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SECURITY OF SENSOR NETWORKS

by

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June 2006

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SECURITY OF SENSOR NETWORKS

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Submitted in partial fulfillment of the
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ABSTRACT

This thesis discusses the security of sensor networks. First, an overview of the security architectures of two dominant implementations of sensor networks in the market today is presented: the TinyOS stack and the IEEE 802.15.4 stack. Their similarities and differences are explored and their strength and limitations are discussed. Where applicable, comparisons are made with IEEE 802.11 Wireless LAN to highlight improvements and lessons learned. It is pointed out that in general, IEEE 802.15.4 offers better security, but replay protection is effectively missing in today's implementations and access control is poorly implemented. Consequently, TinyOS is still the better option for devices with severe resource constraints. Finally, as a tool to aid in the security analysis of sensor network, the design and implementation of a TinyOS sniffer is presented and captured frames for a simple sensor network application are analyzed for the purpose of validation.

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EXECUTIVE SUMMARY

Security in sensor networks is an active but wide-open research field. Past experiences with other wireless technologies have shown that security will be an important factor in deciding the viability of sensor networks. But sensor networks have entirely different physical and network characteristics from conventional wireless networks, so they pose unique security challenges where traditional security techniques cannot be applied directly.

There are two dominant sensor network implementations in the market today, namely TinyOS and IEEE 802.15.4. TinyOS targets devices where energy and computation power are significant resource constraints. IEEE 802.15.4 takes a more modular approach to its design, and is suited for a variety of devices and applications. Currently TinyOS is more popular. But the formal adoption of the IEEE 802.15.4 standard should accelerate its acceptance in the sensor network community.

In this thesis, the security architectures of TinyOS and IEEE 802.15.4 are examined. The focus is on link layer security because, like other wireless networking technologies, the threat of interception by an adversary is always present. The security services they provide are described in terms of access control, message confidentiality, message integrity, and replay protection.

It is pointed out that in general, IEEE 802.15.4 offers higher assurance in terms of cryptographic strength, message integrity, and information leakage from IV reuse. TinyOS applications will need robust re-keying support and countermeasures against forgery attempts to make up the difference. But they both lack effective peer-level access control and replay protection – both important aspects of sensor network security.

For resource-limited sensor networks, TinyOS is still the better choice. For military applications where security and performance needs dominate, a hybrid TinyOS/IEEE 802.15.4 system would be ideal. Given the open source nature of the TinyOS project, it is conceivable that TinyOS can be adapted to leverage on IEEE 802.15.4-compliant hardware for its link layer security, instead of relying on TinySec –

TinyOS's own link layer security implementation. TinyOS packets can be encapsulated inside IEEE 802.15.4 frames, just like TCP/IP packets are encapsulated inside IEEE 802.11 frames. In this way, sensor network applications can be built that enjoy the best of both worlds – the mature and optimized environment of TinyOS, and the superior link layer security offered by IEEE 802.15.4.

The design and implementation of a TinyOS Sniffer tool is presented. A sniffer is the quintessential tool for modern day network and security analysis. But such a tool is presently lacking in today's sensor network development kits. The current design is based on existing sensor network hardware and software components to enable a low-cost sniffer implementation. The sniffer has also been designed to be easily extensible in terms of functionalities. Captured frames for a simple sensor network application are analyzed for the purpose of validation.

The following are recommended areas for further research:

- Improve the functionality of the TinyOS sniffer. Areas of improvement include tighter integration of the Sniffer with the mote hardware, and additional output modes for packet data such as the XML format.
- Integrating TinyOS with 802.15.4-compliant hardware, with support for peer-level access control and replay protection.

I. INTRODUCTION

A. INTRODUCTION

Security in sensor networks is an active but wide-open research field. Initial research efforts in sensor networks have understandably been focused on functionality, stability, and cost effectiveness. But past experiences with other wireless technologies have shown that security will be an equally important factor in deciding the viability of sensor networks. In order for a sensor network to be resilient to the myriad of network attacks that it will inevitably face, security must pervade its entire system design. The good news is that the sensor network is still very much in its infancy, so there are ample opportunities for researchers to ensure that security is designed into sensor networks, and that it is done right. The bad news, however, is that since sensor networks have entirely different physical and network characteristics from conventional wireless networks, they pose unique security challenges where traditional security techniques cannot be applied directly. New and innovative approaches must be sought.

B. THESIS OBJECTIVE

This thesis examines the current state of sensor network security, assesses its adequacy, and identifies potential areas of research. The main objective is to understand the design and implementation issues in realizing a secure deployable sensor network. A secondary objective is the design and development of a sensor network packet sniffer. A sensor network packet sniffer will assist in further analyzing and validating some of the issues identified in this thesis.

C. RELATED WORK

Researchers have known about the challenges facing sensor network security [1,2,3]. These include key establishment and trust setup, secrecy and authentication, privacy of sensed data, denial-of-service, secure routing, node capture, eavesdropping, and malicious use of the technology. For denial of service, researchers have found that a variety of attacks can be mounted at the physical, link, network and transport layers [4].

New classes of routing attacks, called sinkhole and HELLO floods, have been devised [5]. In addition, a variety of ad-hoc and peer-to-peer networking attacks, like the Sybil attack [6], can be adapted into powerful attacks against sensor networks [7]. Commercial tools are available for packet sniffing of a IEEE 802.15.4 network [8].

Researchers have studied the security of IEEE 802.15.4, and a few problems have been found [9]. These include lack of integrity protection for acknowledgement packets, key management issues, and lack of support for group keying models. Nonetheless, they conceded that the 802.15.4 security is fundamentally sound, and that proper use of the security API can lead to secure applications. SNEP (Secure Network Encryption Protocol), part of the SPINS [10] (Secure Protocols for Sensor Networks) framework, appears to be an alternative security architecture specifically targeted at sensor networks. But SNEP was unfortunately not fully specified nor fully implemented.

D. ORGANIZATION

The first step to a secure deployable sensor network is to understand the security from the ground up. Chapters II and III of the thesis examine the link layer security offered by the two dominant sensor network implementations in the market today, namely TinyOS and IEEE 802.15.4. Like other wireless networking technologies, the communications of sensor networks do not enjoy the benefits of physically protected data links, so the threat of interception by an adversary is always present. Hence, link layer security is an especially important consideration for wireless sensor networks. Chapter IV discusses the similarities and differences in the security architecture of TinyOS and IEEE 802.15.4, as well as their strength and limitations. Where applicable, comparisons are made with IEEE 802.11 Wireless LAN to highlight improvements and lessons learnt.

Next, the design and implementation of a sensor network sniffer is described in Chapters V and VI. A sniffer is the quintessential tool for network analysis. But such a tool is presently lacking in today's sensor network development kits. The current design is based on existing sensor network hardware and software components to enable a low-cost sniffer implementation. Captured frames from a simple sensor network application are analyzed for the purpose of validation.

Finally, Chapter VII concludes with a summary of the key points of this thesis, and recommended areas for further research.

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II. SECURITY ARCHITECTURE OF IEEE 802.15.4

A. OVERVIEW

The IEEE 802.15.4 standard [11] (802.15.4) is also known as the Low Rate Wireless Personal Area Network (LR-WPAN). It is designed to be a low-cost, low-complexity and short-range wireless communication network for applications with limited power and relaxed throughput requirements. Strictly speaking, 802.15.4 defines protocols not specifically for sensor networks, but for Wireless Personal Area Networks (WPAN). It is part of the WPAN family of standards that covers a personal operating space (POS) of typically 10 meters. But it has begun to attract strong interest from the sensor network community in using these protocols for sensor networks.

An 802.15.4 network can operate in either a star or peer-to-peer (mesh) topology, as illustrated in Figure 1. Each node in the network can either be a Full-Function Device (FFD), or a Reduced-Function Device (RFD).

The FFD embodies all the functionalities of an 802.15.4 device. It can operate in three roles: a PAN coordinator, a coordinator, or a device. An 802.15.4 network must include at least one FFD acting as the PAN coordinator in order for the network to form. On the other hand, an RFD is an extremely simple device that can talk only to an FFD. RFDs are useful for say, a light switch or a passive infrared sensor. Thus, in a typical sensor network, the “leaves” of the network can be visualized to be either RFDs or FFDs, while the gateway or router is an FFD.

Each device in the 802.15.4 network can be addressed by either a 64-bit extended address, or a 16-bit short address. The former is the global unique address of the device, analogous to the 48-bit Ethernet address of network interface cards. The latter is a convenient shorthand in a network-specific setting.

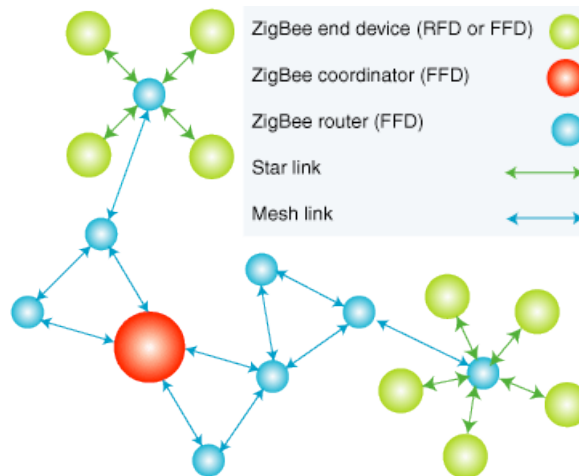


Figure 1: Illustration of a Zigbee/802.15.4 network. The green links and nodes show the star topology, while the blue links and nodes show the mesh topology. Through appropriate routing nodes, star and mesh networks can interoperate.

Source: [From 12].

B. RELATIONSHIP WITH ZIGBEE

Zigbee [13] is often spoken in the same breath as 802.15.4. They are not the same, although Zigbee is designed to work in tandem with 802.15.4. Their relationship is illustrated in Figure 2.

802.15.4 is based on the classic Open Systems Interconnection (OSI) seven-layer model [14], where it defines the physical layer and the media access control layer. The physical layer contains the radio frequency transceiver along with its low-level control mechanism. The media access control layer forms part of the data link layer, and provides access to the physical channel for all types of transfer. This is the typical way that recent IEEE 802.x standards are specified. Its purpose is to provide a common and interoperable communications platform that higher layer protocols can leverage on.

The higher layer protocols are defined by specific applications such as Zigbee. Zigbee builds on the 802.15.4's physical and medium access control layers with a network layer and an application layer that manage routing, discovery, security, and other network-level functions. Of note, the security services provided by Zigbee include methods for key establishment, key transport, frame protection, and device management.

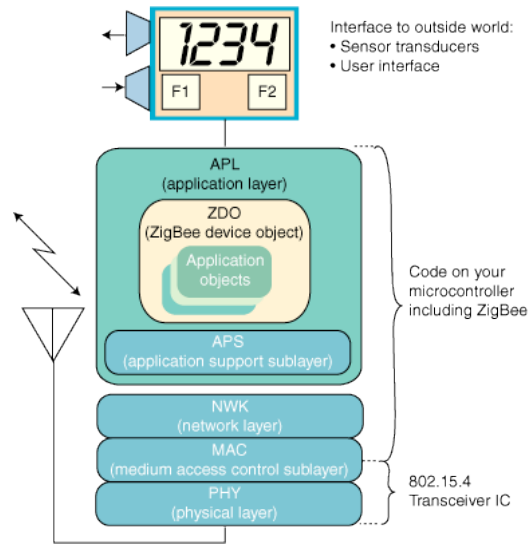


Figure 2: Relationship between Zigbee and 802.15.4. Note the separation point in the medium access control layer.

Source: [From 12].

As such, the security provided by 802.15.4 can be considered to be link layer security primarily aimed at node-to-node security, while the security provided by Zigbee can be considered application layer security primarily aimed at end-to-end security. Zigbee security is thus analogous to SSH [15], SSL/TLS [16] and IPSec [17].

In section 2.4 of his book [18], Stallings noted that with end-to-end security, the user data is secure, but the traffic pattern is not, since packet headers must be transmitted in the clear for the packet to be successfully routed to the destination. User data is therefore subjected to traffic analysis [19]. To achieve greater security, both link and end-to-end security are needed. Hence, 802.15.4 security and Zigbee security should complement but not replace each other.

Karlof, Sastry and Wagner [20] opined that the dominant traffic pattern in sensor networks is not end-to-end communication, but many-to-one communication, where in-network processing such as aggregation and duplicate elimination is used to reduce network traffic and save energy. Since in-network processing requires each intermediate node to access, modify and suppress the contents of messages, the more appropriate security mechanism to study should be node-to-node security instead of end-to-end

security. For this reason, the analysis of the security of Zigbee stack is outside the scope of this thesis. Nonetheless, it is recognized that end-to-end security will still have value for security services like keying.

The following sections discuss key components of the 802.15.4 security architecture.

C. SECURITY SERVICES

The International Telecommunication Union (ITU) Telecommunication Standardization Section (ITU-T) Recommendation X.800 [21] defines four classes of layer 2 security services between communicating open systems, namely authentication, access control, message confidentiality, and message integrity. 802.15.4 uses the following terms for its security services: access control, data encryption, frame integrity, and sequential freshness. In this thesis, the more conventional terms of access control, message confidentiality, message integrity, and replay protection, respectively are adopted.

802.15.4 provides all four of these services, but only three of them are specified in the standard, namely access control, message confidentiality and message integrity. Peer entity authentication is embedded in message integrity. In addition, an optional fourth security service, replay protection, is provided by 802.15.4, although one may say that it can be considered part of message integrity too.

1. Access Control

Access control provides the ability for a device to select the other devices with which it is willing to communicate. At the same time, it also prevents unauthorized parties from participating in the network. In 802.15.4, access control is implemented by an access control list (ACL) that each device maintains for the nodes that it is willing to communicate with. The ACL is explained in more details later.

2. Message Confidentiality

Message confidentiality means keeping information secret from unauthorized observation. In 802.15.4, message confidentiality is achieved through a symmetric cipher, using a key shared by a group of devices (typically stored as the default key) or using a key shared between two peers (typically stored in an individual ACL entry). Message

confidentiality may be provided on beacon payloads, command payloads, and data payloads, but not on acknowledgement payloads.

3. Message Integrity

Message integrity means protecting the data from unauthorized modification. In 802.15.4, message integrity is achieved by using a message authentication code (MAC). 802.15.4 refers to the message authentication code as a message integrity code (MIC) in order to differentiate it from the media access control layer, which also abbreviates to MAC. This is beginning to become the convention used in recent IEEE standards. In this thesis, however, the cryptographic convention of using MAC as an abbreviation for message authentication code is adhered to. To avoid any confusion, media access control is not abbreviated.

A MAC is a key-dependent one-way hash function [22] that is applied over the entire packet, including the packet headers. The key used to compute the MAC is the same key used for data confidentiality. Since the MAC depends on the key, the MAC further provides peer entity authenticity. The MAC may be provided on beacon frames, command frames, and data frames, but not on acknowledgement frames. Note the distinction between *frame* and *payload*. Encryption is applied to the packet payload, while MAC is applied to the entire frame, including the headers.

4. Replay Protection (optional)

Replay protection uses an ordered sequence of inputs to detect and reject frames that have been replayed. The sender assigns a monotonically increasing sequence number to every outgoing packet, and the receiver rejects packets with sequence numbers smaller than the one it has already received. A receiver can optionally enable replay protection when encryption is enabled.

D. SECURITY SUITES

802.15.4 provides the security services via a set of pre-defined security suites (see Table 1). These security suites will only be used when the application specifies that the device shall operate in secured mode.

A security suite consists of a set of operations to perform on medium access control layer frames. The security suite name indicates the symmetric cryptography

algorithm, mode, and integrity code bit length. The encryption algorithm used is Advanced Encryption Standard [23] (AES). The only mandatory security suite that each device that implements security shall support is the AES-CCM-64 security suite [11].

Security suite	Security Services				Description
	Access control	Message encryption	Message integrity	Replay protection	
NONE					No security
AES-CTR	X	X		X	Encryption only with AES with counter (CTR) mode
AES-CCM-128	X	X	X	X	Encryption with AES with counter mode, and authentication with CBC-MAC [24]
AES-CCM-64	X	X	X	X	
AES-CCM-32	X	X	X	X	
AES-CBC-MAC-128	X		X		Authentication only with CBC-MAC
AES-CBC-MAC-64	X		X		
AES-CBC-MAC-32	X		X		

Table 1: IEEE 802.15.4 security suites. The only mandatory security suite that each device that implements security shall support is AES-CCM-64 [11].

E. ACCESS CONTROL LIST (ACL)

The media access controller maintains a single default ACL entry and an ACL table. The default ACL entry is known by every device in the PAN and is used in situations in which the device needs to communicate with a second device or with multiple devices that it may not know individually. It is analogous to a broadcast or group key. This default ACL entry indicates whether default security is to be applied to devices not in the ACL, and if so, the default security suite and security material to use. The default security suite specified in the standard is none, with an empty string for the security material.

Individual ACL entries in the ACL table are used in situations in which the device shares a key with a specific known device. This implies a trusted relationship has been established between these two devices. Therefore, each ACL entry corresponds to a

trusted device, and consists of its PAN identifier, its 64 bit extended address, its 16 bit short address (or 0xffff if this address is not known), and its security suite and related security material. When replay protection is enabled, the security material includes a high water mark of the most recently received sequence number. There can be a maximum of 255 entries in the ACL table.

F. MODE OF OPERATION

The media access controller can be set in one of three security modes, namely unsecured mode, ACL mode, and secured mode. Unsecured mode is self-explanatory. ACL mode does not perform any cryptographic operations on the frames, but provides only a means for the device to indicate to the application whether the frame comes from a device in the ACL table. Secured mode utilizes the ACL functionality and also provides cryptographic protection on incoming and outgoing frames.

When the media access controller receives a packet from the application to send in secured mode, the ACL is consulted to find an entry that matches the destination address of the packet. If there is a match, the security material in the ACL entry is used to encrypt and/or authenticate the packet, according on the security suite specified in the ACL entry. If there is no match, then the default ACL entry is checked to see if default security is to be applied. If this setting is true, then the default security suite and security material is used to process the packet. Note that this can mean no security. Otherwise, the media access controller reports an error to the application.

On packet reception, the media access controller consults a flag in the packet header to determine if any of the security suites have been applied to the packet. If no security has been applied, the packet is passed on to the application as is. Otherwise, a process similar to the sending process is used, but this time based on the source address. If replay protection is enabled, the media access controller also verifies that the sequence number of the packet is greater than the one stored at the corresponding ACL entry. If it is, the ACL entry is updated with the new sequence number as the new high water mark. Otherwise, an error is reported to the application.

G. NONCE OR INITIALIZATION VECTOR (IV)

An important aspect of data confidentiality is semantic security [25]. It means that besides preventing plaintext recovery, the encryption scheme should also prevent adversaries from learning even partial information about the plaintext. One implication of semantic security is that encrypting the same plaintext twice must result in two different ciphertexts. A common technique to achieve this is to use a nonce, or more commonly called the initialization vector (IV), as a side input to the cipher in addition to the key. So long as the IV is unique for each encrypted packet, then no two packets can be encrypted to the same ciphertext, even if they have the same data, which is not an uncommon situation in computer networking. Since the receiver must use the IV to decrypt messages, the security of most encryption schemes do not rely on the IV being secret. Hence, the IV is typically sent in the clear with the encrypted packet. The IV is often a monotonically increasing large number. Another strategy to generate IV is to randomly choose from an n -bit value. But by the birthday paradox, it is likely that the first repetition will occur after $2^{n/2}$ packets have been sent. On the other hand, if the IV is chosen from an n -bit counter, then the first repetition will not occur before 2^n+1 packets have been sent. Hence, the later strategy is often the more popular.

In 802.15.4, the IV is constructed from the following data: a static flags field, the 64 bit extended address, a 4 byte frame counter, a 1 byte key counter, and a 2 byte block counter (See Figure 3).

1 byte	8 bytes	4 bytes	1 byte	2 bytes
Flags	Source Address	Frame counter	Key Counter	Block Counter

Figure 3: Format of the 802.15.4 IV for AES-CTR security suite [11].

There is a cryptographic requirement that the same IV must not be used to encrypt two different packets with the same key. Otherwise, it is possible to recover information about both plaintext messages [26]. Given two ciphertexts produced with the same (IV, K) pair:

$$C_1 = \text{AES}(IV, K) \oplus P_1$$

$$C_2 = \text{AES}(IV, K) \oplus P_2$$

$$C_1 \oplus C_2 = \text{AES}(IV, K) \oplus P_1 \oplus \text{AES}(IV, K) \oplus P_2 = P_1 \oplus P_2$$

Given the well-known structure of network messages, recovering the XOR of the two plaintexts makes it significantly easier to recover the two plaintexts.

The frame counter and key counter are key (pun unintended) in ensuring that this will not be the case. The frame counter is maintained by the media access controller, while the key counter is controlled by the application. The media access controller increments the frame counter for every encrypted packet sent. When the frame counter reaches the maximum value and rolls over, the media access controller notifies the application with an error. The application must increment the key counter to continue encrypting packets.

When both the frame counter and key counter are exhausted, no further encryption is possible with this key, until a new key is established.

Instead of sending the entire IV with the encrypted payload, only the frame counter and key counter are pre-pended to the encrypted payload and sent in the clear. The rest of the fields of the IV can be derived from the packet.

In previous sections, a sequence number that is used in replay protection has been alluded to. In 802.15.4, this sequence number is the five byte value constructed from the concatenation of the frame counter and the key counter.

H. SUMMARY

The basic security architecture of 802.15.4 was presented. A distinction has been made between application-layer security offered by Zigbee, and the link-layer security offered by 802.15.4. The discussion includes its security services and security suites, as well as its mode of operation, and the specification of the access control list and initialization vector. Overall, 802.15.4 has a comprehensive set of services to enable

secure link-layer communications in sensor networks. In the next chapter, the security architecture of TinyOS will be presented.

III. SECURITY ARCHITECTURE OF TINYOS

A. OVERVIEW

TinyOS is a popular research platform for sensor networks, frequently used in conjunction with the Crossbow motes [27] as the preferred microprocessor and radio hardware. From its website [28],

TinyOS is an open-source operating system designed for wireless embedded sensor networks. It features a component-based architecture which enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. TinyOS's component library includes network protocols, distributed services, sensor drivers, and data acquisition tools – all of which can be used as-is or be further refined for a custom application. TinyOS's event-driven execution model enables fine-grained power management yet allows the scheduling flexibility made necessary by the unpredictable nature of wireless communication and physical world interfaces.

The topology of a sensor network based on TinyOS devices depends entirely on the application and the networking stack used. A TinyOS application, and indeed parts of TinyOS itself, is programmed in an object-oriented componentized C language extension, called nesC [29]. For example, *Surge* is a popular mesh networking stack. For *Surge*-based applications, the topology is similar to one based on 802.15.4, but it does not have an implicit hierarchy of nodes like 802.15.4 does.

A TinyOS device is addressed by a 16-bit address, augmented with an 8-bit group ID. The group ID is analogous to the network address for a group of cooperating nodes. It allows multiple distinct groups of motes to share the same radio channel. In addition, TinyOS implements the Active Message (AM) system. AM types are analogous to port numbers in TCP/IP. Each TinyOS packet includes an 8-bit AM type in the header (see Figure 4).

Early versions of TinyOS did not have security built in at all. In late 2004, the developers of TinyOS introduced TinySec [30], a lightweight generic link layer security package that developers can easily integrate into their TinyOS applications. The authors foresee that TinySec will cover the basic security needs of all but the most security

critical applications. To enable TinySec in TinyOS, the application needs to specify `TINYSEC=true` on the command line to `make`, or in the `Makefile`. Unfortunately, at this moment, TinySec only works in the TOSSIM simulator and the Mica and Mica2 motes [38]. It has not yet been ported to the MicaZ and Telos motes.

Since the main focus of this thesis is on security, henceforth, when the term “TinyOS” is used, it is meant to be TinyOS with TinySec enabled.

The following paragraphs discuss the key components of the TinyOS security architecture. Because TinyOS is not a formal specification like 802.15.4, there is no official documentation on TinySec. Almost all the information discussed here is taken from [20,30,38] and the TinyOS source code, which can be downloaded from [28].

B. SECURITY SERVICES

The security provided by TinyOS centers on message integrity and message confidentiality. As in 802.15.4, peer entity authenticity is embedded in message integrity through the use of a MAC. Unlike 802.15.4, however, TinyOS does not explicitly provide access control via an ACL.

TinyOS supports two security options: authenticated-encryption (TinySec-AE) and authentication-only (TinySec-Auth). The former encrypts the data payload, then computes the MAC over the packet header and encrypted payload. The latter does not encrypt the data payload, but only computes the MAC over the packet header and data payload. The default security mode of a TinySec-enabled application is TinySec-Auth. The TinySec mode is indicated in the upper 2 bits (MSB) of the length field of the packet header. This modification is harmless because the maximum size of the data field in a TinyOS packet is 29 bytes, i.e., at most 5 bits of the length field will be used.

It can be seen from Figure 4 that the TinyOS and the TinySec-Auth packets do not have a field for the source address. So it is impossible for the receiver to know where the packet came from. Source address is only included in the TinySec-AE packet, and that was primarily for the benefit of increasing the diversity of the IV. Hence, if an application wants to implement ACL-based access control, then it can only do so with TinySec-AE.

Dest (2)	AM (1)	Len (1)	Src (2)	Ctr (2)	Encrypted Data (0..29)	MAC (4)
IV						

(a) TinySec-AE packet format

Dest (2)	AM (1)	Len (1)	Data (0..29)	MAC (4)
-------------	-----------	------------	-----------------	------------

(b) TinySec-Auth packet format

Dest (2)	AM (1)	Grp (1)	Len (1)	Data (0..29)	CRC (2)
-------------	-----------	------------	------------	-----------------	------------

(c) TinyOS packet format

Figure 4: TinyOS packet formats. The byte sizes of the fields are indicated in parentheses. The shaded fields are protected by the MAC. Note that the Group field is omitted from the TinySec packet formats – group membership is implicit in the knowledge of the secret key [20].

C. SECURITY PRIMITIVES

1. Message Authentication Codes (MAC)

As in 802.15.4, TinySec uses the cipher block chaining construct, CBC-MAC [24], for computing and verifying MACs. The MAC is 32-bit long, and is computed over the headers as well as payload of the packet. The authentication key is 64 bits long.

While the security of the MAC is directly related to the length of the MAC, the developers argued in that given the expected low data rate of the sensor network, a 32-bit MAC may provide an adequate level of security against blind forgeries. Adversaries cannot determine off-line if he has successfully forged a valid MAC for a particular message, hence any forgery attempts will be “blind”. For example, if an adversary tries to flood a 19.2 kb/s channel with blind forgery attempts, it may take him over 20 months to succeed, notwithstanding the fact that he would have effectively conducted a denial-of-service (DoS) attack on the network and exhausted the battery of the device long ago.

Furthermore, sustained forgery attempts can be pre-empted through simple heuristics. For example, nodes can signal the base station when the rate of MAC failures exceeds some reasonable threshold. Such countermeasures would mitigate the need for a longer MAC. Unfortunately, TinyOS leaves the implementation of such countermeasures to the application.

2. Encryption Scheme

The default cipher used in TinyOS is Skipjack in 64-bit cipher block chaining (CBC) mode, in conjunction with an eight byte IV, using a 64-bit encryption key. RC5 is also feasible. These two ciphers were found to be most appropriate for software implementation on embedded microcontroller as far as implementation efficiency and performance are concerned. The TinyOS source code includes implementation for both Skipjack and RC5. AES was later deemed to be equally suitable as well.

The choice of using CBC mode over stream cipher was primarily because with regards to semantic security, CBC mode is believed to degrade more gracefully when IV reuse occurs. This is an important consideration for TinyOS, because between two communicating nodes, the IV could be as small as a 16-bit value. If the IV is long enough so that it is not expected to repeat in a long time, then a stream cipher like AES-CTR performs much better. An additional advantage is that the same block cipher code can be used for the message authentication code (CBC-MAC), thus saving considerable code space.

3. Initialization Vectors (IV)

As in 802.15.4, the encryption scheme uses an IV to achieve semantic security. The format of the IV is shown in Figure 4a. The first four bytes of the IV are borrowed from the existing header fields of the TinyOS packet: the destination address, the AM type, and the length of the packet. The last four bytes are comprised of the source address and a 16-bit counter. The counter is initialized to zero, then incremented by one after every message sent.

The last four bytes of the IV is chosen in this way to maximize the number of packets each node can send before there is a global repetition of the IV. That is, each node can send at least 2^{16} packets before IV reuse occurs. For a network of n nodes, this results in $n \cdot 2^{16}$ packets before IV reuse occurs in the network.

The developers felt that this IV design should provide adequate security. Since sensor networks must conserve power to be long-lived, the average packet rate in most sensor networks will be very low – on the order of one packet per minute. At one packet per minute, IV reuse will not occur for over 45 days. In addition, the selection of CBC encryption mode further mitigates the risk of information leakage when IV reuse occurs. In short, information may only leak when one node sends two different packets with the same first eight bytes and IV, to the same destination, with the same AM type, and of the same length.

D. SUMMARY

The basic security design of the TinyOS, or more specifically TinySec, was presented. The security provided by TinyOS centers on message integrity and message confidentiality. Peer entity authenticity is embedded in message integrity through the use of a MAC. On the other hand, TinyOS does not explicitly provide access control via an ACL. There are 2 security modes: authenticated-encryption, and authenticated only. Security primitives such as message authentication codes, encryption scheme and initialization vector has also been discussed. With the background information on 802.15.4 and TinyOS now in place, the next chapter will discuss their similarities, differences, strength and limitations.

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IV. ANALYSIS OF 802.15.4 AND TINYOS SECURITY

In this chapter, the similarities and differences between the security designs of 802.15.4 and TinyOS will be examined, and their strength and limitations discussed. Where applicable, lessons learned from another wireless standard, IEEE 802.11 Wireless LAN [31] (802.11), will be applied to assess the adequacies of 802.15.4 and TinyOS security.

A. MODULARITY VS OPTIMIZATION

The objectives of 802.15.4 and TinyOS are very similar: ease of deployment, reliability and robustness, short-range operations, extremely low cost, and long battery life. But they are quite different in the way they are architected. The contrast can be summarized as Modularity versus Optimization.

802.15.4 follows the tried-and-tested layered protocol approach of the seven-layer OSI model. 802.15.4 specifies the lower 2 layers, namely physical and media access control. In this regard, it is very similar to 802.11. The inherent modularity of this model allows powerful higher layer specifications like Zigbee to export their own services, which applications can easily take advantage of. The downside is added code complexity, memory overhead, and processing delay in the handling of packets as they traverse the layers – a luxury that some sensor network applications can ill afford.

On the other hand, TinyOS resembles more of a toolkit or library for fast prototyping of sensor network applications. The OS is built-in to abstract the underlying hardware and support an event-driven framework. Unlike 802.15.4, TinyOS is tailor-made for sensor networks, and targets devices with limited memory and power. Many of the design decisions were made under the constraints of significant resource limitations. Between the two, TinyOS would easily offer a more optimized and energy efficient sensor network solution. The cost to pay for this optimization is the loss of some implementation transparency, the ability to modularize the solution, and perhaps some degree of assurances especially for applications where security is critical.

It should be noted that 802.15.4 is intended for hardware implementation on a dedicated radio chip, while TinyOS does not require dedicated hardware. The developers of TinyOS do not see this as a handicap. They claim that with sufficient engineering efforts, it is possible to encrypt and authenticate all communications entirely in software without major performance degradation. This result is a testament to the optimization possible in TinyOS.

As of today, the only radio chip that claims to be fully 802.15.4 compliant is the Chipcon CC2420 (CC2420) [32,33], currently used in Crossbow's MicaZ and the TelosB motes. It operates in the 2.4 GHz frequency band with a data rate of 250 kbps.

B. KEYING MECHANISM AND IV

Neither 802.15.4 nor TinyOS addresses the issue of the keying, that is the manner in which keys are generated, distributed, and securely stored (or destroyed). Section 5.4.6.1 in [11] states,

the security mechanisms in this standard are symmetric-key based using keys provided by higher layer processes. The management and establishment of these keys is the responsibility of the implementer. The security provided by these mechanisms assume[s] the keys are generated, transmitted, and stored in a secure manner.

Given that keying is generally considered a higher layer service, this position is understandable. But keying has a critical inter-dependency with one aspect of link layer security: the IV. Recall that to achieve semantic security, a node must not use the same IV with the same key for encryption. This is especially true when the IV is used with a stream ciphers like AES-CTR used by 802.15.4, or RC4 used by 802.11. 802.11 used a woefully inadequate 24-bit IV. On a network with a moderate load, this IV space was exhausted within a few hours. When there are multiple hosts within the wireless network, the situation is exacerbated since they all share the same encryption key.

Both 802.15.4 and TinyOS learned this lesson: 802.15.4 uses a much longer IV, up to 40 bits. While TinyOS limits itself to a shorter IV, it tries to mitigate the risk of information leakage through the use of CBC encryption mode rather than naively use a stream cipher.

Table 2 illustrates the theoretical IV reuse periods for TinyOS and 802.15.4 between 2 communicating nodes for the various data rates shown. The packet sizes chosen are the maximum packet sizes, so that if the actual packets are smaller, then the IV reuse periods will be shorter than those shown. The IV length of 40 bits for 802.15.4 assumes both the frame counter (4 bytes) and the key counter (1 byte) are in use.

		Data rate (kb/s)	Packet size (bytes)	Maximum throughput (pkt/s)	IV length	IV reuse period	
						100% duty cycle	At 1 pkt/min
TinyOS	Mica2[34]	38.4	41	120	16 bits	9.1 min	45.5 days
	MicaZ[35]	250		780		1.4 min	
802.15.4		20	128	20	40 bits	1743 yrs	>2m yrs
		40		40		872 yrs	
		250		250		139 yrs	

Table 2: IV reuse periods for TinyOS and 802.15.4 between two communicating nodes.

It can be seen from the table that in the worse case, i.e., 100% duty cycle, it will take a matter of minutes in TinyOS for IV reuse to occur, while it will take hundreds of years for 802.15.4. Even in the optimistic case of one packet per minute, it will take slightly more than 45 days in TinyOS for IV reuse to occur, while it will take more than 2 million years for 802.15.4.

This implies that for TinyOS to avoid IV reuse, a new key will have to be established every 45 days. In practice, one may re-key well before that period runs out. On the other hand, re-keying may not even be an issue for 802.15.4, since the IV reuse period will be longer than the lifetime of almost all applications.

It is stated here that the IV length of TinyOS is 16 bits. This warrants some discussion. On paper, TinyOS states that the IV is 8 bytes (see Figure 4a). But between two communicating nodes, only the last 2 bytes will be constantly variable. The destination address, source address and AM type are most likely fixed. Theoretically, the length field may also be variable, but most sensory messages will be fixed length, or have low variances in their lengths. Hence, it can be concluded that the IV length is effectively only 16 bits.

Even if a constantly varying length field is taken into consideration, it will only add five bits to the IV, not eight bits, because the maximum data field size is 29 bytes. This translates into a 32 times increase in the IV reuse period. For the optimistic case of one packet per second, it becomes a more respectable 4 years. But in the worst case, it is still only in the order of hours.

To be fair, it was a conscious design decision by the developers of TinySec to choose a 16-bit IV, and accept that IV reuse will occur, because a longer IV was deemed to add unacceptable overhead to the TinyOS packet size. Thus, CBC mode was specifically chosen because of its robustness to information leakage when IVs repeat. In short, information only leaks when two packets with the same first 8 bytes and IV are sent, assuming the rest of the fields are identical.

In summary, the long IV length of 802.15.4 means that the IV is unlikely to be exhausted in the lifetime of any application. Hence 802.15.4 applications can get away with not having to contend with re-keying issues. On the other hand, the short IV length combined with CBC mode may be sufficient security for most TinyOS applications. For applications requiring higher assurances, however, either a robust re-keying mechanism must be used, or TinyOS's IV must be customized to a longer length.

C. ACCESS CONTROL

802.11 did not specify a mechanism for access control within the wireless network. Most vendors choose to implement Ethernet address-based access control list at the access point. Unfortunately, the Ethernet address alone does not provide a strong enough identity. Attackers can sniff Ethernet addresses wirelessly and then spoof them via software [36] to impersonate legitimate clients. Encrypting the wireless traffic via a shared key may exclude adversaries without the key, but once the key is compromised, the adversary will again be able to impersonate any legitimate client.

Access control is an important consideration in sensor networks, because sensor network nodes are susceptible to physical capture. Therefore if the access control of the network is based on a single shared key, then once a node is captured and the key compromised, the access control for the entire network fails. The remaining sensor nodes

may have to be recovered and securely re-keyed with a new shared key – not always a feasible course of action. On the other hand, if the access control is based on pair-wise keys, then capturing a node will just violate the access control relationship with its peers, not the entire network. If a node is suspected of being captured, the network can simply instruct the captured node's immediate peers to expel the node from their access control list. There is no need to re-key the entire network. Hence, access control via an ACL with pair-wise keying should be the preferred access control mechanism for sensor networks.

TinyOS enforces access control with a MAC computed from a network-wide shared key. On the other hand, 802.15.4 can potentially offer very fine-grained access control. Each device can hold up to 255 entries in its ACL table, one for each trusted peer. Each trust relationship can have its individual security settings; authenticate-only, encrypt-only, or authenticate-encrypt.

An interesting scenario arises when an FFD is physically captured. In this case, an attacker can make use of the captured FFD to impersonate as a PAN coordinator, thus potentially routing all traffic through it. One way to mitigate this threat is to ensure that the edge devices that are susceptible to physical capture are only RFDs. Another way is to employ countermeasures to detect unauthorized or duplicate PAN coordinators.

It must be pointed out, however, that the 802.15.4 specification does not make it mandatory to support the full 255 entries in the ACL table, and in the manner that the specification describes. Figure 5 shows the CC2420 RAM memory map. It can be seen that the CC2420 does not have an ACL table. Instead, it has 2 keys. The application may choose to use one for transmit and the other for receive, or use a single key for both transmit and receive. These keys do not have an address associated with them. Therefore, these keys are more akin to the default ACL entry in the 802.15.4 specifications, and can only effectively support group keying.

Address	Byte Ordering	Name	Description
0x16F – 0x16C	-	-	Not used
0x16B – 0x16A	MSB LSB	SHORTADR	16-bit Short address, used for address recognition.
0x169 – 0x168	MSB LSB	PANID	16-bit PAN identifier, used for address recognition.
0x167 – 0x160	MSB LSB	IEEEADR	64-bit IEEE address of current node, used for address recognition.
0x15F – 0x150	MSB LSB	CBCSTATE	Temporary storage for CBC-MAC calculations
0x14F – 0x140	MSB (Flags) LSB	TXNONCE / TXCTR	Transmitter nonce for in-line authentication and transmitter counter for in-line encryption.
0x13F – 0x130	MSB LSB	KEY1	Encryption key 1
0x12F – 0x120	MSB LSB	SABUF	Stand-alone encryption buffer, for plaintext input and ciphertext output
0x11F – 0x110	MSB (Flags) LSB	RXNONCE / RXCTR	Receiver nonce for in-line authentication or receiver counter for in-line decryption.
0x10F – 0x100	MSB LSB	KEY0	Encryption key 0
0x0FF – 0x080	MSB LSB	RXFIFO	128 bytes receive FIFO
0x07F – 0x000	MSB LSB	TXFIFO	128 bytes transmit FIFO

Figure 5: Chipcon CC2420 RAM memory map.

Source: [From 33]

D. MESSAGE INTEGRITY

In 802.11, message integrity is only protected by a CRC-32 checksum, even when WEP is turn on. Researchers have shown that it is possible to modify WEP encrypted packets in transit without detection, because the CRC checksum is an unkeyed function of the message [37]. The fix is to use a cryptographically secure MAC.

Both 802.15.4 and TinyOS uses a MAC to protect the integrity of their encrypted messages. It is an accepted wisdom that the security of the MAC is directly related to the length of the MAC. 802.15.4 applications can use up to 128-bit MAC. CC2420 supports 128-bit MAC only. This is clearly superior to TinyOS's 32-bit MAC. TinyOS applications requiring higher assurances should implement countermeasures to prevent an attacker from making too many blind forgery attempts.

E. ENCRYPTION SCHEMES

The notable difference between the encryption schemes of 802.15.4 and TinyOS, is that 802.15.4 uses a stream cipher, AES-CTR, and a long IV to avoid the issue of IV reuse, while TinyOS uses a 64-bit block cipher in CBC mode with a shorter IV to mitigate the risk of information leakage associated with IV reuse. The key length of AES can be up to 128 bits long, and CC2420 has hardware cryptographic support for 128-bit keys only. It is reasonable to conclude that 802.15.4 should provide a higher degree of assurance as far as message confidentiality is concerned.

Note that TinyOS does not have an encrypt-only mode. This is no great loss. From the discussion in the previous section, the integrity of an encrypted packet cannot be guaranteed by its CRC checksum. A corollary is that encryption should not be used without a MAC if its integrity needs to be guaranteed. Hence, TinyOS only supports authenticate-only and authenticate-encrypt. Researchers have cautioned against using 802.15.4's AES-CTR security suite [9]. They argued that a simple, single-packet denial-of-service (DoS) attack can be mounted on a 802.15.4 network that uses the AES-CTR security suite with replay protection enabled.

F. REPLAY PROTECTION

TinyOS explicitly omitted replay protection in the security architecture. The main reason is to avoid the extra memory needed to keep the sequence numbers for every node that a receiver communicates with. Another reason is that the developers believe that replay protection is better and more efficiently handled by the application, which has more intimate knowledge of the overall topology and communications pattern of the network.

It is generally a good idea to have replay protection in link layer security. 802.11 did not have replay protection; hence, messages could be intercepted and replayed without modification. The result can be denial-of-service attacks, or it can be used as a launching pad for other attacks, like the man-in-the-middle attacks.

802.15.4 specifies optional replay protection. On paper, peer-to-peer replay protection should work very well under the specification. But researchers have found that

network shared keying using the default ACL entry to be incompatible with replay protection. This is because the receiver can only keep a single sequence number in the default ACL entry as the high water mark while receiving packets from many sources, each maintaining their own sequence numbers.

It must be pointed out that, as can be seen from Figure 5, CC2420 does not have provision for a replay counter in its RAM memory space. So any replay protection will have to be implemented in the application space – just like TinyOS. Therefore, one can conclude that replay protection is currently absent from today’s sensor network link layer security, until another radio chip comes along that supports this important feature.

G. SUMMARY

The security of 802.15.4 and TinyOS was analyzed and compared in five broad categories: IV length, access control, message integrity, encryption scheme, and replay protection. In general, 802.15.4 offers higher assurance in terms of cryptographic strength, message integrity, and information leakage from IV reuse. TinyOS applications will need robust re-keying support and countermeasures against forgery attempts to make up the difference. But they both lack effective peer-level access control and replay protection – both important aspects of sensor network security.

To validate this security analysis, a sensor network sniffer is needed. A sniffer is the quintessential tool for modern day network and security analysis. But such a tool is presently lacking in today’s sensor network development kits. In the following chapters, the design and implementation of a TinyOS sensor network sniffer will be presented.

V. ANATOMY OF THE TINYOS SNIFFER

In the previous chapters, the link-layer security design of TinyOS and 802.15.4 was described and analyzed. To validate the analysis, we need to use a sensor network sniffer. A sniffer is the quintessential tool for network analysis. But such a tool is presently lacking in today's sensor network development kits. In the following chapters, we will present the design and implementation of a TinyOS sensor network sniffer. The current design is based on existing sensor network hardware and software components to enable a low-cost sniffer implementation.

To understand how the sniffer works, it is necessary to first understand how TinyOS handles incoming network messages, and hence the hardware and software components necessary to implement such a sniffer.

A. TINYOS FILTERING MECHANISM

A TinyOS packet has the format shown in Figure 4c. The fields of interest are the following:

1. Destination Address

The destination address refers to the 16-bit node address of the mote. It is programmed into the mote along with the TinyOS application when the following command is issued:

```
make <platform> re|install,<n> <programmer>,<port>
```

where <n> is the 16-bit node address. The address 0 is typically reserved for the base station mote.

2. Group ID

The group ID is analogous to the network address for a group of cooperating motes. It allows multiple distinct groups of motes to share the same radio channel. The group ID can be set by defining the preprocessor symbol `DEFAULT_LOCAL_GROUP`. For example, this symbol can be located in the `MakeXbowlocal` file in the `tinycos-1.x/contrib/xbow/apps` directory. This file is automatically included in the compilation of almost all TinyOS programs in the `tinycos-1.x/contrib/xbow/apps` directory. The default group ID is `0x7D`.

3. AM Type

TinyOS implements the Active Message (AM) system. AM types are analogous to port numbers in TCP/IP. Different applications may use different AM types. For example, for the *Surge_Reliable* application, the AM type is defined in the *surge.h* header file:

```
enum {  
    AM_SURGEMSG = 17  
};
```

TinyOS automatically filters incoming packets by matching the destination address in the packet header with the node address of the mote. If the node address is 0, then TinyOS skips this step – the mote is effectively operating in promiscuous mode. If the destination address matches the node address, then the entire packet, including the header, is passed on to the application. It is the application’s responsibility to handle the group ID and AM fields.

In summary, a TinyOS sniffer can simply be a mote programmed with a node address of 0, and an application that ignores the group ID and AM fields (assuming no *a-priori* knowledge of either of them).

B. COMPONENTS OF THE SNIFFER

The TinyOS sniffer is based on readily available hardware and software components, and a Java-based application analogous to *tcpdump* [39].

1. Hardware components

The hardware platform is simply an off-the-shelf mote connected to a PC. The traditional connection is via the MIB510 programming board to a PC’s serial port. The TelosB mote offers a more convenient on-board USB connector that plugs directly into the PC for both the power and serial connections; hence, a more compact solution (see Figure 6). Connecting via the MIB510 would require not only an external serial cable, but also an external power supply for the MIB510 programming board. However, the message format forwarded by a Mica, MicaZ, or TelosB mote is quite different. So the application will have to decode the message appropriately according to the hardware used.



Figure 6 TelosB mote connected to the USB port of a PC.

2. Software Components

The software consists of one TinyOS application, *TransparentBase*, and two Java applications, *SerialForwarder* and *Sniffer*.

TransparentBase is one of the many examples of TinyOS applications that can be found in the `tinys-1.x/apps` directory. It acts as a simple bidirectional bridge between the serial and radio links. *TransparentBase* has the additional property that it ignores the Group ID. Programming the TelosB mote with *TransparentBase* and a node address of 0 gives a promiscuous receiver receiving TinyOS packets from the MicaZ sensor network, and forwarding them to the PC via the serial link. So long as no data is sent to the serial link, *TransparentBase* will also be a unidirectional passive receiver.

As mentioned earlier, it is the responsibility of the TinyOS application to handle the filtering of group ID and AM type. *TransparentBase* ignores both the group ID and AM type fields, so Group ID and AM filtering is not a problem.

At this point, this is pretty much have a functional TinyOS sniffer mote. Next, an application is needed to communicate with the mote via the serial port. In TinyOS world, the standard way to this is to use *SerialForwarder*.

SerialForwarder is a Java application that can be found in the `tinys/tools/java/net/tinys` directory. *SerialForwarder* runs on the PC and instantiates a network server that forwards TinyOS packets read from the serial port to a network port,

and vice versa. Typically, it is used to allow applications to communicate with the mote via a network interface instead of a serial interface – this is especially useful for distributed network clients, or Java clients like *Surge*.

The final piece of the puzzle is an application that reads the packet from *Serial Forwarder*, extracts the protocol and application information, and outputs the information in a usable form. There is no such tool in current TinyOS development kits. For this reason, the Java application *Sniffer* has been developed. The design and implementation of *Sniffer* will be discussed in the next chapter.

Figure 7 illustrates the block diagram of the sniffer.

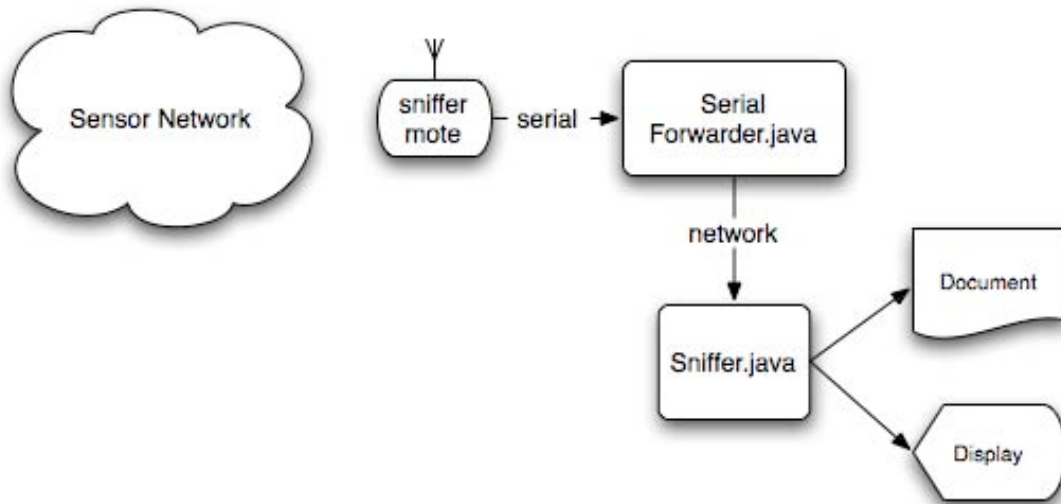


Figure 7 Block diagram of TinyOS Sniffer.

C. SUMMARY

The TinyOS packet filtering mechanism was discussed, and explained how it can be used for the purpose of frame capture. The necessary hardware and software components of a TinyOS sniffer was also presented. However, an application, *Sniffer.java*, is still needed that reads the packet from *Serial Forwarder*, extracts the protocol and application information, and outputs the information in a usable form. This will be discussed in the next chapter

VI. DESIGN AND IMPLEMENTATION OF THE SNIFFER APPLICATION

In addition to the analysis of the security architectures of 802.15.4 and TinyOS, the main development effort in this thesis is the design and implementation of *Sniffer*. This is a multi-threaded, *tcpdump*-like application that reads raw packets from *Serial Forwarder*, extracts the protocol and application layer information, and outputs it in a usable form.

The developmental paradigm of TinyOS is that mote applications running on the motes are written in nesC, while user applications running on the PC are written in Java. Keeping in line with this paradigm, *Sniffer* is also written in Java.

The remainder of this chapter explains the *Sniffer* application in more details. To follow the discussion, some working knowledge of Java is assumed, e.g. how to run Java programs, what are Java classes etc.

A. USAGE

Sniffer is a command line tool with usage as follows:

```
usage: java Sniffer [-m mica|micaz|telos] [-h host] [-ob filename]
[-?] [-p port] [-l filename] [-oc filename]
-m <mica|micaz|telos>    Specifies TOS message format when auto-
                        detection fails.
-?                        Print this help text.
-h <host>                The host running Serial Forwarder. Can be
                        a valid hostname or IP address. Default is
                        local host.
-l <filename>            Log screen output to file.
-ob <filename>            Output to file in raw binary format.
-oc <filename>            Output to file in CSV format.
-p <port>                Network port used by Serial Forwarder.
                        Default is 9001.
```

The meaning of some of these options will become clear as the implementation of the program is explained.

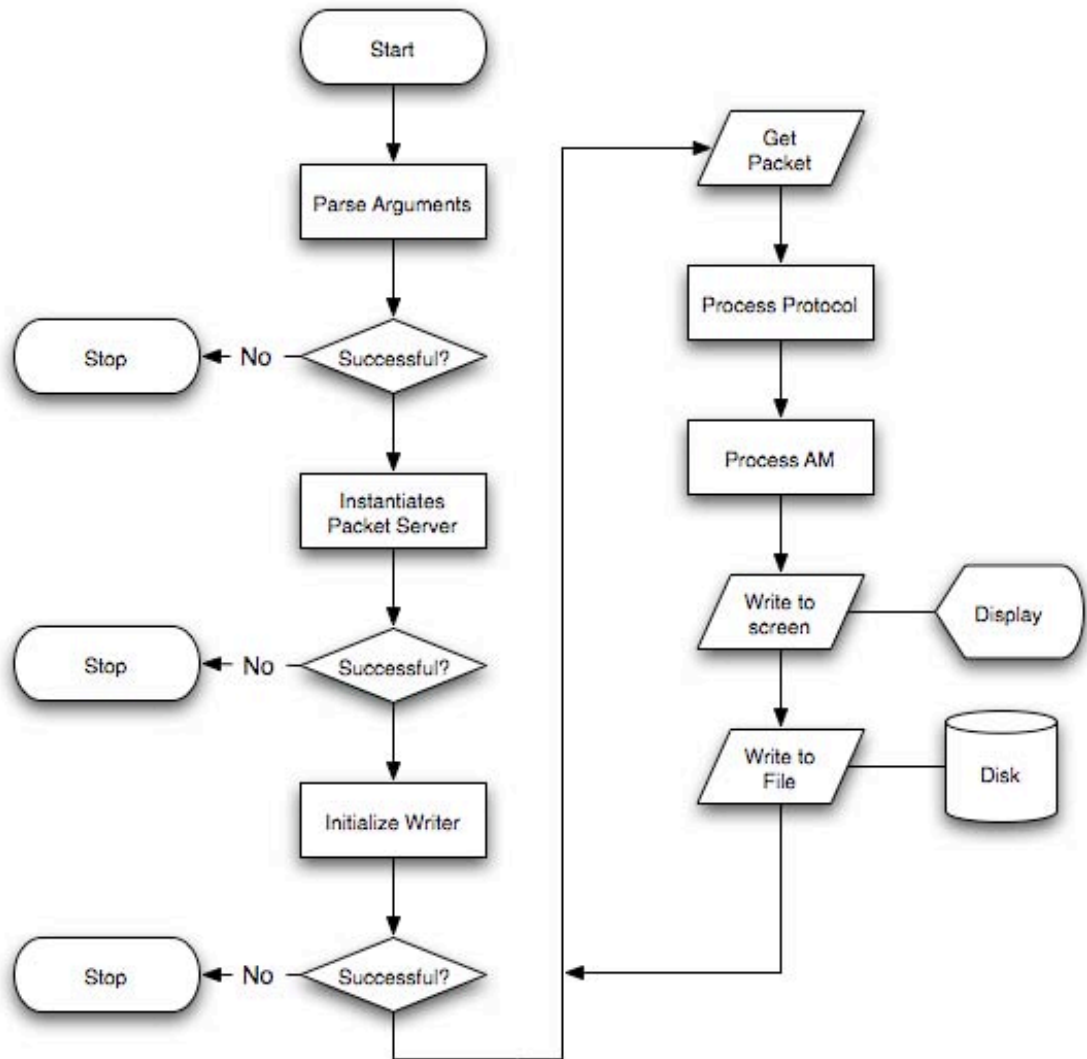


Figure 8 Process flow chart for Sniffer.

B. PROCESS FLOW

The process flow of *Sniffer* is depicted in Figure 8. The program first parses the command line to determine the user specified options, and exits upon detecting invalid options, or if “-?” is specified to display the help text. Once the options are set, the program attempts to instantiate a *PacketServer* class and initialize the *Writer* class with the registered outputs. If either of these fails, for example due to a failure to communicate with a *SerialForwarder* source, or a file I/O error, the program exits.

At this point, the program is ready to enter into its main processing loop. First, it requests a packet from *PacketServer*. Then it passes the packet to the *Protocol* and *AM*

classes in sequence to process the protocol and application layer information respectively. Finally, the processed packet is passed to the Writer class for output to the screen, and is optionally written to file in a variety of formats if the user so specifies. The process loop continues indefinitely until the user terminates with *Ctrl-C*.

C. DESCRIPTION OF THE MAJOR JAVA CLASSES

The Java classes that are implemented for *Sniffer*, and their relationships to each other, are depicted by the unified modeling language (UML) diagram in Figure 9. Note two exceptions. Firstly, the Thread super-class is a system provided class. It is included in the illustration to highlight the fact that *Sniffer* is a multi-threaded application. Secondly, the *CLI* utility library from the Apache Jakarta Commons project [40], not shown in the illustration, is used to provide the API for working with command line arguments and options. The user has to ensure that the *CLI* library is located in the Java *CLASSPATH*.

The Sniffer class contains the *main* function of *Sniffer*. This is the entry point of the program, and implements the process flow illustrated in Figure 8. In addition, it keeps track of packets received as well as packets with protocol processing errors. This information is displayed on the screen when the user terminates the program with *Ctrl-C*.

It is useful to look at the UML diagram in the following way. The leftmost branch consisting of the PacketServer class and its children comprise the *input* subsystem. The middle branches consisting of the Protocol and AM classes comprise the *processing* subsystem, while the rightmost branch consisting of the Writer class and its children comprise the *output* subsystem. Underpinning these subsystems is a collection of data classes called Packet and Field.

The data classes, and the input, processing and output subsystems are now discussed in more details.

1. Data Classes

In order to capture the representation of a packet accurately as it is processed through the program, *Sniffer* defines a Field class and a Packet class. A Field is simply some value with an associated name. A Packet is represented as a triplet of header, payload data unit (PDU), and trailer. It may also have a description string. The description is useful for displaying human-readable packet information on the screen.

The header and trailer are defined as linked lists of Fields. Perhaps more intriguingly, the PDU is itself defined as a Packet. The Packet class is therefore a *nested* class. This allows packets to be encapsulated inside another packet easily.

If the PDU is null, then this Packet is the *uppermost* packet, and all the information about the packet is stored in the header. In OSI parlance, an upper layer payload is encapsulated inside a lower layer protocol. So *uppermost*, in this case, means the higher layer payload. The current processing system should only concern itself with the uppermost packet and payload.

In this case, there are two possibilities. On one hand, the header list may consist of just a single field containing the data payload waiting to be processed. On the other hand, the header can be null, indicating that there is no more data to be process, i.e. this packet has been fully resolved.

Hence, packet protocol processing works as follows:

- 1) Use the `getUppermostPacket` method to get the uppermost packet.
- 2) Use the `getUppermostPayload` method to get the uppermost payload to be processed.
- 3) Process the payload accordingly to derive new header, trailer and PDU information.
- 4) Replace the uppermost packet's header, PDU and trailer attributes with the new information. The new PDU will now become the new *uppermost* packet to the next protocol layer.

2. Input Subsystem

The heart of the input subsystem is the ByteServer class. A ByteServer object is instantiated by PacketServer, when it is in turn instantiated by the Sniffer class. ByteServer is a separate thread of execution from the main Sniffer class. This allows input from the sniffer mote to be received in the most responsive way, independent from the execution of the rest of the program.

The ByteServer receives data from the sniffer mote through objects subclassed from the Source class. Currently, only the SFSource (or Serial Forwarder Source) class is implemented. However, it is perfectly possible to implement other sources if necessary, for example a SerialSource class that communicates with the mote directly via serial port communications, or a file source to read data previously archived in a file. It shall be seen later that additional sources can be easily created and added to the system. By default, *Serial Forwarder* is assumed to be running on the local host, port 9001. If this is not the case, then the user can specify a host and port using the “-h” and “-p” options.

Data read from the source is stored in a First-In-First-Out (FIFO) buffer. In the current implementation, when the buffer is full, further packet data are dropped, instead of overriding the earliest received data.

The Sniffer class does not talk to the ByteServer directly, instead it instantiates and requests packets from the PacketServer class. PacketServer provides a packet-level input abstraction to Sniffer. PacketServer makes requests for received data from ByteServer, and then packages the data bytes into a Packet object as its payload. At the same time, PacketServer adds a timestamp to this Packet’s header. This timestamp information allows for temporal analysis of the packets. Strictly speaking, the timestamp does not represent the time the packet is received by the sniffer mote, but the time PacketServer receives the data from ByteServer.

3. Processing Subsystem

Packet objects received from the input subsystem are passed to the processing subsystem, to extract protocol and application layer information. Packet objects are passed to the Protocol class and then the AM class in sequence.

The first thing that the Protocol class does is to see if it needs to determine the message format. TinyOS messages can have 4 different formats, depending on the mote used [41]:

- 1) The original TOS_Msg format used on mica, mica2, and mica2dot,
- 2) the IEEE802.15.4 format used on telos family motes,
- 3) the modified TOS_Msg format used on micaz motes, and
- 4) the Infineon's eyesIFX platform [42].

The Packet class has a static attribute, *msgFormat*, that is used to identify the format. The Protocol class first checks if this attribute is set. If it has not been set, the Protocol class applies some heuristics to try to guess the message format, and set it to the appropriate value. If the heuristics fail, then the message format is unknown, and no further processing will be done on the packet. It is assumed that a given sensor networks is homogenous, so the message format should be consistent. So the guessing of the message format is only done once. However, the heuristic rules are not foolproof by any means, so the fallback is for the user to specify the message format on the command line via the “-m” option. Once the message format is known, the Protocol class performs the appropriate protocol processing on the packet.

Once protocol processing is completed, the packet object is passed to the AM class for application processing. Recall that the AM type of a TinyOS message is analogous to the port number in TCP/IP. So it is conceivable that in a given sensor network, there can be more than one AM type. The AM class maintains a list of AM handlers. The AM class iterates through the list, passing the packet object to each AM handler. Once an AM handler signals that it has handled the AM type, application processing is complete.

Currently, the only AM handler implemented is the AMCountMsgHandler class, for the test application CountRadio. But it is easy to create and add AM handlers.

4. Output Subsystem

The Writer class is responsible for writing the packet information to a variety of output channels. One of the features of the output subsystem is that packet information

can be written to more than one channel *simultaneously*. Thus the user has the maximum flexibility in storing packet information.

The Writer class maintains a list of Output objects. The ScreenOutput object is always available. At the same time, the user can choose to enable other output channels using command line options. Currently, the following FileOutputStream objects are available: logging the screen output to file (“-l”), writing to a binary file (“-ob”), and writing to a comma separated value (CSV) file (“-oc”). The CSV file, for example, is readily imported into Microsoft Excel for data analysis purposes. The binary file, on the other hand, provides a more efficient format to store packet information.

When an Output object is instantiated, its *run* method is also immediately registered with the JVM runtime as a *shutdown hook*. This is a little known feature of Java that was recently added to allow programs to perform last minute clean-ups before JVM termination. In this case, the shutdown hooks enable the ScreenOutput object to print out packet accounting information, and the FileOutputStream objects to flush their I/O buffers and close the file properly.

Again, if a particular output channel is not available, it can be easily created and added to the system.

D. EXTENDING SNIFFER

The *Sniffer* program has been designed so that it is easy to create and add functionalities to the various subsystem, without affecting how the rest of the system works. Part of the reason for this capability lies in the object oriented nature of Java. In general, adding functionality to *Sniffer* can be done in two steps: subclassing an existing class, then making the new class known to the *Sniffer* at the appropriate code locations.

1. Adding Input Sources

New input sources should subclass the Source class, or any of its subclasses, and override the *open*, *close*, and *read* methods where necessary.

Within the main Sniffer class, a new command line option may be specified so that the user can choose this input source instead of the default SFSOURCE. Then inside the code that checks for this option in *parseArgs*, the new Source object must be instantiated,

and assigned it to the *source* static variable. ByteServer will automatically interface with the new input source.

2. Adding AM Handlers

Handlers for new AM types should subclass the AMHandler class, and override the *processAM* method.

The new AM handler class must then register with the AM class within the following code static segment of *AM.java*:

```
/*
 * Static code block.
 * This is where new AM handlers are registered.
 */
static {
    appsList.add(new AMCountMsgHandler ());
    // Add new AM handlers here, like above.
}
```

3. Adding output channels

New output channels should subclass the Output class, and override the *open*, *close*, *write*, and *run* methods where necessary.

Similar to the input subsystem, within the main Sniffer class, a new command line option may be specified so that the user can choose to enable this new output channel. Then inside the code that checks for this option in *parseArgs*, the new Output object must be instantiated, and added to Writer's list of Output objects using the *addOutput* method. Packet information will then be automatically written to the output channel.

E. TEST AND EVALUATION

The sniffing functionality of the TinyOS sniffer was tested and evaluated using a simple test application. For the purpose of this study, the target sensor network is a pair of MicaZ motes running the *CountRadio* application. The sniffer consists of a TelosB mote connected to a PC.

For convenience, it was assumed that the operating radio channel was known. It is not difficult to find out anyway – a simple sequential scan through the radio frequency channels, or a spectrum analyzer, will easily reveal the operating radio channel.

1. CountRadio application

CountRadio is an example application that can be found under the `tinycos/apps/` directory. From its `README.CountRadio` file:

“CountRadio is a simple led/radio count program. The default application built from this directory is *CountDual*. *CountDual* either sends a count over the radio if the node address is equal to 1, or displays a count received over the radio otherwise.”

The transmitting mote broadcasts a packet every 200 milliseconds, or five packets per second. The payload of the packet has the format defined in the `CountMsg.h` file:

```
enum
{
    AM_COUNT_MSG = 4,
};

typedef struct
{
    uint16_t n;
    uint16_t src;
} CountMsg_t;
```

Hence the payload is of constant four byte length, where the first two bytes represent a monotonically increasing sequence number, followed by a constant source address which should be 1. Therefore, this provides a very predictable data source to verify the correctness of our *Sniffer* program.

2. Output

With the motes up and running, *Sniffer* is started from the command line with no additional options. Figure 10 shows the captured screen output of *Sniffer*. Each line represents one packet. The format of the output is designed to mimic *tcpdump* to a certain extent. It has the following form:

```
<Timestamp> <Protocol> <Grp>.<Dest>.<AM> (<Len>) [<Payload>] <CRC>
```

The timestamp is in the 24-hour notation, with up to millisecond precision. The protocol is denoted as “TOS”, meaning TinyOS with TinySec disabled. The group ID, destination address and AM types are grouped into a “dotted” decimal notation that resembles an IP address with its port number.

Then using the CSV file output of *Sniffer*, and importing into Excel, it can be further verified that the sequence number N runs in consecutive order, so no packets were missed.

```

17:31:28.157 TOS 125.65535.4 (4) [N=496 Src=1]
17:31:28.557 TOS 125.65535.4 (4) [N=497 Src=1]
17:31:28.757 TOS 125.65535.4 (4) [N=498 Src=1]
17:31:28.957 TOS 125.65535.4 (4) [N=499 Src=1]
17:31:28.964 TOS 125.65535.4 (4) [N=500 Src=1]
17:31:29.197 TOS 125.65535.4 (4) [N=501 Src=1]
17:31:29.446 TOS 125.65535.4 (4) [N=502 Src=1]
17:31:29.701 TOS 125.65535.4 (4) [N=503 Src=1]
17:31:29.757 TOS 125.65535.4 (4) [N=504 Src=1]
17:31:29.960 TOS 125.65535.4 (4) [N=505 Src=1]
17:31:30.212 TOS 125.65535.4 (4) [N=506 Src=1]
17:31:30.432 TOS 125.65535.4 (4) [N=507 Src=1]
17:31:30.668 TOS 125.65535.4 (4) [N=508 Src=1]
17:31:30.845 TOS 125.65535.4 (4) [N=509 Src=1]
17:31:31.098 TOS 125.65535.4 (4) [N=510 Src=1]
17:31:31.358 TOS 125.65535.4 (4) [N=511 Src=1]
17:31:31.363 TOS 125.65535.4 (4) [N=512 Src=1]
17:31:31.599 TOS 125.65535.4 (4) [N=513 Src=1]
17:31:31.838 TOS 125.65535.4 (4) [N=514 Src=1]
17:31:32.039 TOS 125.65535.4 (4) [N=515 Src=1]
17:31:32.369 TOS 125.65535.4 (4) [N=516 Src=1]
17:31:32.373 TOS 125.65535.4 (4) [N=517 Src=1]
17:31:32.558 TOS 125.65535.4 (4) [N=518 Src=1]
17:31:32.849 TOS 125.65535.4 (4) [N=519 Src=1]
17:31:32.985 TOS 125.65535.4 (4) [N=520 Src=1]
17:31:33.193 TOS 125.65535.4 (4) [N=521 Src=1]
17:31:33.454 TOS 125.65535.4 (4) [N=522 Src=1]
17:31:33.701 TOS 125.65535.4 (4) [N=523 Src=1]
17:31:33.758 TOS 125.65535.4 (4) [N=524 Src=1]
17:31:33.970 TOS 125.65535.4 (4) [N=525 Src=1]
17:31:34.212 TOS 125.65535.4 (4) [N=526 Src=1]
17:31:34.365 TOS 125.65535.4 (4) [N=527 Src=1]
17:31:34.585 TOS 125.65535.4 (4) [N=528 Src=1]
17:31:34.759 TOS 125.65535.4 (4) [N=529 Src=1]
17:31:34.959 TOS 125.65535.4 (4) [N=530 Src=1]
17:31:35.159 TOS 125.65535.4 (4) [N=531 Src=1]
17:31:35.372 TOS 125.65535.4 (4) [N=532 Src=1]
17:31:35.631 TOS 125.65535.4 (4) [N=533 Src=1]
17:31:35.635 TOS 125.65535.4 (4) [N=534 Src=1]
17:31:35.959 TOS 125.65535.4 (4) [N=535 Src=1]
17:31:36.159 TOS 125.65535.4 (4) [N=536 Src=1]
^C17:31:36.379 TOS 125.65535.4 (4) [N=537 Src=1]
17:31:36.383 TOS 125.65535.4 (4) [N=538 Src=1]

525 packets read, 0 packets with protocol error
Chelsea:~/Projects/Sensor Network Sniffer hteo$

```

Figure 10 Captured screen output of Sniffer sniffing on 2 motes running the CountRadio application. The sniffer was started after the motes. Hence the lower packet count.

3. Observations and Recommendations

While it would appear that the *Sniffer* is functioning correctly, the following observations are made.

Timestamp: The first observation is that the intervals between sequential packets are not exactly 200 milliseconds, give or take some acceptable deviations. In fact, just from the snapshot shown in Figure 10 alone, the interval can be as short as four milliseconds, to as large as 400 milliseconds. In a network where the data rate is on the order of tens to hundreds of kilobits per second, an error of 400 milliseconds may be enough to skew certain traffic analysis.

The inaccuracy of the timestamp is mainly due to the fact that the sniffer mote does not currently have the ability to affix timestamps to sniffed packets as it receives them. Instead, the timestamp is only added at the PacketServer level. The fact that the Source object is a network interface, while convenient from programming point of view, inevitably adds further errors to the timestamp. There is clearly room for improvement.

CRC: The second, and more important, observation is that CRC information is missing. Unfortunately, the point along the TinyOS chain where the CRC information is lost could not be determined. But it does point out that the current implementation is incomplete, since it cannot provide the packet in its entirety for analysis.

To address these deficiencies, the Sniffer program should be more tightly integrated with the mote hardware. One possibility is to implement a Source object that interfaces with the mote directly via the serial link without any mediation. In this way, the Source object can also be responsible to affix a timestamp on the received packets for a higher degree of accuracy in the timestamp.

F. SUMMARY

The design and implementation of the *Sniffer* program has been described in detail, including its usage, process flow, and the functions of the major Java classes. It has also been explained how new input sources, application handlers, and output channels can be easily created and added to the program in a very modular way.

The testing of the *Sniffer* program indicates that there are deficiencies in its implementation: firstly, the timestamp has too much deviation. Secondly, the Sniffer does not have access to the sniffed packet in its entirety. A tighter integration of the Sniffer program and the mote hardware should be able to address these deficiencies.

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VII. CONCLUSION

TinyOS and IEEE 802.15.4 are the two dominant implementations of sensor networks today. TinyOS targets devices where energy and computational power are the significant resource constraints. 802.15.4 takes a more modular approach to its design, and is suited for a variety of devices and applications. Currently TinyOS is more popular in the sensor network community, but that is probably because it has been around longer. With 802.15.4 being formally adopted as a standard recently, it should not be long before 802.15.4 starts to take root in the sensor network community.

This thesis examined the security architectures of TinyOS and 802.15.4. It found that 802.15.4 generally offers higher assurances in terms of cryptographic strength, message integrity, and information leakage from IV reuse. TinyOS applications will need robust re-keying support and countermeasures against forgery attempts to make up the difference. But they both lack effective peer-level access control and replay protection – both important aspects of sensor network security.

For resource-limited sensor networks, TinyOS is still the better choice. For military applications where security and performance needs dominate, it is envisioned that a hybrid TinyOS/802.15.4 system would be ideal. Given the open source nature of the TinyOS project, it is conceivable that TinyOS can be adapted to leverage on 802.15.4-compliant hardware for its link layer security, instead of relying on TinySec. TinyOS packets can be encapsulated inside 802.15.4 frames, just like TCP/IP packets are encapsulated inside 802.11 frames. In this way, sensor network applications can be built that enjoy the best of both worlds – the mature and optimized environment of TinyOS, and the superior link layer security offered by 802.15.4.

As a tool for validating the above security analysis and also to perform further analysis, the design and implementation of a TinyOS sniffer application was presented. A sniffer is the quintessential tool for modern day network analysis. But such a tool is presently lacking in today's sensor network development kits. The current design is based on existing sensor network hardware and software components to enable a low-cost

sniffer implementation. The sniffer has also been designed to be easily extensible in terms of functionalities.

The following topics are the recommended for further research:

- Improve the functionality of the TinyOS sniffer. Areas of improvement include tighter integration of the Sniffer with the mote hardware, and additional output modes for packet data such as the extensible markup language (XML) format.
- Integrate TinyOS with 802.15.4-compliant hardware for high assurance applications, with support for peer-level access control and replay protection.

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