The U.S. regulations [37] mandate in §15.5 that “harmful interference,” an emission that “obstructs or repeatedly interrupts a radiocommunications service operating in accordance with [Chapter 15],” is forbidden. However, as we limit the interference to adversarial packets by analyzing and deciding on a per-packet basis, we might argue that no “service” is interrupted.

Regarding unintentional interference with co-existing networks, we point out that the guardian accesses the channel scarcely. The guardian emits a 26  $\mu$ s signal per packet and is silent for the rest of the time (e.g., 998  $\mu$ s for 32 byte packets). From the view of a single channel, such a behavior is also observed for frequency hopping systems such as Bluetooth. In fact, Bluetooth Power Class 1 devices [38, §7.2] use the same transmit power (100 mW) as our guardians and occupy a 2 MHz 802.15.4 channel for approximately 25 ms per second, which is comparable to the emissions of a guardian reacting to an attacker with maximum rate (1000 packets/s). This also shows that attacking the guardian infrastructure itself (by deliberately triggering interference) leads only to a limited channel occupancy. In addition, as we consider the operation in the 2.4 GHz band, co-existing devices such as IEEE 802.11 receivers commonly filter out the simple sinusoidal waveform we chose. Thus, while a comprehensive discussion of the legal aspects of RF interference is out of scope for this paper (as well as out of our expertise), we observe that the selective and efficient operation of the guardians effectively limits interference, and finally remark that sometimes legislation follows technical innovation.

**Economic Aspects.** The guardians are additional infrastructure that is deployed alongside the sensor network. While this offers several benefits (central control, on-demand security, or the possibility to “patch” legacy networks), it may raise the question of cost. The number of guardian devices depends on the WSN deployment area and on the desired level of

protection. Thus, the cost per device should be small; one option is to implement the system with COTS transceiver and micro-controller chips, possibly sacrificing flexibility. On the other hand, recent results also show that it is possible to build cheaper ( $\sim$ \$100) and more energy-efficient SDR platforms [39].

### C. Future Work Opportunities

There are several interesting research opportunities to extend and refine the guardian concept. In addition to an extension with more physical layer protocols and physical feature detectors, we briefly discuss two promising paths.

**Optimal guardian deployment.** Operating on the physical layer has benefits but also generates new challenges: we must aim to detect any packet that might arrive at a network node, and ensure that all violating packets are destroyed. These issues make the position and number of guardians important factors during deployment of the guardian system, and an optimization based on analytical models along the lines of Section III would be desirable. Methods that may be applied for this purpose are presented in information theory literature in the context of physical layer confidentiality in wireless networks [40], [41]. These results suggest that by using a security perimeter around the network attacks can be mitigated completely because no network devices are then located in the attack range from all reachable attacker locations. Alternatively, a training phase or site survey can be helpful to support the optimization of the guardian deployment.

**Alternative uses.** While the concept of protecting sensor networks with the guardian system is our main focus, we note that the generation of selective interference can also be useful for research on the effects of interference on network performance, allowing to perform repeatable experiments with real hardware. Related work in this area uses sensor mote hardware for interference generation, which limits the capabilities of such interference generation systems [18], [42]. Using the selective and protocol-aware interference generation capabilities of the guardians, a more fine-grained control over interference can be achieved. For example, the guardian system can be deployed in a wireless testbed to generate arbitrary interference patterns based on packet content. In this spirit, the guardians may enforce that all ACK packets of Node 1 are lost, or 10% of all network traffic is affected by microwave/WLAN/Bluetooth-like interference following a bursty pattern. We presented initial steps in this direction recently [43].

## VIII. RELATED WORK

The concept of using selective interference has recently been proposed in several application areas: to protect implanted medical devices (IMDs) from malicious readers, to increase the privacy of RFID tags, and to ensure authentic communication in WSNs. In contrast to these works, we provide a system that allows configurable security policies based on packet content and aims to provide a central protection over larger distances in a *networked* setting, in contrast to a reader-single device setting. A summary of the following comparison is provided in Table IV.

<sup>6</sup>While spoofing can still be achieved [35], the attacker must increase its effort significantly.

System	Application area	Maximum reaction time	Guard distance	Blocking criteria	Prototype evaluation
IMD shield [6]	Implanted medical devices (IMDs)	10 ms	20 cm	Each packet is blocked and selectively forwarded	✓ (USRP2)
IMDGuard [7]	IMDs	Tens of ms	20 cm	Guard notices a spoofing attack	~ (MICAz)
Warlock Duke [44]	Improvised explosives (IEDs)	n/a	n/a (100 m)	Any signal in guarded freq. bands	✓ (custom)
Blocker Tags [45], [46]	RFID	300 $\mu$ s	20 cm	Tag query to protected prefix	× (tag)
RFID Guardian [47], [48]	RFID	300 $\mu$ s	1 m	Tag query to tag in ACL	× (handheld)
Jamming for Good [8]	Sensor networks	5 ms	2–3 m	Address+RSSI of registration packet	✓ (MICAz)
<b>[This work], [49]</b>	<b>Sensor networks</b>	<b>64 <math>\mu</math>s</b>	<b>10–20 m</b>	<b>Per-packet decision (header+payload)</b>	<b>✓ (USRP2)</b>

Table IV: Comparison of related protection systems using physical layer responses.

IMDs face challenges similar to WSNs, namely low computational resources and limited energy. Gollakota et al. [6] describe an external IMD protection system, or IMD “shield,” that allows to regulate access to the device using selective interference, protecting it from malicious readers. The shield is a battery-powered device that is worn close the implanted device ( $\sim 20$  cm), e.g., in the form of a pendant. It acts as a proxy that simultaneously receives and destroys any packet related to the protected IMD. If the packet is going to the IMD, the shield checks whether the reader is trusted and forwards the packet. If the packet originated from the IMD, the packet is forwarded in encrypted form to the querying reader to protect the patients’s privacy. A USRP2-based prototype system is presented, showing that an attacker can only succeed if it uses high transmit power and close proximity. Xu et al. [7] also describe an external guardian system that protects IMDs from untrusted readers. However, the concept relies on cryptographic protocols and uses the physical layer response only as a countermeasure to spoofing attacks. In contrast to these works, we offer configurable policies for several devices in a distributed sensor network setting.

To protect the privacy of RFID tags from malicious readers, Juels et al. [45] introduce the “blocker tag” to prevent the tag discovery by confusing readers with artificial collisions. The attacker queries a prefix of node IDs (e.g., the first two bits), and on collisions the reader refines the prefix, such that the blocker tag can force the reader to traverse the full address space by generating intentional interference. Juels and Brainard [46] extend this concept to signal privacy policies to benign readers. Rieback et al. [47], [48] offer a similar solution but support the protection of configurable sets of RFIDs (blocker tags only support address blocks). A handheld device, the “RFID Guardian,” monitors all queries and interferes with a tag’s response to hide its presence from malicious readers. Again, these concepts rely on close proximity to the protected tags. However, the main difference to our work is that these schemes do not operate on a per-packet basis: malicious queries are actually received by the tag, and only the tag’s response is blocked. This is not problematic because RFID tags commonly do not keep state information. With our implementation, we can prevent sensor motes from receiving any malicious packet, also protecting their internal state.

A closely related work protects sensor motes from spoofed packets (based on RSSI information) using selective interfer-

ence [8], [50]. Each data transmission is split in two packets, a registration packet and a data packet. The protection is performed by the network motes themselves, analyzing if the RSSI signature of the registration packet matches with the claimed source address, and scheduling the transmission of an interfering packet concurrent with the data packet in case of a mismatch. However, the requirement that motes must receive packets that are not addressed to them and send packets for interference is expensive in terms of energy. So, while the goals are similar, the approach is different. We explore the use of specially designed guardian devices that provide a per-packet central enforcement of access policies, without requiring a custom MAC protocol.

In the context of firewalls and WSNs, there are also efforts to bring an on-mote “personal firewall” to sensor networks [9]. Each incoming packet is inspected, compared to a set of filter rules, and dropped from the receive queue if necessary. In contrast to this work, we perform packet filtering using a centralized infrastructure, lifting the requirement to distribute and manage the security configuration of each node individually from a remote position.

In the military context, the U.S. military employs mobile jamming systems to protect convoys in Iraq from improvised roadside bombs, stopping a bomb trigger signal from arriving at the bomb’s receiver [44].<sup>7</sup> However, not much is known about the system’s implementation and operation.

In information theory the concept of *secrecy capacity* of broadcast channels with noise was studied extensively, starting with Wyner’s work on wiretap channels [51]. The goal is to enable confidential communications without secrets over a public broadcast channel. Recently, several authors augmented the wiretap channel by considering the creation of intentional noise to boost the secrecy capacity of the channel. This approach is known under various designation, such as *artificial noise* [52], [53], *cooperative jamming* [54], [55], *friendly jamming* [56], the *relay-eavesdropper channel* [57], or the *wiretap channel with helping interferer* [58]. These works show that confidentiality in the sense of information theory can be achieved even if the SINR of the adversary is higher. Our work is orthogonal to these approaches because we exploit jamming to *control* medium access instead of ensuring message confidentiality at the physical layer, i.e., while the jamming in the related work is targeting attackers

<sup>7</sup>A news article on IED jammers used in the Iraq campaign is available at <http://edition.cnn.com/2007/TECH/08/13/cied.jamming.tech>

to prevent them to receive messages, our approach here is to jam the nodes in the protected network, preventing them from receiving unauthorized messages.

Work on wireless network security applies result on the wiretap channel to prevent information leakage from a protected geographical area by hindering eavesdroppers using intentional interference in more practical scenarios. Kim et al. [40] propose *defensive jamming*, a method to hinder eavesdroppers from detecting messages correctly by using jamming directed towards the outside of the area. The basic assumption of this approach is that the network deployment area itself is physically secured, so that the eavesdropper must remain outside a surrounding security perimeter. The authors perform an analysis of jammer placement strategies based on the SINR model and show that eavesdropping can be prevented successfully by an appropriate geometrical jammer placement. The work of Sankararaman et al. [41] analyzes similar attack scenarios and presents algorithms for optimal jamming power assignment and jammer placement, both for a fixed number of jammers and a near-optimal number of jammers. While the methods used on these works can be adapted to analyze the performance and deployment of our guardian system, this work is orthogonal because they consider passive (eavesdropping) attackers, while we focus on active (injecting) attackers.

## IX. CONCLUSION

Wireless sensor networks are exposed to various kinds of attacks that can be launched by exploiting the open access characteristics of the physical broadcast medium. While cryptographic techniques at higher layers may often counter these threats, real-world networks often do not apply those techniques or have flawed implementations that still open possible attack vectors to adversaries. We have presented a guardian system operating on the physical layer as a practical solution to solve the wireless channel access problem, and demonstrated the feasibility of our approach with a full system implementation. Our concept offers flexible solution with per-packet access rules and the ability to enforce them from a central point in the network. Our evaluation shows that our implementation fulfills the strict real-time constraints when blocking high-throughput traffic with a reaction time of 39  $\mu$ s while achieving a blocking success rate of over 99.9%. We have further shown in several application scenarios that the guardians prevent attacks that exploit the open channel characteristics of wireless networks, and successfully reclaim air dominance from the adversary.

## REFERENCES

- [1] O. Chipara, C. Lu, T. C. Bailey, and G.-C. Roman, "Reliable clinical monitoring using wireless sensor networks: experiences in a step-down hospital unit," in *Proc. 8th Int'l Conf. Embedded Networked Sensor Systems (SenSys '10)*. ACM, Nov. 2010, pp. 155–168.
- [2] A. Wood, J. Stankovic, G. Virone, L. Selavo, Z. He, Q. Cao, T. Doan, Y. Wu, L. Fang, and R. Stoleru, "Context-aware wireless sensor networks for assisted living and residential monitoring," *IEEE Network*, vol. 22, no. 4, pp. 26–33, Jul. 2008.
- [3] X. Jiang, M. Van Ly, J. Taneja, P. Dutta, and D. Culler, "Experiences with a high-fidelity wireless building energy auditing network," in *Proc. 7th Int'l Conf. Embedded Networked Sensor Systems (SenSys '09)*. ACM, Nov. 2009, pp. 113–126.
- [4] J. Lu, T. Sookoor, V. Srinivasan, G. Gao, B. Holben, J. Stankovic, E. Field, and K. Whitehouse, "The smart thermostat: using occupancy sensors to save energy in homes," in *Proc. 8th Int'l Conf. Embedded Networked Sensor Systems (SenSys '10)*. ACM, Nov. 2010, pp. 211–224.
- [5] J. Wright, "KillerBee—framework and tools for exploiting ZigBee and IEEE 802.15.4 networks," Oct. 2010. [Online]. Available: <http://code.google.com/p/killerbee>
- [6] S. Gollakota, H. Hassanieh, B. Ransford, D. Katabi, and K. Fu, "They can hear your heartbeats: non-invasive security for implantable medical devices," in *Proc. ACM SIGCOMM '11*. ACM, Aug. 2011, pp. 2–13.
- [7] F. Xu, Z. Qin, C. C. Tan, B. Wang, and Q. Li, "IMDGuard: Securing implantable medical devices with the external wearable guardian," in *Proc. IEEE INFOCOM '11*. IEEE, Apr. 2011, pp. 1862–1870.
- [8] I. Martinovic, P. Pichota, and J. B. Schmitt, "Jamming for good: a fresh approach to authentic communication in WSNs," in *Proc. 2nd ACM Conf. Wireless Network Security (WiSec '09)*. ACM, Mar. 2009, pp. 161–168.
- [9] M. Hossain and V. Raghunathan, "AEGIS: A lightweight firewall for wireless sensor networks," in *Distributed Computing in Sensor Systems*, ser. LNCS. Springer, 2010, vol. 6131, pp. 258–272.
- [10] C.-J. M. Liang, N. B. Priyantha, J. Liu, and A. Terzis, "Surviving wi-fi interference in low power ZigBee networks," in *Proc. 8th Int'l Conf. Embedded Networked Sensor Systems (SenSys '10)*. ACM, 2010, pp. 309–322.
- [11] IEEE Computer Society, "IEEE Standard 802 Part 15.4," <http://www.ieee802.org/15/>, Sep. 2006.
- [12] A. Hodjat and I. Verbauwhede, "A 21.54 Gbits/s fully pipelined AES processor on FPGA," in *Proc. 12th Annual IEEE Symposium on Field-Programmable Custom Computing Machines (FCCM '04)*. IEEE, Apr. 2004, pp. 308–309.
- [13] D. Adamy, *EW 101: A First Course in Electronic Warfare*. Boston, MA: Artech House Publishers, Sep. 2001.
- [14] S. Lanzisera and K. S. J. Pister, "Theoretical and practical limits to sensitivity in IEEE 802.15.4 receivers," in *Proc. 14th IEEE Int'l Conf. Electronics, Circuits, and Systems (ICECS '07)*. IEEE, Dec. 2007, pp. 1344–1347.
- [15] R. A. Poisel, *Modern Communications Jamming: Principles and Techniques*. Boston, MA: Artech House Publishers, Nov. 2003.
- [16] B. DeBruhl and P. Tague, "Digital filter design for jamming mitigation in 802.15.4 communication," in *Proc. 20th Int'l Conf. Computer Comm. and Networks (ICCCN '11)*. IEEE, Aug. 2011, pp. 1–6.
- [17] T. Karhima, A. Silvenoinen, M. Hall, and S.-G. Haggman, "IEEE 802.11b/g WLAN tolerance to jamming," in *Proc. Military Comm. Conf. (MILCOM '04)*, vol. 3. IEEE, Nov. 2004, pp. 1364–1370.
- [18] Z. He and T. Voigt, "Precise packet loss pattern generation by intentional interference," in *Proc. 7th IEEE Int'l Conf. and Workshops on Distributed Computing in Sensor Systems (DCOSS '11)*. IEEE, Jun. 2011, pp. 1–6.
- [19] C. P. O'Flynn, "Message denial and alteration on IEEE 802.15.4 low-power radio networks," in *Proc. 4th IFIP Int'l Conf. New Technologies, Mobility and Security (NTMS '11)*. International Federation for Information Processing, Feb. 2011, pp. 1–5.
- [20] G. Nychis, T. Hottelier, Z. Yang, S. Seshan, and P. Steenkiste, "Enabling MAC protocol implementations on software-defined radios," in *Proc. 6th USENIX Symposium on Networked Systems Design and Implementation (NSDI '09)*. USENIX Association, Apr. 2009, pp. 91–105.
- [21] M. Wilhelm, I. Martinovic, J. B. Schmitt, and V. Lenders, "Short paper: reactive jamming in wireless networks—how realistic is the threat?" in *Proc. 4rd ACM Conf. Wireless Network Security (WiSec '11)*. ACM, Jun. 2011, pp. 47–52.
- [22] —, "WiSec 2011 demo: RFReact—a real-time capable and channel-aware jamming platform," *SIGMOBILE Mobile Comput. Comm. Review*, vol. 15, no. 3, pp. 41–42, Nov. 2011.
- [23] J.-W. Ho, M. Wright, and S. K. Das, "Fast detection of mobile replica node attacks in wireless sensor networks using sequential hypothesis testing," *IEEE Trans. Mobile Comput.*, vol. 10, no. 6, pp. 767–782, Jun. 2011.
- [24] B. Zhu, S. Setia, S. Jajodia, S. Roy, and L. Wang, "Localized multicast: Efficient and distributed replica detection in large-scale sensor networks," *IEEE Trans. Mobile Comput.*, vol. 9, no. 7, pp. 913–926, Jul. 2010.
- [25] H. Chan, V. Gligor, A. Perrig, and G. Muralidharan, "On the distribution and revocation of cryptographic keys in sensor networks," *IEEE Trans. Dependable Secure Comput.*, vol. 2, no. 3, pp. 233–247, Sep. 2005.

- [26] B. Parno, A. Perrig, and V. Gligor, "Distributed detection of node replication attacks in sensor networks," in *Proc. IEEE Symposium on Security and Privacy (S&P '05)*. IEEE, May 2005, pp. 49–63.
- [27] P. Bahl and V. N. Padmanabhan, "RADAR: an in-building RF-based user location and tracking system," in *Proc. IEEE INFOCOM '00*, vol. 2. IEEE, Aug. 2000, pp. 775–784.
- [28] A. Haeberlen, E. Flannery, A. M. Ladd, A. Rudys, D. S. Wallach, and L. E. Kavasaki, "Practical robust localization over large-scale 802.11 wireless networks," in *Proc. ACM MobiCom '04*. ACM, Sep. 2004, pp. 70–84.
- [29] A. Sheth, S. Seshan, and D. Wetherall, "Geo-fencing: Confining Wi-Fi coverage to physical boundaries," in *Proc. 7th Int'l Conf. Pervasive Computing (Pervasive '09)*, ser. LNCS, vol. 5538. Springer, May 2009, pp. 274–290.
- [30] Y. Sheng, K. Tan, G. Chen, D. Kotz, and A. Campbell, "Detecting 802.11 MAC layer spoofing using received signal strength," in *Proc. IEEE INFOCOM '08*. IEEE, Apr. 2008, pp. 1768–1776.
- [31] J. Xiong and K. Jamieson, "SecureAngle: improving wireless security using angle-of-arrival information," in *Proc. 9th ACM Workshop on Hot Topics in Networks (HotNets-IX)*. ACM, Oct. 2010, pp. 11:1–11:6.
- [32] N. Patwari and S. K. Kaseria, "Robust location distinction using temporal link signatures," in *Proc. ACM MobiCom '07*. ACM, Sep. 2007, pp. 111–122.
- [33] B. Danev, D. Zanetti, and S. Čapkun, "On physical-layer identification of wireless devices," *ACM Computing Surveys*, 2011, to appear. [Online]. Available: <http://www.syssec.ethz.ch/research/OnPhysId.pdf>
- [34] V. Briik, S. Banerjee, M. Gruteser, and S. Oh, "Wireless device identification with radiometric signatures," in *Proc. ACM MobiCom '08*. ACM, Sep. 2008, pp. 116–127.
- [35] B. Danev, H. Luecken, S. Čapkun, and K. El Defrawy, "Attacks on physical-layer identification," in *Proc. 3rd ACM Conf. Wireless Network Security (WiSec '10)*. ACM, Mar. 2010, pp. 89–98.
- [36] L. Choong, "Multi-channel IEEE 802.15.4 packet capture using software defined radio," Networked & Embedded Systems Laboratory, UCLA, Tech. Rep. TR-UCLA-NESL-200904-01, Apr. 2009.
- [37] "Radio Frequency Devices," *Code of Federal Regulations Title 47, Part 15*, pp. 752–871, Jan. 2010.
- [38] IEEE Computer Society, "IEEE Standard 802 Part 15.1," <http://www.ieee802.org/15/>, Jun. 2005.
- [39] P. Dutta, Y.-S. Kuo, A. Ledeczi, T. Schmid, and P. Volgyesi, "Putting the software radio on a low-calorie diet," in *Proc. 9th ACM Workshop on Hot Topics in Networks (HotNets-IX)*. ACM, Oct. 2010, pp. 20:1–20:6.
- [40] Y. S. Kim, P. Tague, H. Lee, and H. Kim, "Carving secure Wi-Fi zones with defensive jamming," in *Proc. 7th ACM Symposium on Information, Computer, and Communication Security (AsiaCCS '12)*. ACM, May 2012.
- [41] S. Sankararaman, K. Abu-Affash, A. Efrat, S. D. Eriksson-Bique, V. Polishchuk, S. Ramasubramanian, and M. Segal, "Optimization schemes for protective jamming," in *Proc. 13th ACM Int'l Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc '12)*. ACM, Jun. 2012, pp. 65–74.
- [42] C. A. Boano, T. Voigt, C. Noda, K. Romer, and M. Zúñiga, "JamLab: Augmenting sensor network testbeds with realistic and controlled interference generation," in *Proc. 10th Int'l Conf. Inf. Processing in Sensor Networks (IPSN '11)*. IEEE, Apr. 2011, pp. 175–186.
- [43] M. Wilhelm and J. B. Schmitt, "Interference Scripting: Protocol-aware interference generation for repeatable wireless testbed experiments," in *Proc. 4th Annual Wireless of the Students, by the Students, for the Students Workshop (S3 '12)*. ACM, Aug. 2012, pp. 1–3.
- [44] L. LaShomb, "Making the impossible a reality," in *DCMA Communicator*. Defense Contract Management Agency (DCMA), Summer 2006, vol. 6, no. 3, pp. 50–53.
- [45] A. Juels, R. L. Rivest, and M. Szydlo, "The Blocker Tag: selective blocking of RFID tags for consumer privacy," in *Proc. 10th ACM Conf. Computer and Comm. Security (CCS '03)*. ACM, Oct. 2003, pp. 103–111.
- [46] A. Juels and J. Brainard, "Soft Blocking: flexible blocker tags on the cheap," in *Proc. 2004 ACM Workshop on Privacy in the Electronic Society (WPES '04)*. ACM, Oct. 2004, pp. 1–7.
- [47] M. Rieback, B. Crispo, and A. Tanenbaum, "RFID Guardian: A battery-powered mobile device for RFID privacy management," in *Information Security and Privacy*, ser. LNCS. Springer, 2005, vol. 3574, pp. 259–273.
- [48] —, "Keep on blockin' in the free world: Personal access control for low-cost RFID tags," in *Security Protocols*, ser. LNCS. Springer, Apr. 2007, vol. 4631, pp. 51–59.
- [49] M. Wilhelm, I. Martinovic, J. B. Schmitt, and V. Lenders, "WiFire: A firewall for wireless networks," in *Proc. ACM SIGCOMM '11*. ACM, Aug. 2011, pp. 456–457.
- [50] I. Martinovic, N. Gollan, and J. B. Schmitt, "Firewalling wireless sensor networks: Security by wireless," in *Proc. Workshop on Practical Issues in Building Sensor Network Applications (SenseApp '08)*, Montreal, Canada, Oct. 2008, pp. 770–777.
- [51] A. D. Wyner, "The wire-tap channel," *Bell System Technical Journal*, vol. 54, no. 8, pp. 1355–1387, Oct. 1975.
- [52] S. Goel and R. Negi, "Guaranteeing secrecy using artificial noise," *IEEE Trans. Wireless Commun.*, vol. 7, no. 6, pp. 2180–2189, Jun. 2008.
- [53] R. Liu, I. Marić, P. Spasojević, and R. D. Yates, "Discrete memoryless interference and broadcast channels with confidential messages: Secrecy rate regions," *IEEE Trans. Inf. Theory*, vol. 54, no. 6, pp. 2493–2507, Jun. 2008.
- [54] E. Tekin and A. Yener, "The general Gaussian multiple-access and two-way wiretap channels: Achievable rates and cooperative jamming," *IEEE Trans. Inf. Theory*, vol. 54, no. 6, pp. 2735–2751, Jun. 2008.
- [55] X. He and A. Yener, "Cooperative jamming: The tale of friendly interference for secrecy," in *Securing Wireless Communications at the Physical Layer*, R. Liu and W. Trappe, Eds. Springer U.S., Dec. 2009, ch. 4, pp. 65–88.
- [56] J. P. Vilela, M. Bloch, J. Barros, and S. W. McLaughlin, "Wireless secrecy regions with friendly jamming," *IEEE Trans. Inf. Forensics Security*, vol. 6, no. 2, pp. 256–266, Jun. 2011.
- [57] L. Lai and H. El Gamal, "The relay-eavesdropper channel: Cooperation for secrecy," *IEEE Trans. Inf. Theory*, vol. 54, no. 9, pp. 4005–4019, Sep. 2008.
- [58] X. Tang, R. Liu, P. Spasojević, and H. V. Poor, "Interference assisted secret communication," *IEEE Trans. Inf. Theory*, vol. 57, no. 5, pp. 3153–3167, May 2011.