IoT Security and Privacy: Basic Knowledge

CPS and IoT Security

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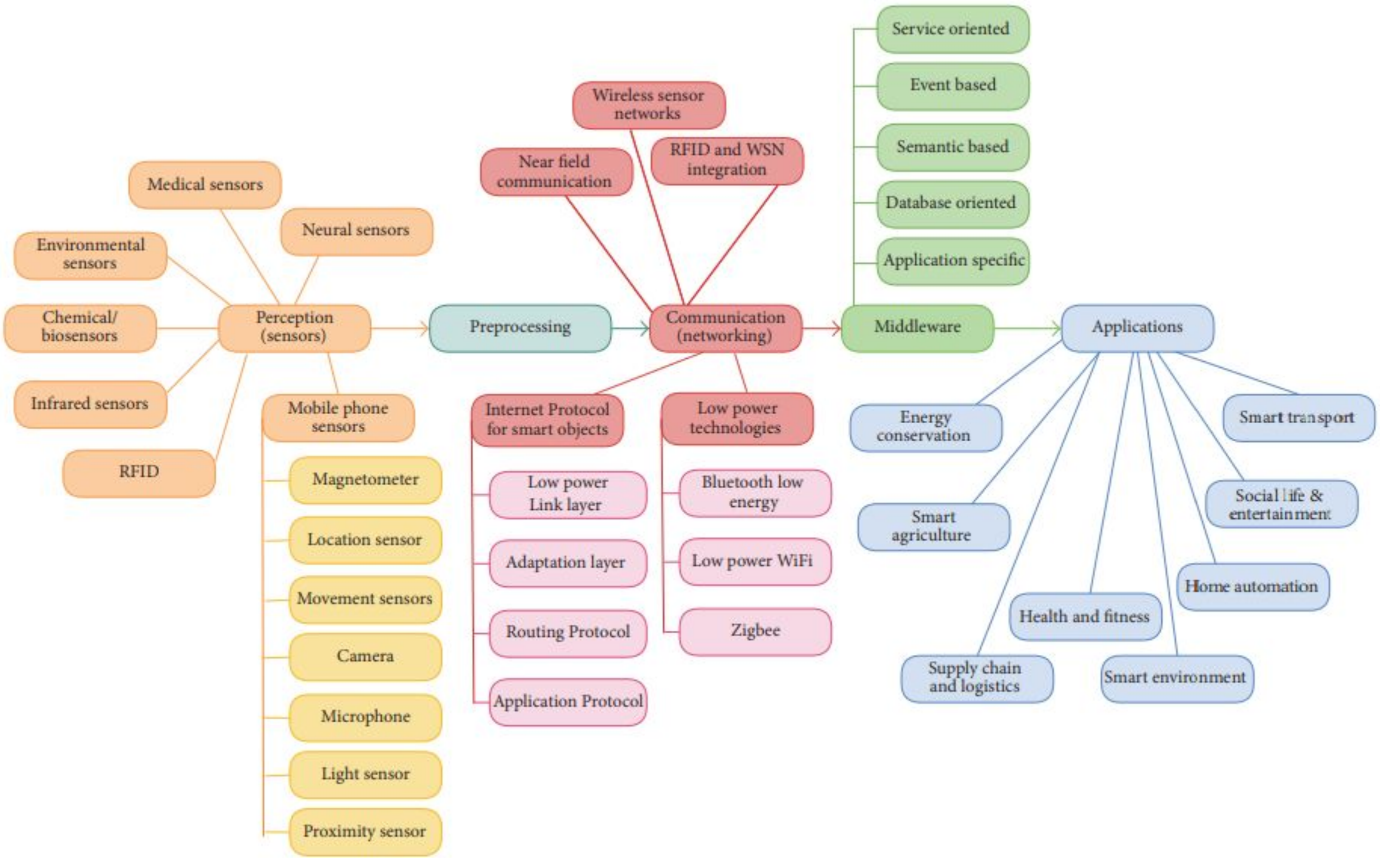
The Internet of Things

- An Internet of Things (IoT) describes a group of physical devices equipped with sensing, processing, and communication capabilities able to exchange information with each other over the Internet or other communication networks
- It is a result of development in different fields, including embedded devices, sensor networks, automation, and control systems
- We have already seen examples of internet of things

IoT Taxonomy



IoT Architecture

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- An IoT system consist of three main layers: i) devices, ii) edge gateway, iii) cloud
- Devices are the *things*, i.e., those devices equipped with sensors and actuators that collect data and report it to the gateway
- Gateway is a data aggregation system to pre-process data, securing connectivity to cloud, the event hub, and sometimes fog computing
- Cloud contains the applications built using microservices, storage, event queuing, and messaging systems

Network Architecture

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- We expect IoT networks to comprise a huge number of devices
- We use IETF IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN)
- Usually operates on top of IEEE 802.15.4 defined for low rate - PAN
- For industrial networks, we have IPv6 over TSCH model of IEEE 802.15.4e (6TiSCH)
- Data transport is provided by IETF Constrained Application Protocol (CoAP), ZeroMQ, and MQTT

IEEE 802.15.4

- Low Rate PAN standard specifying lower protocol layers (physical and MAC)
- Addressing uses a 64 bit node ID and 16 bit net ID
- Basic channel access mode is carrier-sense multiple access with collision avoidance (CSMA/CA)
- Check whether channel is occupied, if not send a RTS packet and wait for CTS
- If CTS received, send packet
- Uses data packets and ack packets

IEEE 802.15.4

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Data Packet format

1 byte	2 bytes	1 byte	0/2/4/10 bytes	0/2/4/10 bytes	variable	2 bytes
Len.	Flags	Seq. No	Dest. Address	Source Address	Data payload	CRC

Also indicates whether security is enabled

ACK Packet format

1 byte	2 bytes	1 byte	2 bytes
Len.	Flags	Seq. No	CRC

IEEE 802.15.4 Security

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- A link layer security protocol needs to provide four basic security services: access control, message integrity, message confidentiality, and replay protection
- In 802.15.4 security is handled at the media access control layer
- The application specifies the security stack and sets the appropriate control parameters
- Security is <u>not</u> enabled by default

IEEE 802.15.4 Security

- An application has a choice of *security suites* that controls the type of security protections provided for the transmitted data
- It defines eight different security suites
  - No security
  - Encryption onli (AES-CTR)
  - Authentication only (AES-CBC-MAC)
  - Encryption and authentication (AES-CCM)
- Each category that supports authentication comes into three variants depending on the size of the MAC (4, 8, or 16 bytes)

AES-CTR

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- confidentiality protection using AES block cypher with counter mode
- The sender breaks the cleartext packet into 16 byte blocks $p_1, \ldots, p_n$ and computes $c_i = p_i \oplus E_k(x_i)$ where each block uses its own counter x
- The receiver recovers the plaintext as $p_i = c_i \oplus E_k(x_i)$
- The counter, known as nonce or IV, is composed of a static flags filed, sender's address, and three separate counters

1 byte	8 bytes	4 bytes	1 byte	2 bytes
Flags	Source address	Frame Ctr	Key Ctr	Block Ctr

AES-CTR

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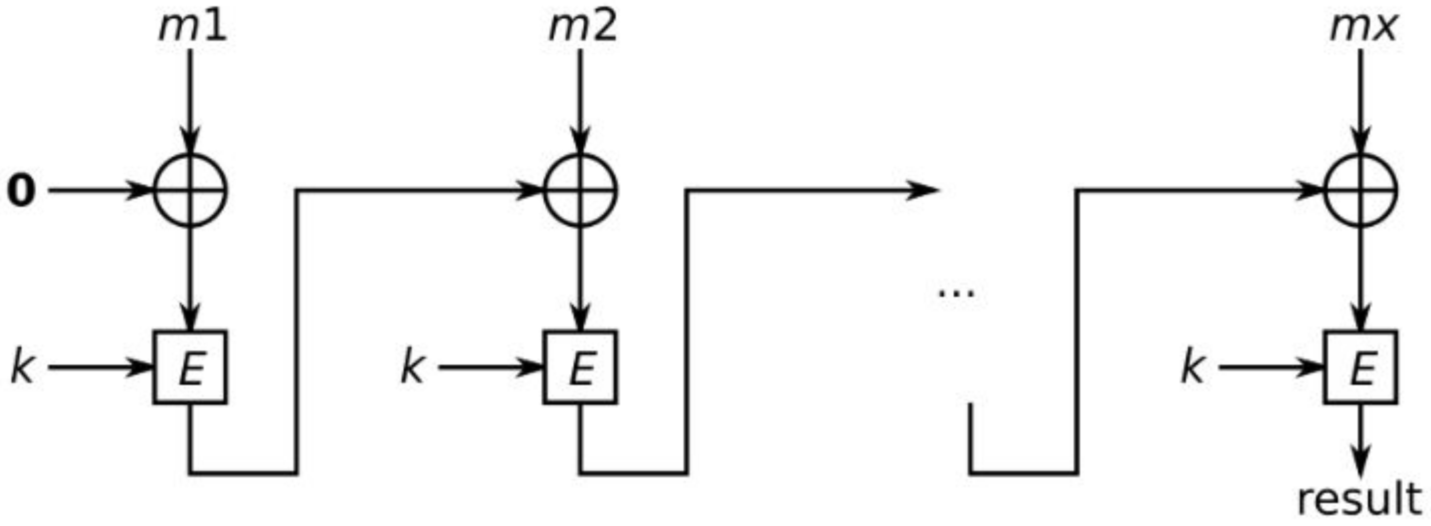
- The frame counter is maintained by the hardware radio and the sender increments it after encrypting each packet
- The key counter is under application control
- Requirement: nonce must never repeat within the lifetime of any single key and frame and key counter should prevent nonce reuse
- The 2 bytes block counter ensures that each block will use a different nonce value

AES-CBC-MAC

- Provide integrity protection via CBC-MAC algorithm
- It can only be computed by parts having symmetric key
- MAC protects the packet headers and data payload



AES-CCM

- Provides both encryption and authentication
- It first applies integrity protection over header and data payload using CBC-MAC
- Encrypts data payload and MAC using AES-CTR mode

4 bytes	1 byte	variable	4/8/16 bytes
Frame Counter	Key Ctr	Encrypted Payload	Encrypted MAC

Keying models

- Govern what key a node uses to communicate with another node
- Network shared keying: single network-wide shared key. Key management becomes trivial and memory requirements are minimal
- However, vulnerable to insider attacks and single key compromise
- A single compromised node can undermine the security guarantees of the entire network
- If we expect nodes to be occasionally compromised or captured, not a good approach

Keying models

- Pairwise keying: limit the scope of every key
- Each pair of nodes shares a different key
- Thus, if a node is compromised, only the security of communication with its pair is undermined
- Comes with an increased overhead
- Each node must store a key for every other node it communicates to
- Select the proper key when communication with a node
- IoT nodes have limited resources

Keying models

- Group keying: compromise between pairwise and network keying
- A single key is shared among a set of nodes and is used on all links between any two nodes in that group
- Groups can be created based on locations, network topology, or similarity of function
- Partial resistance to node compromise and partial improved management of resources

Zigbee

- Zigbee is a higher layer protocol based on IEEE 802.15.4 to create PAN networks
- It is usually leveraged for home automation, medical device data collection, and small scale projects
- It has a range of 10-100 m in line of sight
- Longer distances are achieved via multi-hop in amish network of intermediate devices

Zigbee Devices

Three type of devices in Zigbee:

- Zigbee Coordinator (ZC): root of the network tree and bridge with other networks. Only one ZC, since it is the originator of the network. Trusted node containing e.g., keys
- Zigbee Router (ZR): act as intermediate device to pass data to other devices. They are usually mains powered to always be available
- Zigbee End Device (ZED): minimal functionalities to talk to the parent node. Battery powered and wake up only when has something to say

Zigbee Security

- Zigbee security builds on top of IEEE 802.15.4 security
- Keys and modes we’ve seen for 802.15.4 are basic for Zigbee
- A momentary exception exists for the addition of a previously unpaired and unconfigured device
- We need to assume trust in the initial installation of keys
- Within the protocol stack, we need access policies to cope with the lack of cryptographic separation between different layers

Security Architecture

- Zigbee uses 128-bit keys to implement its security mechanism
- A key can be associated to a network or to a link, acquired via pre-installation, agreement, or transport
- There should be an initial master key obtained via a secure medium
- Establishment of link keys is based on a master key
- <u>Trust center:</u> special device in the network which other services trust for the distribution of secure keys
- Ideally, all devices will have the trust center address and initial master key

Security Architecture

- The security architecture is distributed to different layers

MAC layer

Layer	**Capabilities**
MAC	• Single hop reliable communications • Security level specified by upper layers
Network	• Outgoing frames use the appropriate link key according to routing
Application	• Key established and transport services to both ZDO and applications

Device Authentication

- After joining the network, an end-device needs to exchange security information with the trust center
- Needs to obtain the current network key from the trust center and establish a new end-to-end trust center link key
- It consists of four steps

Device Authentication

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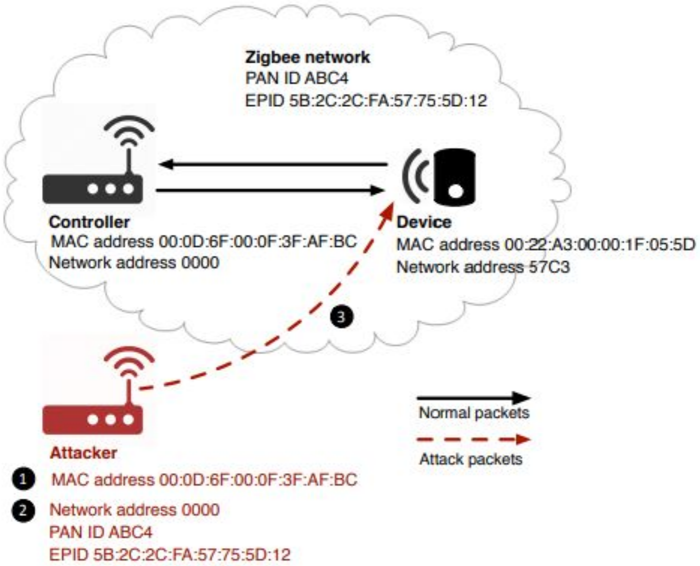
- Establish the Trust Center Link Key (TCLK): each device has a pre-installed TCLK typically obtained from the device installation code
- This key is provided to the TC through out-of-band means
- Establish the transport key: the TC and node can derive a transport key from the TCLK
- Distribute the network key: the TC can send to the new node the network key encrypted via transport key
- Establish new link key: as soon as the join procedure is completed, the TC updates the TCLK of the joining device

Attack to Authentication

- There are two factors that makes it challenging to compromise Zigbee networks
- Closed nature: Zigbee devices are equipped with a dedicated commissioning process to add new devices to the network
- Commissioning usually requires users’ actions to enable the controller to accept joining requests (e.g., pushing a button on the controller)
- Except commissioning, the Zigbee network is closed and the controller will not process the joining request

Attack to Authentication

- Encryption and authentications: Zigbee encrypts with AES and authentication with the CCM mode
- Without knowing the correct keys exchanged during the commissioning period, it is not possible to infiltrate Zigbee systems



Impersonation Attack

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- The attacker impersonates a node that is already in the target Zigbee network
- Since the controller has the most capabilities, we focus on impersonation of the controller
- The following attack steps can be launched at arbitrary time during the closed normal operations of Zigbee networks

Impersonation Attack

- Step 1: the attack device needs to overwrite its manufacturer-produced physical address and pretend to be the controller
- This can be obtained by sniffing Zigbee packets, since the MAC address is contained in plaintext in the header
- Step 2: The attacker extracts the controller address and network PAN ID by eavesdropping regular Zigbee packets

Impersonation Attack

- To get EPID, the adversary broadcasts a beacon request
- The controller will send a beacon reply with EPID and state that the network is closed and does not accept join requests
- The adversary selects a target device and obtain its address via packet sniffing
- Step 3: the attack device constructs packets and injects them into the Zigbee network
- The goal is to cause the target device to process forged control packets

Impersonation Attack

- Though Zigbee uses encryption on the network layer payload, packets crafted with specific control fields and commands can induce vulnerabilities
- The objective is to force devices to leave the network or to leak their encryption keys
- We need a way to find and generate such packets: semantic-aware fuzzing

Semantic Exploration of Packets

- A first approach would be to randomly put content into the generated packets and blindly test whether they cause the Zigbee network to malfunction
- However, this is highly inefficient
- Two challenges that we want to address in the fuzzing process:
  - Zigbee uses encryption
  - Packets have varied length and formats according to header values

Managing Encryption and Auth.

- To have the payload of a layer encrypted, there are three security-related fields on that layer: security enabled bit, security AUX header, and message integrity code
- The security bit plays a decisive role: if set to 0, no security mechanism, so no AUX header, nor MIC
- Packets with security bit to 1 may have impact if the system has implementation flaws
- We can develop strategies to fuzz this

Managing Encryption and Auth.

- If security bit is set to 1, use AES with CCM
- The counter mode preserves the content lengths, so we can leverage the length structure of Zigbee commands to prioritize cases that are likely to lead to meaningful results
- All defined Network commands are one byte, and we add at most another one byte as attributes
- Since we do not have the network key, we set random MIC values (to fulfill the MIC lengths) and fuzz the payload only with the lengths of possible commands.

Managing Encryption and Auth.

- To examine the flaws of bypassing the integrity check, we fuzz encryption payload lengths of 8 and 16 bits
- 65791 combinations in this category
- The NWK header has 3 unencrypted bits that can be fuzzed for different packet settings
- The total fuzzing number is 526,336
- In total, we can show that it takes 57-120 hours depending on the number of found vulnerabilities

- Personal Area Networks sometimes are not sufficient for IoT purposes
- Long Range (LoRa) is a proprietary radio communication technique
- LoRa Wide Area Network (LoRaWAN) defines the communication protocols and system architecture to create a larger network than PAN
- Also in this case, we consider battery powered resource constrained devices
- It is a cloud based Medium Access Control (MAC) layer protocol
- Manages communications between LPWAN gateways and end-node devices

LoRAWAN Security

- The LoRa alliance designed security measures for LoRaWAN accounting for low power consumption, low complexity, low cost, and high scalability
- As part of the network join procedure, a LoRaWAN end-device establishes a mutual authentication with the LoRaWAN network
- MAC and application messaging are origin authenticated, integrity and replay protected, and encrypted
- End-to-end encryption for application payloads

LoRAWAN Security

- LoRaWAN uses AES, and each device has a unique 128 bit AES key and a globally unique identifier (EUI-64-based DevEUI)
- Allocation of EUI-64 identifiers require the assignor to have an Organizationally Unique Identifier from IEEE registration authority
- LoRaWAN networks are identified by a 24-bit globally unique identifier assigned by the LoRa Alliance

Mutual Authentication

- The Over-the-air activation (or join procedure) test whether both devices know the AppKey
- The proof is obtained by computing an AES-CMAC(AppKey) on the device's join request and by the backend receiver
- CMAC is a One-Key MAC that fixes security deficiencies of CBC-MAC, i.e., the fact that the latter is secure only for fixed-length messages
- Nevertheless, a variation of CBC-MAC

Mutual Authentication

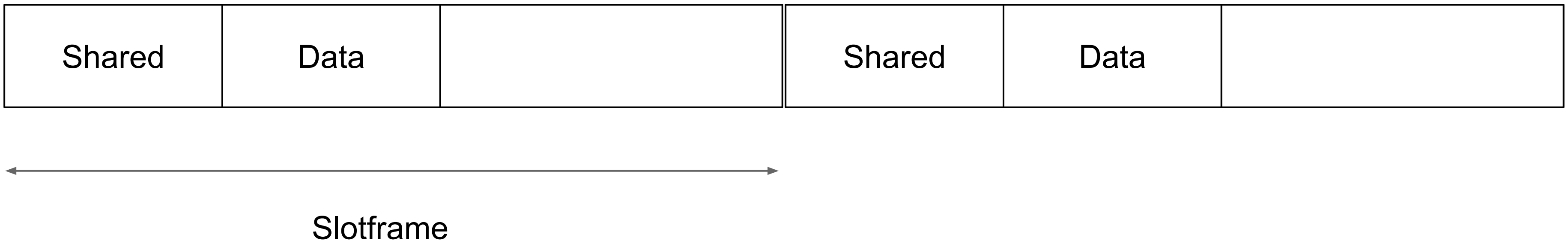
- Two keys are derived by LoRaWAN authentication:
  - Providing integrity protection and encryption of the LoRaWAN MAC commands (NwkSKey)
  - E2E encryption of application payloads (AppSKey)
- NwkSKey is distributed to the LoRaWAN network to prove and verify packet integrity and authenticity
- AppSKey is distributed to the application server to encrypt/decrypt the application payload

IoT Network Formation

- We consider the formation of a 6TiSCH network
- There exists a root node, called Joint Registrar/Coordinator (JRC) which periodically broadcasts Enhanced Beacon (EB) frames
- EBs contain basic network information such as the JRC ID, duration of a timeslot, number of time slots in a slot frame, channel hopping sequence, location of the shared cell
- Pledges are new nodes willing to join a 6TiSCH network

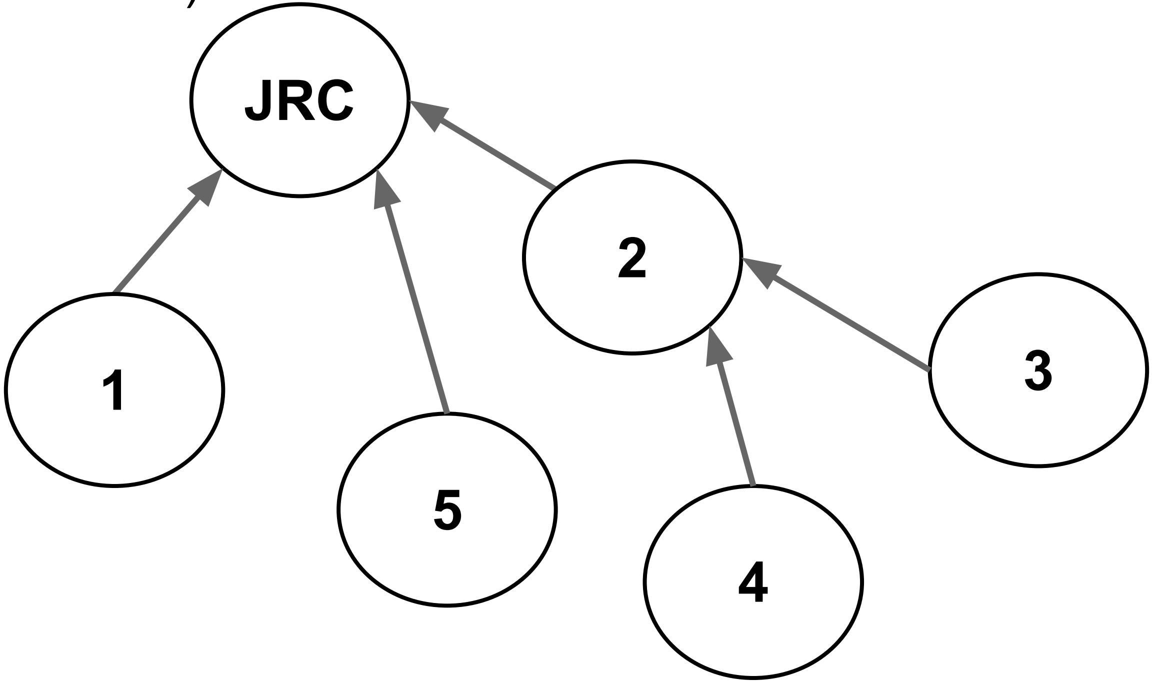
IoT Network Formation

- When pledges want to join the network, they start scanning until they receive a valid EB
- When it receives an EB from an already joined node, it becomes a TSCH synchronized node
- The channel is slotted, and is divided into control slots and shared slots

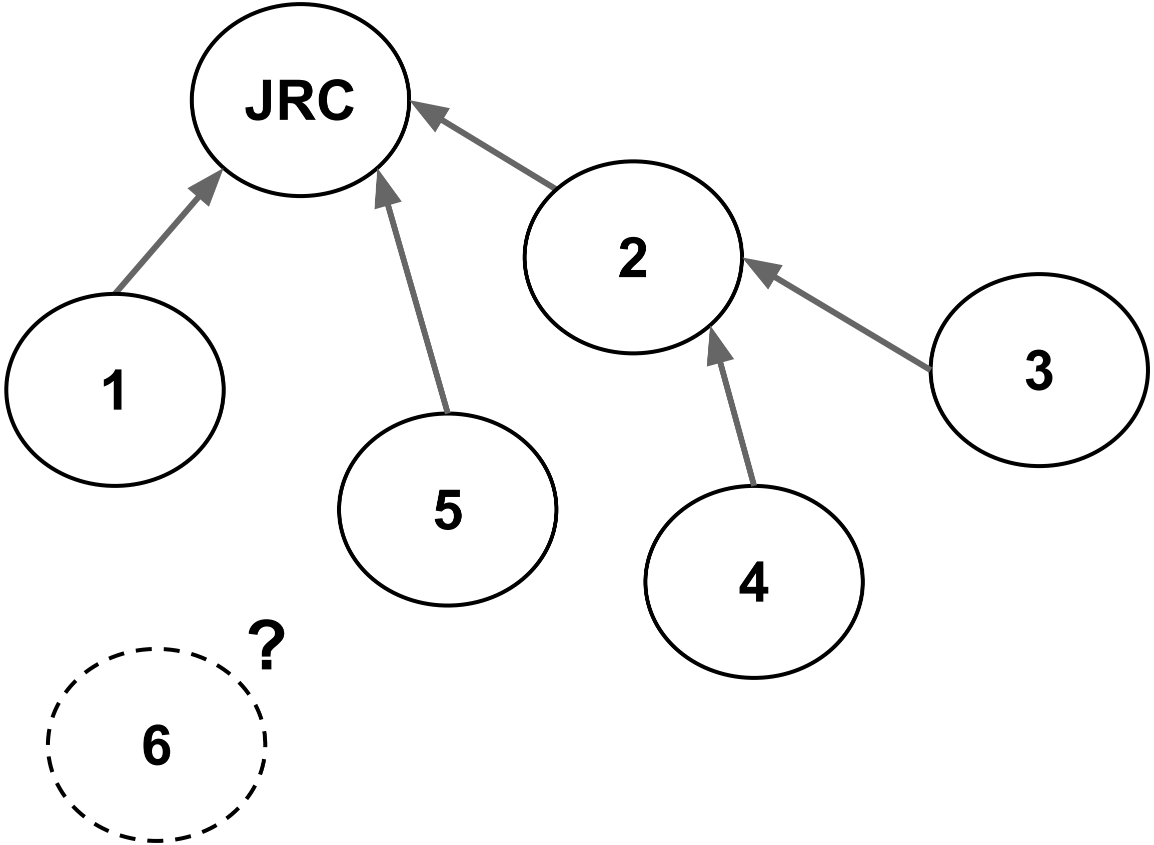


IoT Network Formation

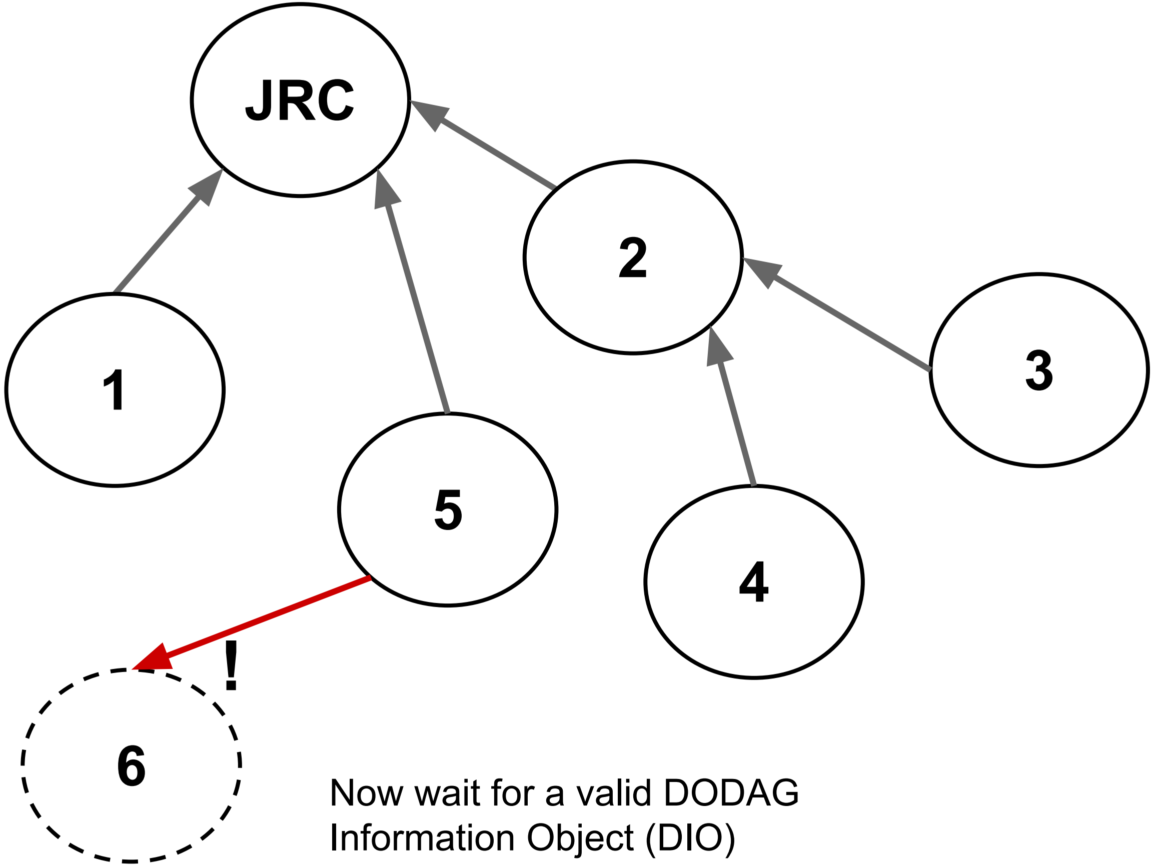
- The network is organized as a Destination Oriented Directed Acyclic Graph (DODAG)



When to Join?

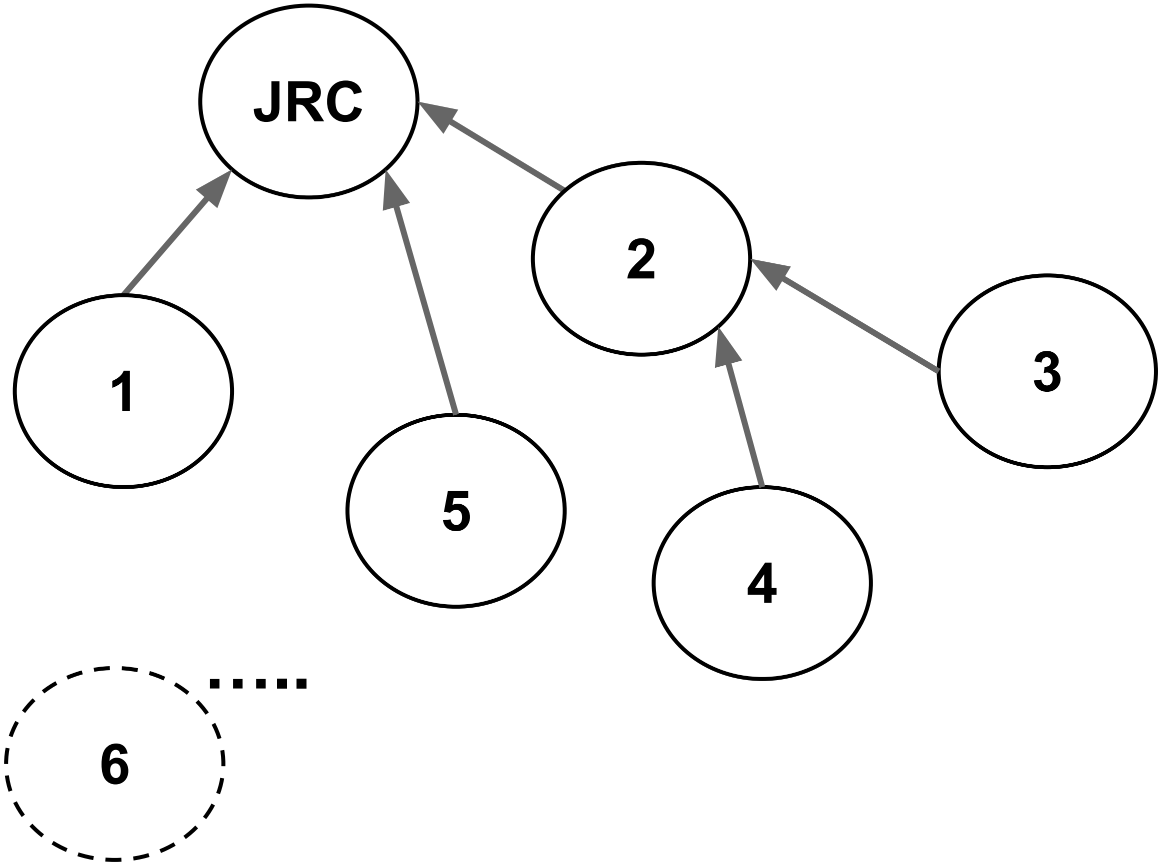


When to Join?



Now wait for a valid DODAG Information Object (DIO)

When to Join?



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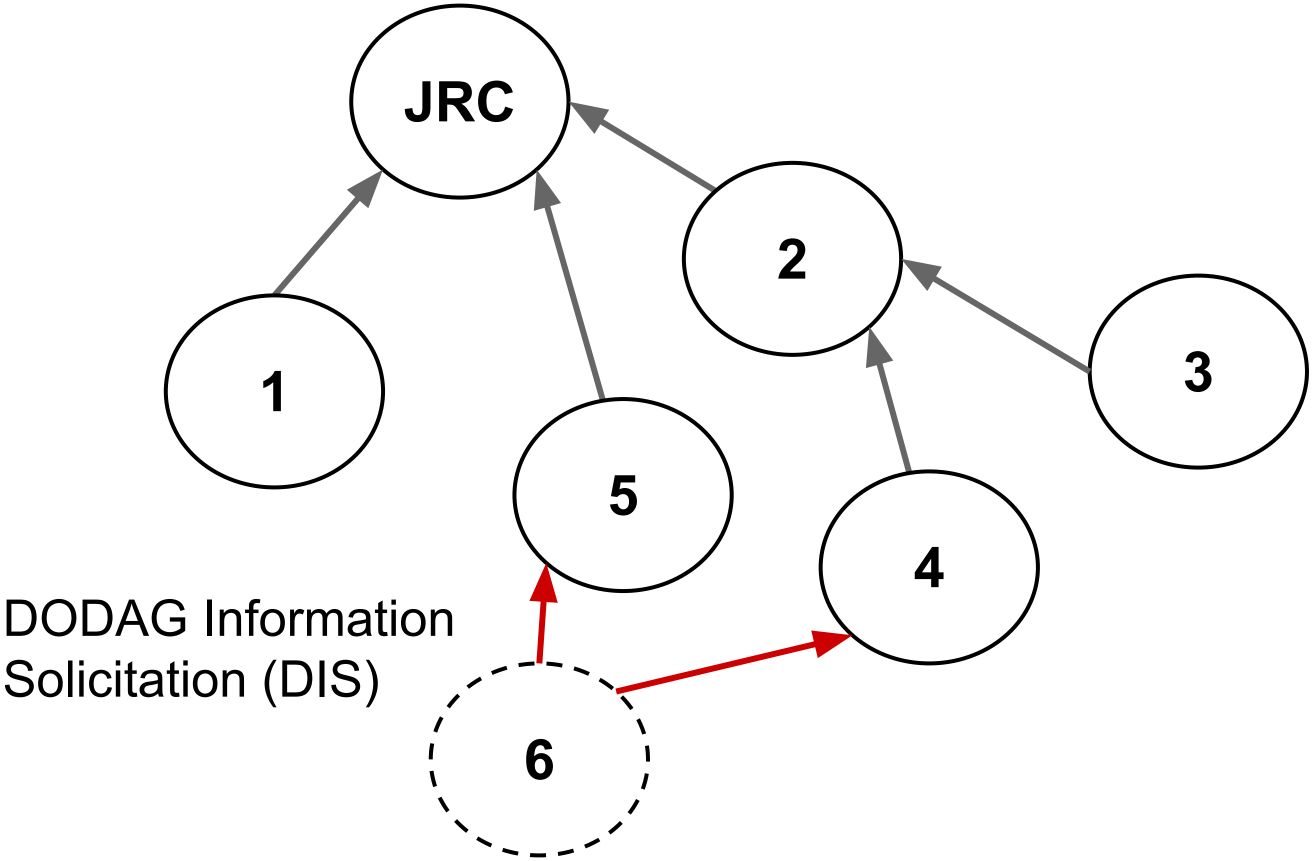
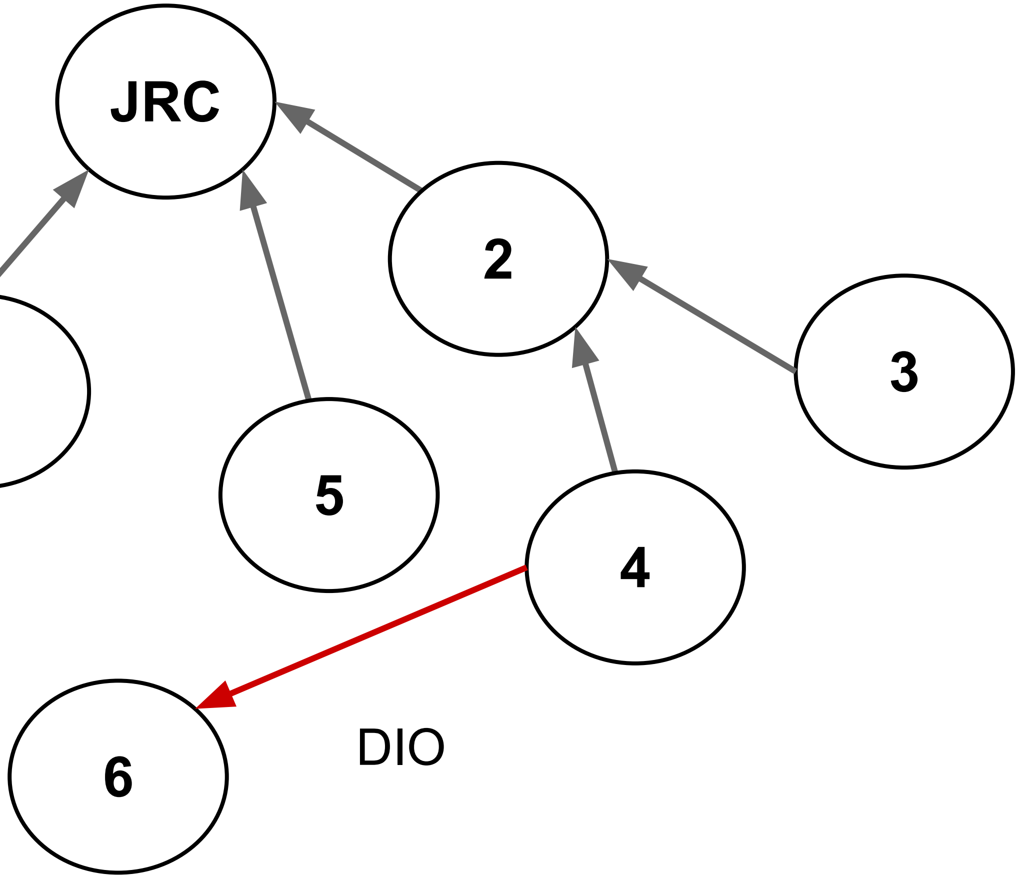


When to Join?

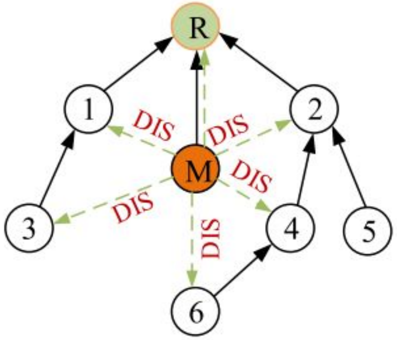


RPL Joined Node

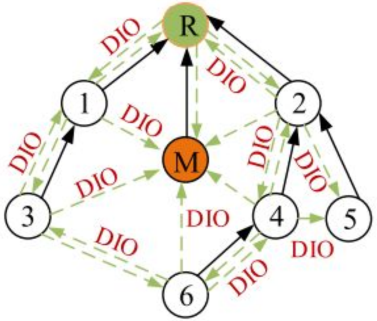
DIS Attack

- DIS packets can be sent by arbitrary nodes to solicit the sending of DIO packets
- DIS attack: increase the number of transmissions in DIO packets in the network
- Goal: increase energy consumption and congest the shared slot

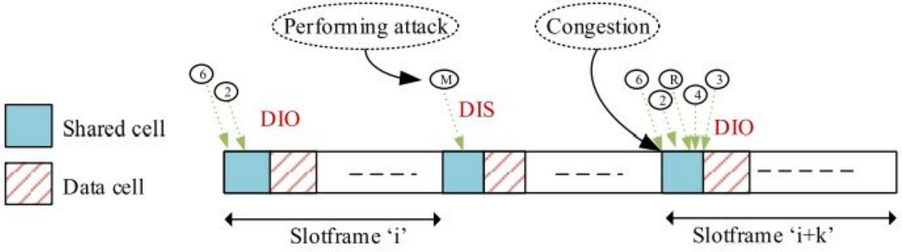
DIS Attack



(a) A malicious node transmits its DIS packet.



(b) Legitimate joined nodes transmit their DIO packet in response.



(c) Effect of DIS attack on shared cell's congestion.

Rank Attack

- Each node chooses its parent based on two values: the rank and objective function
- The rank should increase going downward in the DODAG, and the role of the preferred parent selection is to select the one with the best rank
- The objective of the attacker is to manipulate these values to affect the network topology

Rank Attack

- Each node chooses its parent based on two values: the rank and objective function
- The rank should increase going downward in the DODAG, and the role of the preferred parent selection is to select the one with the best rank
- The objective of the attacker is to manipulate these values to affect the network topology

Rank Attack

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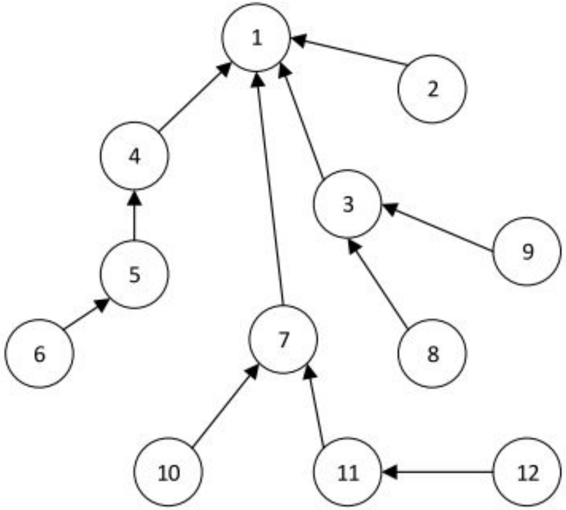
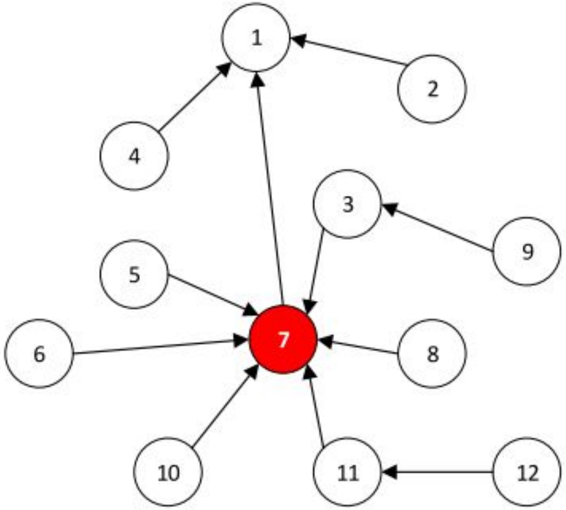
- Manipulation can be performed in two ways
- First, the attacker changes its rank by a specific values based on its neighbors rank value
- Second, the adversary manipulates its rank through the use of a different objective function to deceive legitimate nodes into giving the malicious node a better rank

Types of Rank Attack

- Decreased rank attack: malicious nodes advertise lower rank to other nodes resulting in many of them selecting the adversary as preferred



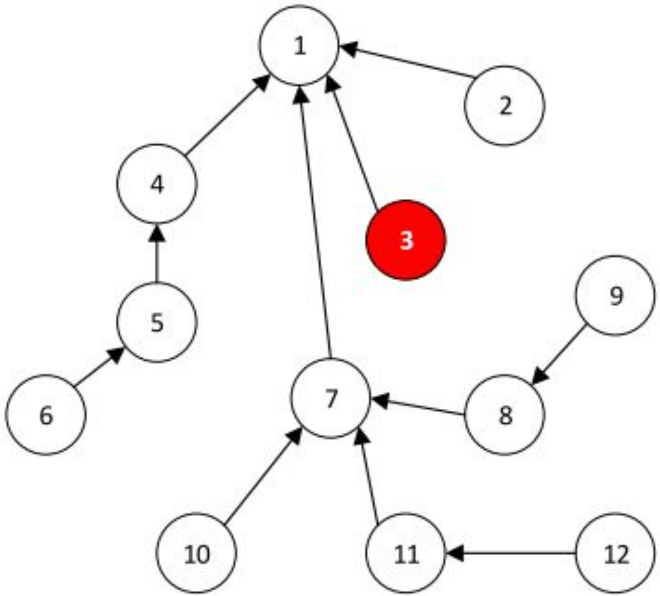
(a) Normal topology



(b) Decreased rank attack

Types of Rank Attack

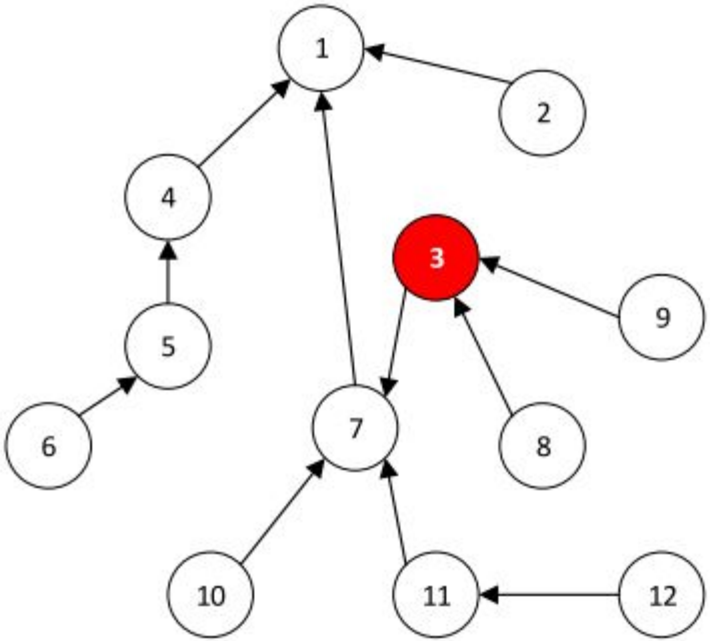
- Increased rank attack: the attacker is near the routing node and advertises higher rank and worse routing metrics
- The idea is to cause topology disruptions and delays, sa nodes will need to select further nodes as parents



(c) Increased rank attack

Types of Rank Attack

- Worst parent attack: the attacker advertises its tru rank but selects the worst parent for itself
- Deceive nodes into connecting to the attacker and cause delays due to the worst path they unwillingly select



Neighboring Attack

- In this attack, the attacker node will forward any received DIO message it gets to its neighboring nodes (no modification)
- This creates the illusion that the original sender is in the range of the neighboring nodes
- Worst case scenario: the original sender has a good rank and adversary's neighbors choose it as preferred parent although being out of range

Neighboring Attack

- Alone, the neighboring attack only causes a slight increase in the end-to-end delay
- However, suitably combined with other attacks gets more dangerous
- An adversary could launch a DIS attack to get DIO messages with better metrics, then selecting one of these messages to perform a neighbor attack, increasing the effect of such an attack

RPL Storing Mode

- RPL can work in a Point-to-Point fashion, i.e., create traffic between two nodes that are not root nodes of the DODAG
- In storing mode, each node keeps a downward routing table for its sub-DODAG and use it to forwards P”P traffic
- In practice, traffic goes upward up to a common ancestor of sender and destination that routes the packet to the destination node

RPL Storing Mode Attack

- Routing table overload: the adversary sends many bogus routes (via DAO) until the node saturates
- Route table falsification: a malicious node advertises fake routes to other nodes that might exists but not be part of the attacker's sub-DODAG causing packet losses or longer delays
- All these attacks also cause resource exhaustion due to the increased overhead and repetitive repair attempts

Attacks Inherited from WSN

- Wireless Sensor Networks (WSNs) are the networks from which IoT was born
- Therefore, IoT inherited part of the routing attacks that existed in WSNs
- Although the working principle is the same, attacks needed to adapt to the new IoT paradigm

Blackhole and Selective Forward

- In a blackhole attack, a malicious node(s) will drop all packets it receives instead of forwarding them (DoS)
- To be less detectable, an attacker may decide to selectively drop packets (i.e., only forward RPL control messages) → selective forward or greyhole attacks
- Selective-forward attacks cannot be detected nor mitigated by the self-healing mechanisms of RPL because they pass control messages

Sinkhole attacks

- Malicious node(s) try to be sink for as much nodes as possible by advertising a fabricated link with better metrics
- Sinkhole by themselves are not very powerful, they need to be combined with other attacks
- These attacks can be performed by advertising DIOs with better metrics or having several adversaries directing all passing traffic toward another adversary

Wormhole attacks

- To create this attack, two adversaries need to cooperate to create a tunnel between them and transmit traffic through it instead of the regular path
- Three ways to create a wormhole:
  - Packet encapsulation: malicious nodes use a legitimate path between them and encapsulate packets to hide the hop count
  - Relay: deceive nodes to be neighbors
  - Out-of.band link: create links that are not part of the network

Clone ID and Sybil attacks

- In Clone ID attack, a malicious node(s) takes the identity of another legitimate node
- In Sybil attacks, each malicious node takes several identities from legitimate nodes
- With sybil attacks an attacker can submit forged information to manipulate the system, disturb the routing topology and reputation-based systems
- Can be mitigated by adding location information and DHTs

Mitigation Techniques

- To detect some of these attacks (or their declinations) there have been many proposals in terms of Intrusion Detection Systems (IDSs)
- Signature-based IDSs: use a database of signature patterns of the attacks
- Anomaly-based IDSs: create a normal behavior profile and compare the current observations with the normal behavior
- Specification-based: create a normal profile based on protocol specification
- Hybrid IDSs: combine two of the aforementioned methods

Placement of IDSs

- Centralized IDS: the IDS resides either on the root node or on a dedicated host and uses the traffic passing by to detect attacks
- In many cases, it is required that the central node of the IDS send periodic request for updates to unmonitored areas
- Advantage: most of the heavy works occurs inside a powerful node, usually capable of performing firewall functionalities as well
- On the other hand, challenging to monitor the network during the attack

Placement of IDSs

- Distributed IDS: each node will have a full IDS implementation, making it responsible for detecting attacks around it
- Usually nodes collaborate to increase the efficiency of the detection
- However, this approach consumes a lot of resources throughout the network
- It is usually required to optimize the IDS periodically to minimize its effects

Placement of IDSs

- Hybrid IDS placement: to get the best of both worlds
- Central nodes with more resources are responsible for computationally intensive tasks (analyzing data, decision making)
- Normal nodes are responsible for lightweight duties (e.g., monitoring neighbor nodes, send info about traffic passing through them, responding to requests from central nodes)
- Requires optimization