Security in ZigBee Wireless Sensor Networks

Presented By:
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Agenda

- General Background
- 802.15.4 Background
- ZigBee Background
  - Network Layers
  - Stack Layer
  - ZigBee Profiles
  - ZigBee Security
  - ZigBee Cluster Library

Agenda (2)

- Dini, G. and Tiloca, M., “Considerations on Security in ZigBee Networks”, Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC), 2010 IEEE International Conference on, 2010
  - Smart Energy Profile (SEP)
  - Security, Keys and Commissioning
    - Forward Security
    - Backward Security
    - Certificate Management

Agenda (3)

- Sokullu, R. et al. "An Investigation on IEEE 802.15.4 MAC Layer Attacks" Proceedings of The 10th International Symposium on Wireless Personal Multimedia Communications (WPMC), 2007.
  - Radio Jamming
  - Link Layer Jamming
  - Backoff Manipulation
  - Same-nonce Attack
  - Replay Protection Attack
  - ACK Attack
  - PANid Conflict Attack

Disclaimer

- You could easily run a series of lectures on each of the network layers of the ZigBee protocol
- I am not an RF expert or a networking expert
- These papers are broad “Survey” type papers – often lead to more questions than answers. I've tried to include references where I can

General Background

- ZigBee is a communication specification built upon the PHY and MAC layers of IEEE 802.15.4 Wireless specification.
- Designed for:
  - Low cost
  - Low power
  - Mesh networking
  - Fits in niche between Bluetooth and WiFi
- ZigBee 2004, ZigBee 2006, ZigBee Pro

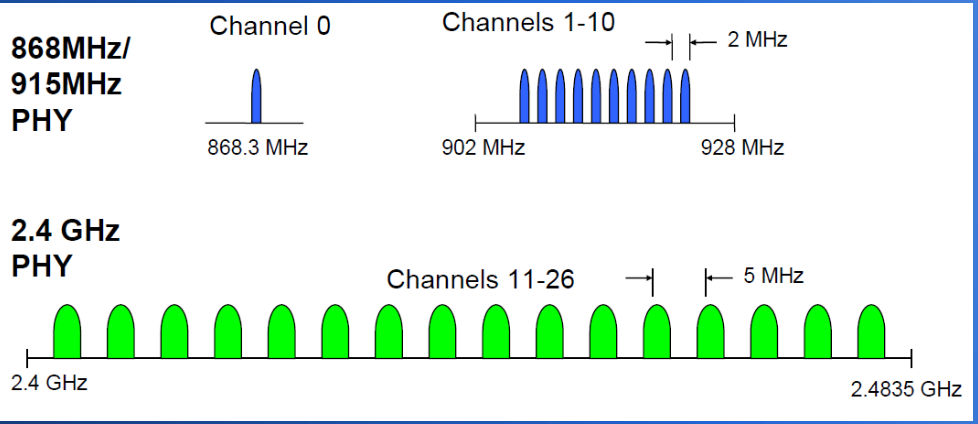
General Background (2)

- Rationale for ZigBee and 802.15.4

	ZigBee and 802.15.4	GSM/GPRS CDMA	802.11	Bluetooth
Focus Application	Monitoring and Control	Wide Area Voice and Data	High-Speed Internet	Device Connectivity
Battery Life	Years	1 Week	1 Week	1 Week
Bandwidth	250 Kbps	Up to 2 Mbps	Up to 54 Mbps	720 Kbps
Typical Range	100+ Meters	Several Kilometers	50-100 Meters	10-100 Meters
Advantages	Low Power, Cost	Existing Infrastructure	Speed, Ubiquity	Convenience

802.15.4 Background

- 868/900 MHz – Channels 0 to 10
  - 2 MHz between bands
  - 20 or 40 kbit/s
  - Not used by ZigBee
- 2.4 GHz – Channels 11-26
  - 5 MHz between bands
  - 100 and 250 kbit/s
  - DSSS (Direct Sequence Spread Spectrum)
  - QPSK (Quadrature Phase Shift Keying)



Extra sources: Ergen, S.C., “ZigBee/IEEE 802.15.4 Summary”, 2004.

802.15.4 Background (2)

- Full Function Devices (FFD)
  - Capable of being a PAN Coordinator, Coordinator or device
  - Implements entire protocol
  - Can talk to FFDs or RFDs
- Reduced Function Devices (RFD)
  - Reduced protocol set
  - Must connect to some established PAN

802.15.4 Background (3)

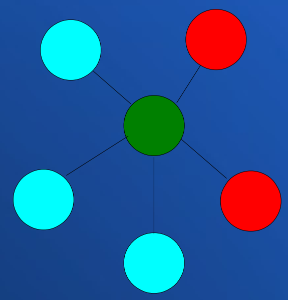
- PAN Coordinator (FFD)
  - Coordinates and acts as control node for entire WPAN
- Coordinator (FFD)
  - A device capable of routing and relaying messages between other devices. (Beacon based networks)
- End Device (FFD or RFD)
  - Simplest device, not capable of routing

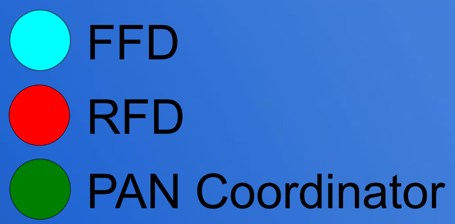
802.15.4 Background (4)

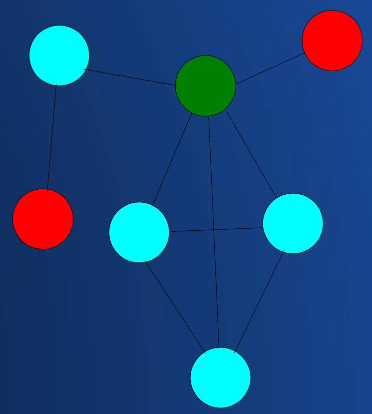
- Network Device: Any device that connects to other devices via the 802.15.4 MAC and PHY layer
- Coordinator: A FFD that provides coordination between other FFDs and RFDs.
- PAN Coordinator: A coordinator device that is a principal controller of a PAN. Each network has a single PAN coordinator

802.15.4 Background (5)

- Topologies
  - Star
  - Peer to Peer
  - Combined

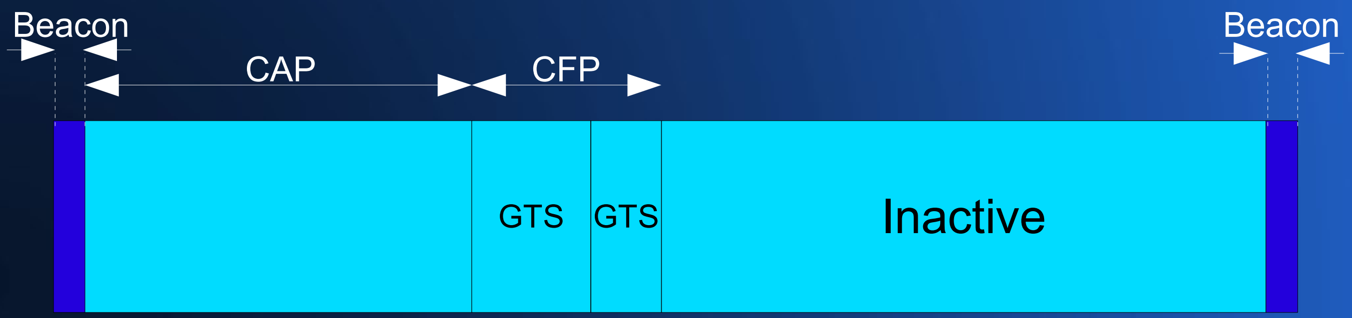






802.15.4 Background (5)

- Beacon Mode –
  - Divides time into periods
    - Beacon
    - Contention Access Period (CSMA/CA)
    - Contention Free Period
      - Guaranteed Time Slots

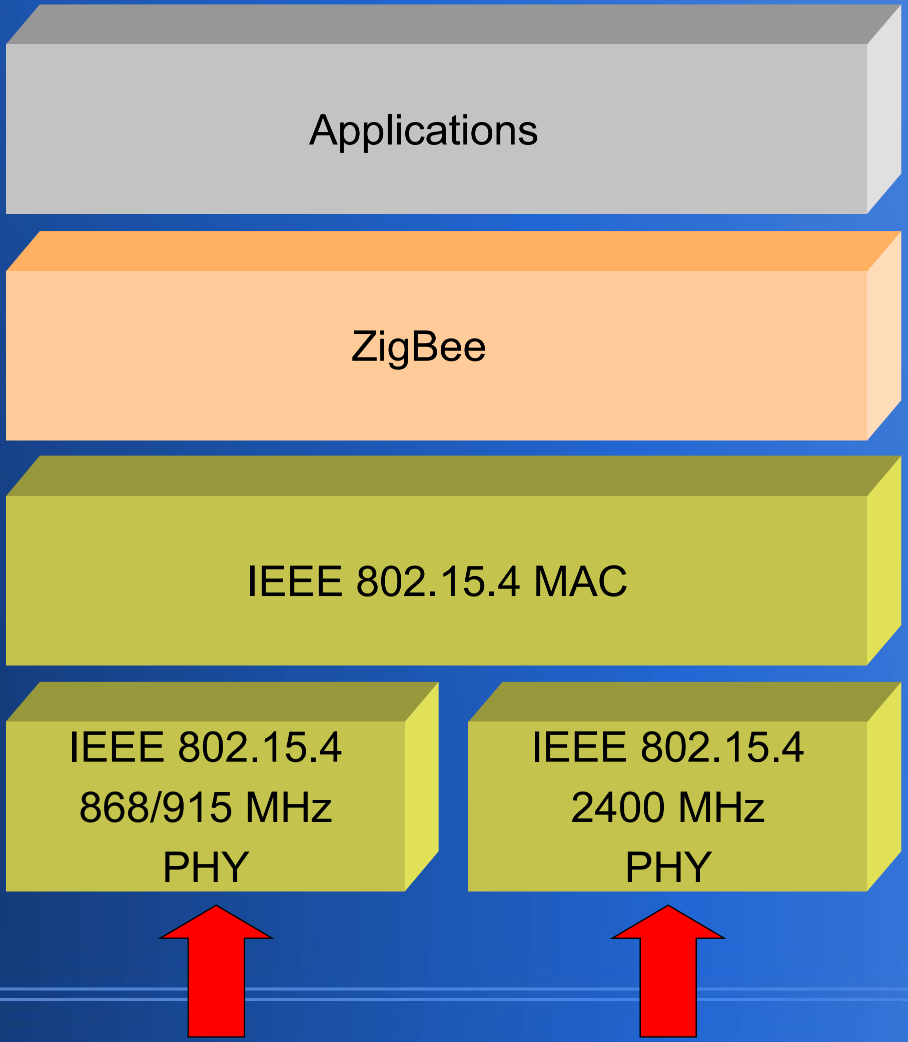


802.15.4 Background (6)

- Non-beacon Mode –
  - CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance)
  - CCA (Clear Channel Assessment)
    - Energy level threshold
    - Pattern matching of modulation and spreading characteristics
  - Wait until channel is clear before trying to transmit

ZigBee Background

- ZigBee Stack
  - PHY layer:
  - Adopted the 802.15.4 PHY and MAC layers
- PAN Coordinator → Coordinator
- Router → Coordinator
- End device → End device



ZigBee Background (2)

- ZigBee Stack
  - PHY layer:

Preamble provides sync pattern for receiver and decommutator

Start of packet is similar

Frame length is needed because no footer exists at this level

Finally, a payload of up to 127 bytes can be sent with each frame.

Preamble	Start of Packet Delimeter	Frame Length	Payload
4 Octets	1	1	0-127

ZigBee Background (3)

- ZigBee Stack
  - MAC layer: MAC Frame Format

MAC header							MAC payload	MAC footer
Frame Control	Sequence Number	Dest. PAN ID	Dest. Address	Src. PAN ID	Src. Address	Aux. Security Header	Payload	Frame-check Sequence
2 Octet	1	0/2	0/2/8	0/2	0/2/8	0/14	Variable	2

Frame Type	Security enabled	Frame pending	Ack. Req.	Intra PAN	Reserved	Dest. address mode	Reserved	Src. Address mode
Bits: 0-2	3	4	5	6	7-9	10-11	12-13	14-15

ZigBee Background (4)

- ZigBee Stack
  - MAC layer: MAC Beacon Frame Format

MAC header			MAC payload				MAC footer
Frame Control	Data Sequence Number	Address	Superframe Spec.	GTS fields	Pending Addr.	Beacon Payload	Frame-check Sequence
2 Octet	1	4/20	2	Variable	Variable	Variable	2

Beacon order	Superframe order	Final CAP slot	Batt. Life extension	Reserved	PAN Coordinator	Association permit
Bits: 0-3	4-7	8-11	12	13	14	15

ZigBee Background (5)

- ZigBee Stack
  - MAC layer: MAC Command Frame Format

MAC header			MAC payload		MAC footer
Frame Control	Data Sequence Number	Src Address	Command Type	Beacon Payload	Frame-check Sequence
2 Octet	1	4/10	1	Variable	2

- Association Request
- Association Response
- Disassociation notification
- Data request
- PAN id conflict notification
- Orphan Notification
- Beacon Request
- Coordinator Realignment
- GTS Request

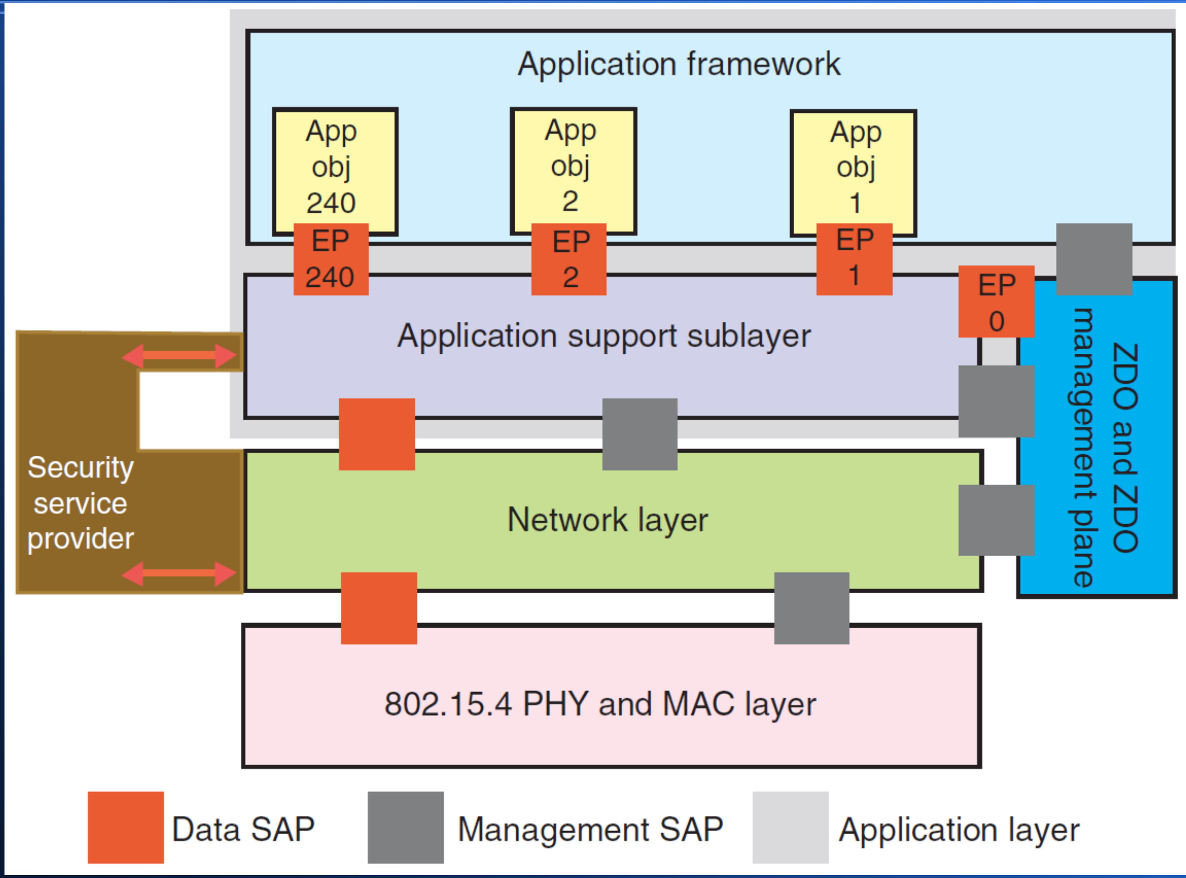
ZigBee Background (6)

- ZigBee Stack
  - MAC layer: MAC Data/ACK Frame Format

MAC header			MAC payload	MAC footer
Frame Control	Data Sequence Number	Address	Beacon Payload	Frame-check Sequence
2 Octet	1	4/20	Variable	2

MAC header		MAC footer
Frame Control	Data Sequence Number	Frame-check Sequence
2 Octet	1	2

ZigBee Stack Details



Previous stack details have allowed for the transmission of data frames, ZigBee provides an Application Framework on top of this

ZigBee Clusters and ZCL

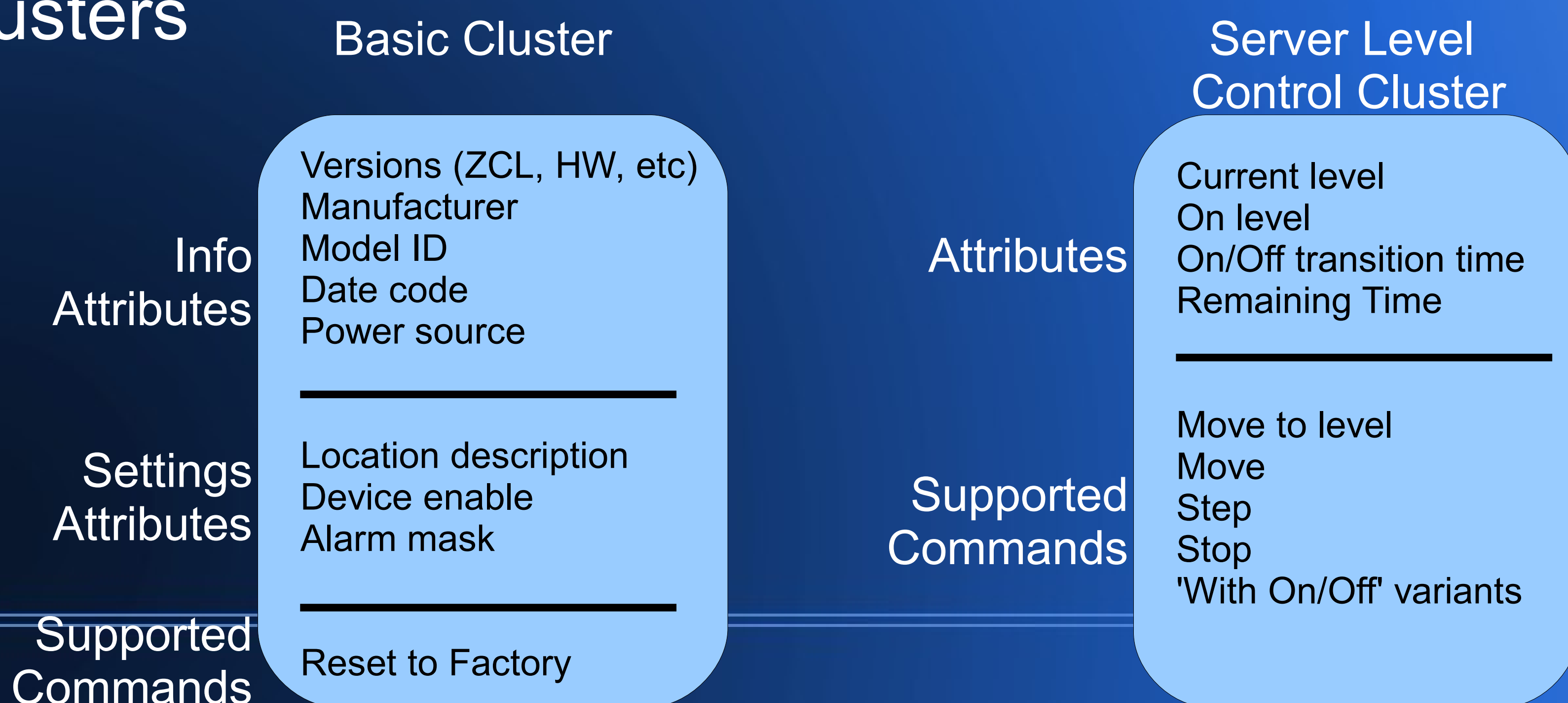
- Application Objects and Endpoints
  - Lowest addressable object in the model
    - Addresses 1-240
  - Typically represents a physical device or at least something that models something physical
    - Ex: lightswitch, lamp, temperature probe, filter
  - Lends itself very much to an Object-oriented view of the stack
  - Special Endpoint 0 called ZDO used to communicate with other layers
  - Special Endpoint 255 for broadcasting to ALL endpoints

ZigBee Clusters and ZCL (2)

- Endpoints consist of a set of clusters
  - Each cluster is a set of attributes and a set of commands with respect to the attributes
- Clusters are client/server oriented
  - Server: also known as an input, responsible for storing the attribute values
  - Client: also known as an output, manipulates or requests the attribute values
  - Compatible Client and Server clusters on different Endpoints can be “bound”

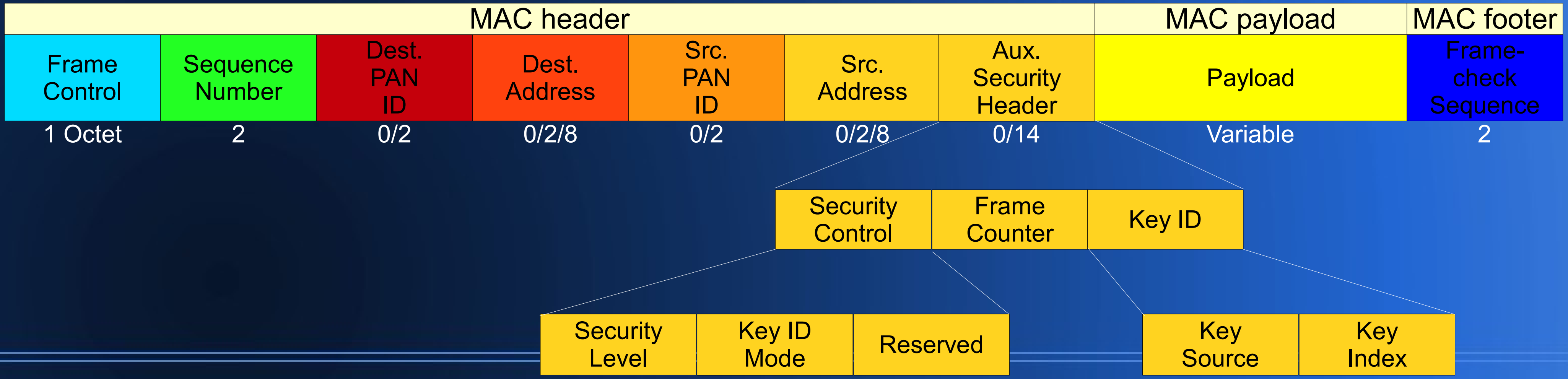
ZigBee Clusters and ZCL (3)

- **ZigBee Cluster Library** - Standardized set of Cluster definitions organized together into Profiles. Profiles allow for grouping and reuse of Cluster IDs as well as for user-defined Profiles for non-standardized Clusters



ZigBee Security Model

- IEEE 802.15.4 Security
  - Data confidentiality
  - Data authenticity
  - Replay protection
- ZigBee Security
  - Trust Centers
  - Keys



Security Model of Smart Energy Profile

- New devices must be "commissioned"
  - Devices can form a new network or join an established one
  - Out of band means (buttons, web login, phone, etc.) are used to notify network that the device ID that is authorized to join
  - Network enters *permit joining ON* state
  - Device attempts to join network and keys are established

Security Keys

- Link Key
  - An end-to-end key that a device may share with another device.
    - Established through Trust Center
  - Devices MUST share a Link Key with the Trust Center (TCLK)
  - TCLK is established during Join procedure
  - Protects App layer and Stack commands:
    - Time, commissioning, price, demand response, load control, simple metering, message smart energy tunneling and pre-payment
  - Infrequently refreshed from Trust Center

Security Keys (2)

- Network Key
  - Shared by all devices on a network
  - Protects management and control communications
  - Can be used to protect app layer in cases where Link Key unavailable or unaccepted
  - Protected clusters:
    - Basic, Identify, Alarms, Power configuration and Key establishment
  - Should be periodically refreshed

Security Keys (3)

- Transport Key
  - Shared with the Trust Center and derived from the TCLK
  - Secures the Network Key refresh
    - This refresh is point-to-point with no broadcast mechanism
  - SWITCH_KEY command signals to start using newly established key

JOIN Procedure

- TCLK LK_i provided to Trust Center by out-of-band means
  - usually while informing the TC that the device wants to join
- Trust Center and device i obtain Transport Key TK_i from LK_i
- Trust Center now sends device i the Network Key NK encrypted by TK_i.
- Trust Center updates the Link Key LK_i of device i

Certificate Based Key Establishment

- Every device holds a certificate from a Certificate Authority (CA)
- Can derive the public key from the Certificate
  - Elliptic Curve MQV key agreement scheme
    - Basically provides a safe/secret way for 2 devices to agree on a shared value using a public channel
  - Key Derivative Function
    - Used in conjunction with non-secret parameters to derive one or more keys from a common secret value

LEAVE and REJOIN Procedure

- Secured REJOIN using currently known Network Key
  - May fail if Network Key has been refreshed in the meantime
- Unsecured REJOIN uses the LK that the Trust Center shares with the device to retransmit Network Key
- If Unsecured REJOIN fails device must go back and do a normal join
  - Usually requiring some out-of-band method again
- If a device leaves the network, the Trust Center removes their Link Key LK_i

Forward Security

Problems with Smart Energy Profile (SEP)

- Devices SHOULD be prevented from accessing communication on the network after it has left
- SEP specifies revocation of the Trust Center Link Key for a leaving device
- Specifies nothing about Network Key and Link Key
- Device can continue to listen to traffic encoded with Network Key and communicate with devices it shares a Link Key with
- Network and Application layer commands are at risk
  - Highly disruptive routing attacks from a compromised device

Forward Security (2)

Proposed Solution

- Network Key
  - Revoke and refresh the Network Key every time a device leaves the network
  - Utilize point-to-point rather than Broadcast based refresh for Network Key
    - Limits scalability
- Link Key
  - Propose defining a Key Revocation Cluster within the application layer
  - Trust Center would use a broadcast to notify all remaining devices that a device has left the network
  - Each device then invalidates LK_{ij}

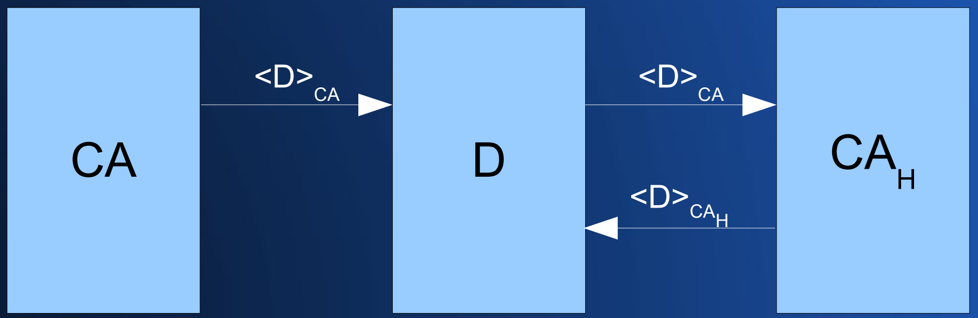
Certificate Management
(Problem)

- Every device holds a certificate issued by Certificate Authority (CA) and the public key of the certificate called the Root Key
- ZigBee Key Establishment Cluster allows many organizations to issue certificates (manufacturers, device distributors, end-users, etc.)
- This means that a Coordinator must authenticate certificates from various organizations
  - Every device must store Root Key of every possible certificate source
  - This is counter to the idea of small, fast, low-power RFDs

Certificate Management

(Proposed Solution)

- Home Certification Authority (CA_H)
  - Root Key Database: Stores root keys of the certificate authorities
  - Verifies the certificates pre-installed in a device and issues a new certificate for that device



Certificate Management (2)

(Proposed Solution)

- Assume Device D, with public key K_D and certificate $<D>_{CA}$ from certificate authority CA
  - Home Certificate Authority CA_H obtains the device's certificate $<D>_{CA}$
  - CA_H retrieves the CA's root key from the Root Key Database
    - Verifies $<D>_{CA}$ by that key
    - May possibly access larger database over internet
  - CA_H issues new home-certificate for D, $<D>_{CA_H}$
  - $<D>_{CA_H}$ is installed in device D

Critiques

- Great outline of the security of IEEE 802.15.4/ZigBee/Smart Energy Profile
- Proposals seem logical given the stated issues
  - No formal verification of these proposals
  - Simulation/Implementation to show effects (or lack of) on a realistic network

An Investigation on IEEE 802.15.4 MAC Layer Attacks

- Wireless Sensor Networks general present in unrestricted environments – thus prone to attacks
- Attacker: One who attacks the network with the aim of damaging nodes or gaining selfish benefits from the network itself.
- Can occur at any level of the protocol stack
- In general attacks are unpredictable

An Investigation on IEEE 802.15.4 MAC Layer Attacks

- Literature Survey of MAC Layer attacks
- 2 attack and solution contributions of their own

Radio Jamming

- Description
  - Simplest of the attacks
  - Act of emitting competing radio signals directed at a specific channel
  - Classified as a misbehavior attack of the 802.15.4 PHY layer
- Evaluation
  - Constant jamming is the easiest
  - Jammer continuously emits signal to corrupt communication
  - Simple to detect using statistical analysis of signal strength and SNR

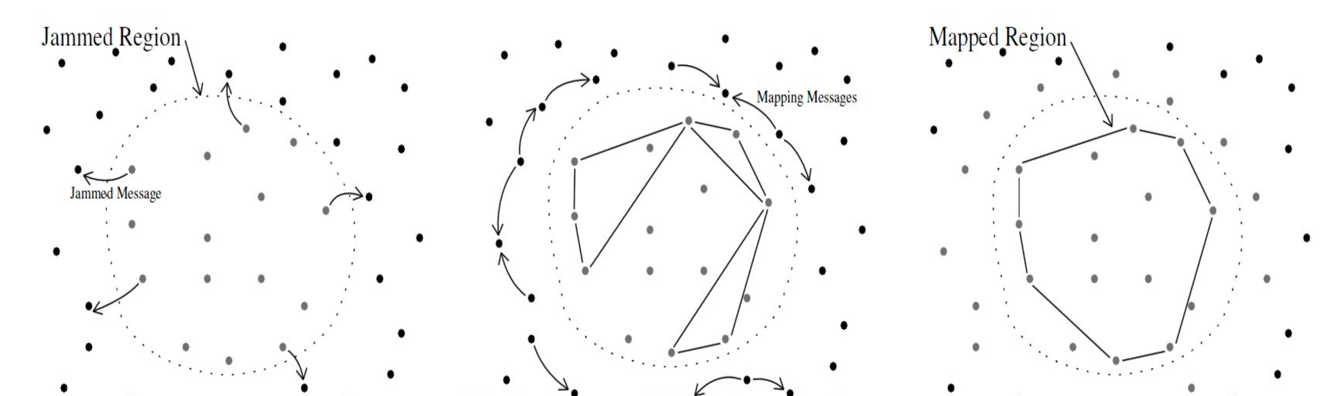
W. Xu, K. Ma, W. Trappe and Y. Zhang, ”Jamming sensor networks: attack and defense strategies”, IEEE Network, vol.20, no.3, 2006, pp.41-47.

Radio Jamming (2)

- Deceptive Jamming
  - Emits “regular” packets as an interference pattern. More difficult to detect than simple jamming but security schemes can be used to detect bogus node. Assumed constant
- Random Jamming
  - Emits “regular” packets or noise at random intervals. Less likely to be detected due to non-constant nature as well as saving power

Radio Jamming (3)

- Reactive Jamming:
  - Based on sensing network activity
  - Stays quiet while network is idle and begins transmitting only upon sensing activity
  - More energy efficient and harder to detect
  - Detection necessitates more advanced methods such as Jammed Area Mapping



(a) Upon detecting local jamming, nodes blindly report it to their neighbors.

(b) Receivers outside the jamming form groups and exchange mapping messages.

(c) Groups are coalesced to yield a mapped region.

Link Layer Jamming

- Description
  - Utilizes knowledge of the Link Layer to be as effective as radio jamming on much less power
- Evalulation
  - Typical reaction times against this attack are similar to reactive radio attacks

Y.W. Law, P. Hartel, J. den Hartog and P. Havinga, ”Link-layer jamming attacks on S-MAC”, in Proceedings of IEEE WSN’05, 2005, pp.217- 225.

Backoff Manipulation

- Description
  - IEEE 802.15.4 CSMA uses a back-off period if a node finds the medium to be busy when it wishes to transmit
  - Backoff period is randomly chosen in a contention window (which increases)
  - A malicious node may consistently choose a shorter back-off period to give unequal medium access

S. Radosavac, A. A. Crdenas, J. S. Baras and G. V. Moustakides, ”Detecting IEEE 802.11 MAC Layer Misbehavior in Ad Hoc Networks: Robust strategies against individual and colluding attackers”, Journal of Computer Security, special Issue on Security of Ad Hoc and Sensor Networks, vol.15, no.1, 2007, pp.103-128.

Backoff Manipulation (2)

- Evaluation
  - Very difficult to discern between legitimate node and misbehaving node
  - Indiscernible with low congestion
  - Sequential Probability Ratio Test (SPRT)

$$S_k = \sum_{j=1}^{k} \Lambda_j = \sum_{j=1}^{k} \ln \frac{f_1(x_j)}{f_0(x_j)},$$

$$S_k \geqslant a \Rightarrow \text{accept } \mathbf{H}_1,$$

$$S_k < b \Rightarrow \text{accept } \mathbf{H}_0,$$

$$b \leqslant S_k < a \Rightarrow \text{take another observation.}$$

with $f_i(\cdot)$ the probability density function of hypothesis $\mathbf{H}_i$, $i = 0, 1$. The decision is taken based on the criteria:

Same-nonce Attack

Nonce - arbitrary number used only once to sign a cryptographic communication.

- Description
  - 802.15.4 Secured Mode uses Access Control Lists (ACL) made of destination address, secured mode options, keys and nonce info.
  - In the case where a sender has 2 ACL entries with the same keys and nonce
  - When encoded message C_1 and C_2 use the same nonce data and keys
    - C_1=[D_1 XOR E_{key}(nonce)]
    - C_2=[D_2 XOR E_{key}(nonce)]
    - [C_1 XOR C_2] = [D_1 XOR D_2]

Address	Security Suite	Key	Last IV	Replay Ctr

ACL Entry format

Another great paper

N. Sastry and D. Wagner, "Security Considerations for IEEE 802.15.4 Networks", in Proceedings of the 2004 ACM workshop on Wireless security, 2004, pp-32-42.

Same-nonce Attack (2)

- Example
  - AES-CCM-64 Security Suite, recipients r_1 and r_2 use the same key k.
  - Frame and key counters inited to 0x0 (common)
  - Sender transmits D_1=0xAA00 to r_1 as C_1
  - Sender transmits D_2=0x00BB to r_2 as C_2
  - Using previous formula, an adversary can obtain
  - [D_1 XOR D_2] = [C_1 XOR C_2] = 0xAABB
- Evaluation
  - Likely occurrence if nonce data is not managed
  - "The general principle to prevent nonce reuse is that the nonce state should never be separated from the key"

Replay Protection Attack

- Description
  - Replay protection in 802.15.4 checks a counter of a message with the previously obtained counter. Rejects message is counter is less than or equal to previous one (can't go backwards)
  - Attack repeatedly sends high value counters.
  - Legitimate frame has lower counter value and is rejected

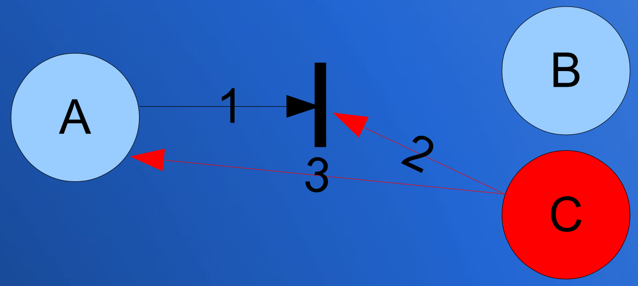
Y. Xiao, S. Sethi, H.-H. Chen and B. Sun, ”Security services and enhancements in the IEEE 802.15.4 wireless sensor networks”, in Proceedings of IEEE GLOBECOM’05, vol.3, 2005.

Replay Protection Attack (2)

- Evaluation
  - Proposed solution of utilizing a timestamp as the frame counter field
  - Timestamp updated using Beacon frame from coordinator and updates all ACL entries with new time stamp
  - Attacker cannot send future times and so Replay protection attack fails
  - Requires larger field to support timestamp

ACK Attack

- Frame sequence numbers are unencrypted
- Attacker uses MAC or PHY layer interference to prevent transmission after Frame sequence number is seen
- Then sends fake ACK frame to sender, preventing retry
- Proposed solution: Use Message Integrity Bits (MIC) which encode even ACK frames



1.Legitimate node A tries to send frame to node B
2. Attacker Node C listens to enough of 1 to retrieve Frame sequence number, then sends interference to prevent proper receipt of A's frame
3. Attacker Node C uses Frame sequence number from 2 to send spoofed ACK Frame

Y. Xiao, S. Sethi, H.-H. Chen and B. Sun, ”Security services and enhancements in the IEEE 802.15.4 wireless sensor networks”, in Proceedings of IEEE GLOBECOM’05, vol.3, 2005.

PANid Conflict Attack
(original work)

- PANid conflict occurs when two Coordinators contain the same PANid
- Can be detected via Beacons or a member node can inform its coordinator
- Induced Conflict Resolution Procedure
  - Initiate scan, choose new PANid, broadcast to PANid member nodes
  - Nodes resync'ed at next Beacon Frame
- Attacker can perform DoS by generating fake PANid conflict notifications (PCN) causing entire PAN to reset and resync

PANid Conflict Attack (2)
(original work)

- Simple formula for detection time:
  - p1: Max number of PCN from an attacker
  - p2: Max number of PCN in fixed duration
  - p3: Fixed duration length
  - ε: Misbehavior detection algorithm running time

Coordinator keeps track of this

$$f(p_1) = successful\_(p_1+1)^{th}\_attack\_time + \epsilon_2 \qquad (1)$$

$$f(p_2, p_3) = successful\_(p_2+1)^{th}\_attack\_time \_in\_the\_last\_p_3\_duration + \epsilon_2 \qquad (2)$$

$$detection\_time = min(f(p_1), f(p_2, p_3)) \qquad (3)$$

PANid Conflict Attack (3)
(original work)

- **Methodology:**
- Simulated on ns2.31 IEEE 802.15.4 simulator
- Star topology with 5 and 10 nodes
- Attackers send fake PCN at random times
- Set initial first attack at 15 second to allow initial network establishment
- Observed realignment time upon conflict at approximately 3 seconds
  - Attackers do not attack within this range of (3-e, 3+e) where e is the realignment message. Doing some could leave them orphaned

PANid Conflict Attack (4)
(original work)

$P_1=4$ $P_2=2$ $P_3=20$	Attack Times(s)											Misbehavior Type	Attack Solution Time
Single Attacker	15	19	27	31	35	100						2	$27+\varepsilon_2$
	16	23	39	44	63	71						1	$63+\varepsilon_2$
Double Attacker	15	19	27	31	35	100						2	$27+\varepsilon_2$
	16	23	39	44	63	71						1	$71+\varepsilon_2$
Triple Attacker	15	19	27	31	35	100						2	$27+\varepsilon_2$
	16	23	39	44	63	71	81	96				1	$71+\varepsilon_2$
	17	21	33	40	50	56	67	73	80	85	95	2	$67+\varepsilon_2$

Attack times vs number of attackers

Double Attacker	Attack Times(s)											Misbehavior Type	Attack Solution Time
$P_1=2$ $P_2=2$ $P_3=20$	15	19	27	31	35	100						3	$27+\varepsilon_2$
	16	23	39	44	63	71						1	$44+\varepsilon_2$
$P_1=3$ $P_2=2$ $P_3=20$	15	19	27	31	35	100						2	$27+\varepsilon_2$
	16	23	39	44	63	71						1	$63+\varepsilon_2$

Attack times vs coordinator detection parameters

Type 1: Max per node

Type 2: Max per time period

Green: Successful attack

Red: Detected attack

Uncolored: Redundant attack (ignored at MAC layer)

GTS Attack
(original work)

- A more targeted version of the MAC layer interference DoS attack
- Use the Beacon frame which contains the GTS descriptions to target a specific adversary node
- Interfere specifically during the GTS slot of the adversary
- Jamming can be noise-based or legitimate messaged based
- Fine-grained nature makes attack difficult to detect
- If detected, difficult to pinpoint source node

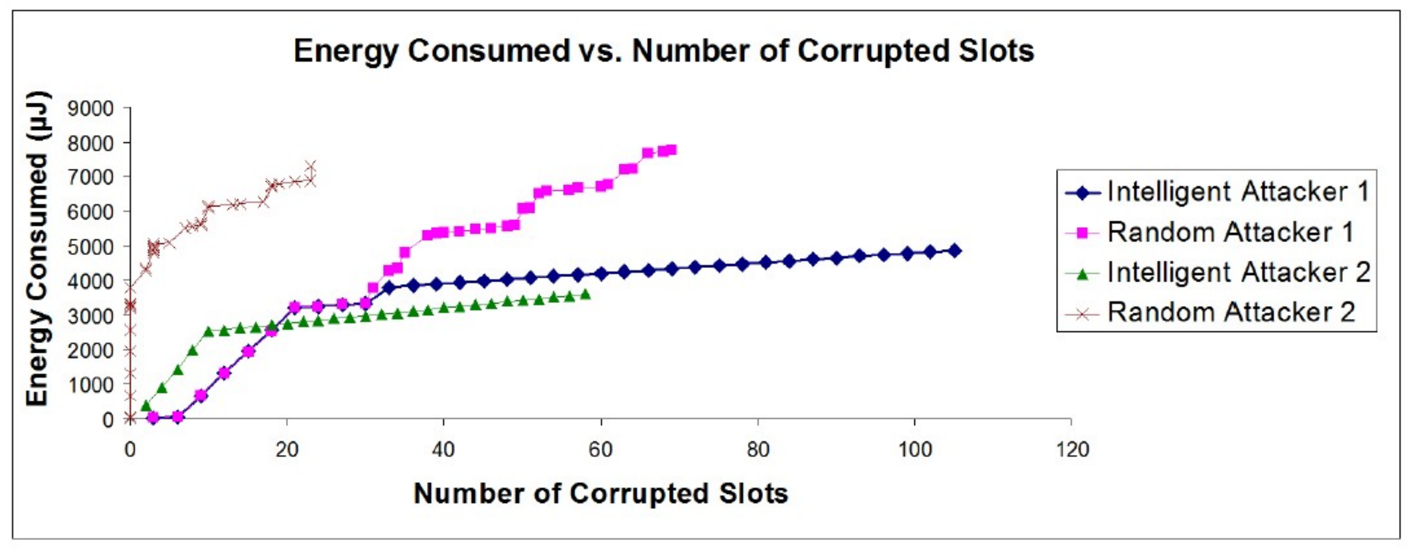
Sokullu, R., Dagdeviren, O., Korkmax, I. “On the IEEE 802.15.4 MAC Layer Attacks GTS Attack”, Second International Conference on Sensor Technologies and Applications, SENSORCOMM 2008, pp. 673-678.

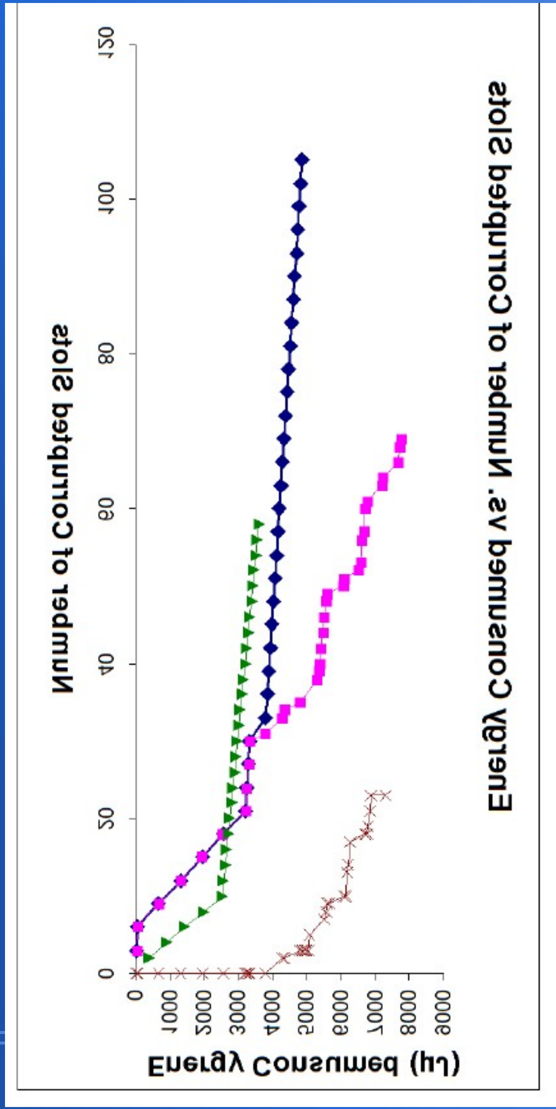
GTS Attack (2)
(original work)

- Simulated using ns2.31 IEEE 802.15.4 simulator modified to support full MAC layer standard
- Simulated targeted and random attackers
  - Targeted attackers chose same slot
  - Random attackers randomly chose slot
- Attackers jammed using legitimate messages

GTS Attack (3)
(original work)

- Results
  - (with more useful rotation)





Critiques

- Rehashes the same kinds of attacks that almost every paper does
- Doesn't do as good a job reviewing those attacks as other papers do (didn't find this out until later)
- Paper proposes 2 original attacks
  - PANid work is good, but analysis and simulation data is weak
  - GTS attack was not even properly simulated until a later paper which I had to find separately