Zigator: Analyzing the Security of Zigbee-Enabled Smart Homes

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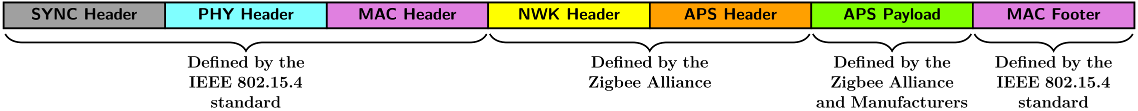

SYNC Header | PHY Header | MAC Header | NWK Header | APS Header | APS Payload | MAC Footer

Defined by the IEEE 802.15.4 standard

Defined by the Zigbee Alliance

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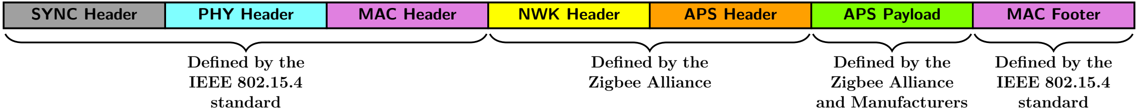

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We study the security consequences of the design choice to disable **MAC-layer security** in centralized Zigbee networks

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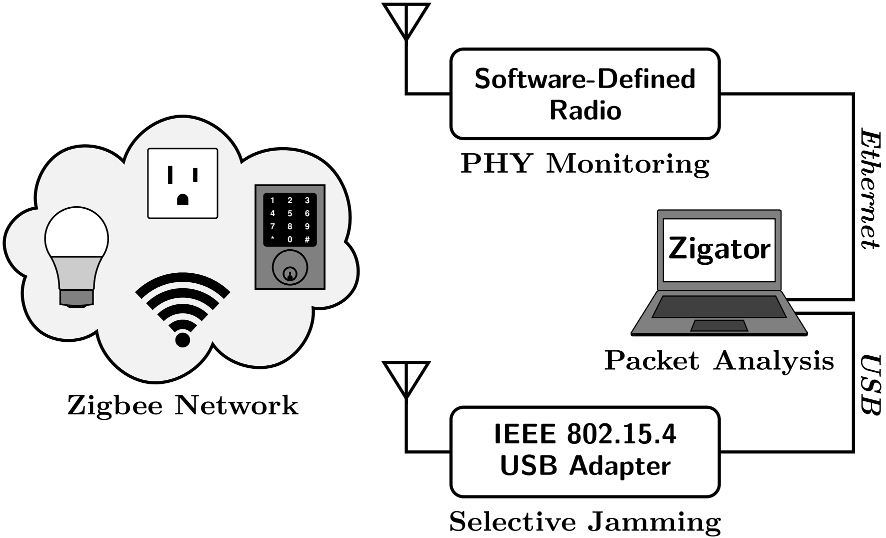
  - We do not consider uncommon device configurations like low-power routers
- **Attacker’s goal:**
  - Obtaining the network key from an already formed Zigbee network

Security Analysis with Zigator



Zigbee Network

Software-Defined Radio

PHY Monitoring

Ethernet

Zigator

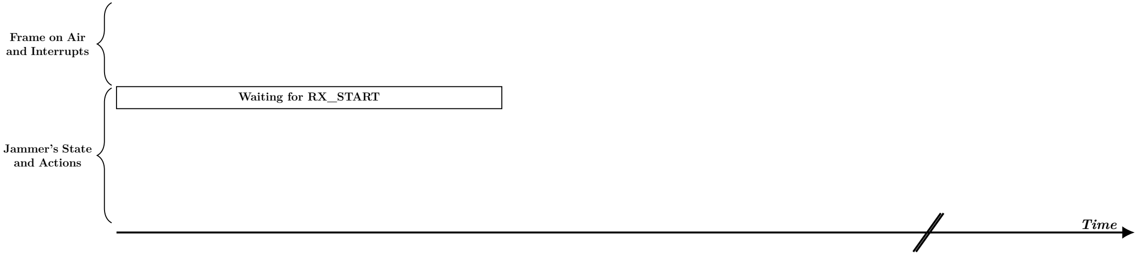
Packet Analysis

USB

IEEE 802.15.4 USB Adapter

Selective Jamming

Our implementation of a selective jammer



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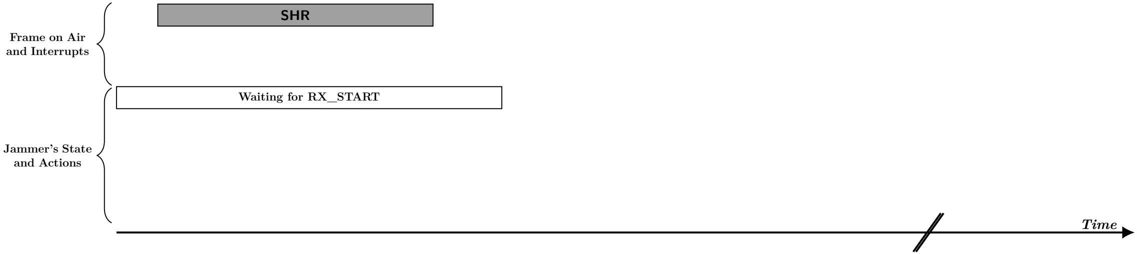

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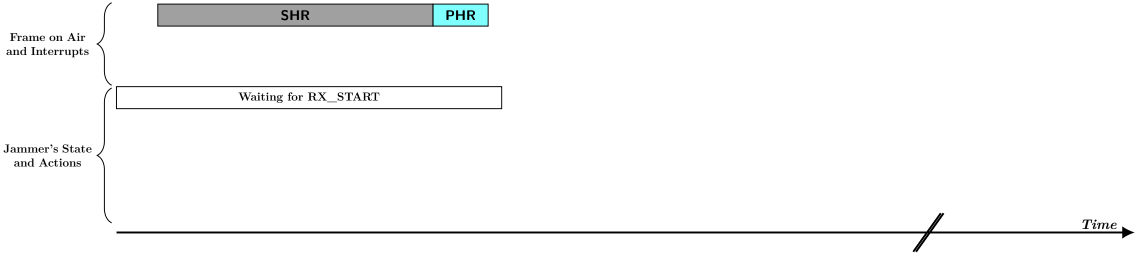

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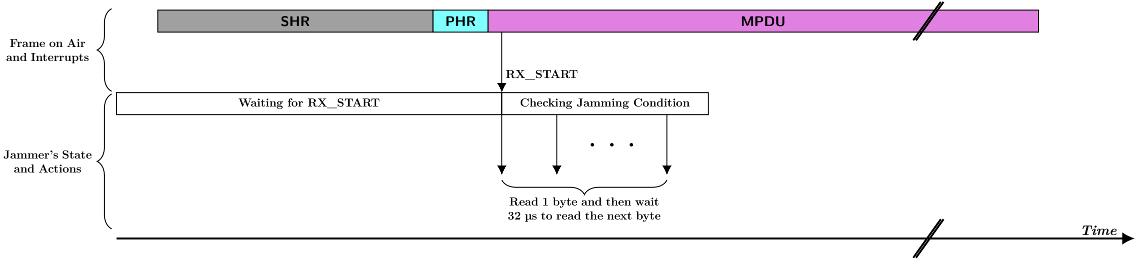
SHR
PHR
MPDU
Frame on Air and Interrupts
RX_START
Waiting for RX_START
Checking Jamming Condition
Jammer's State and Actions
. . .
Read 1 byte and then wait 32 µs to read the next byte
Time

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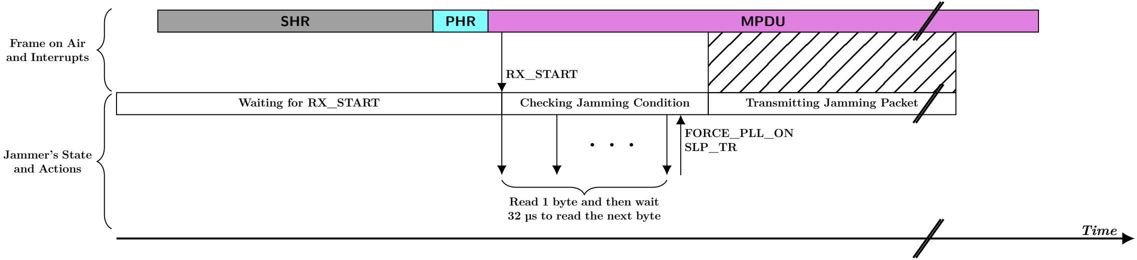
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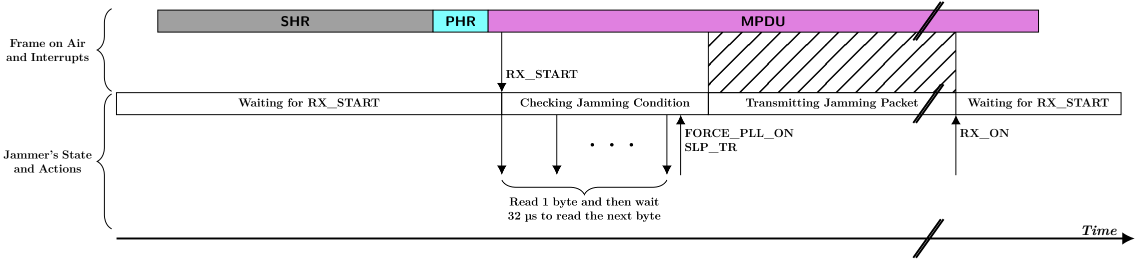
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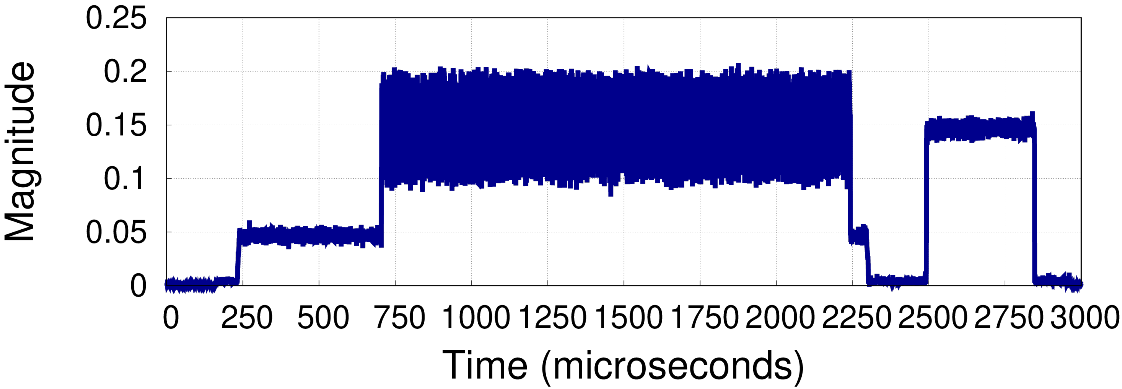
Combining Core Functionalities



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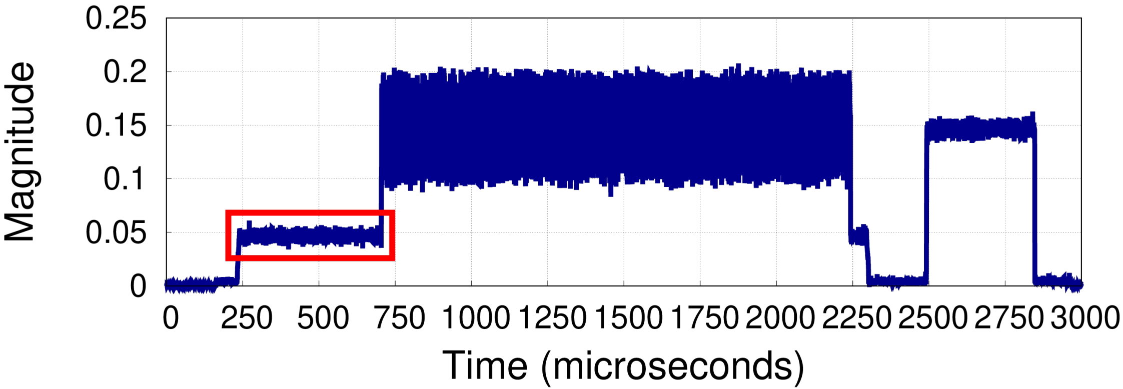

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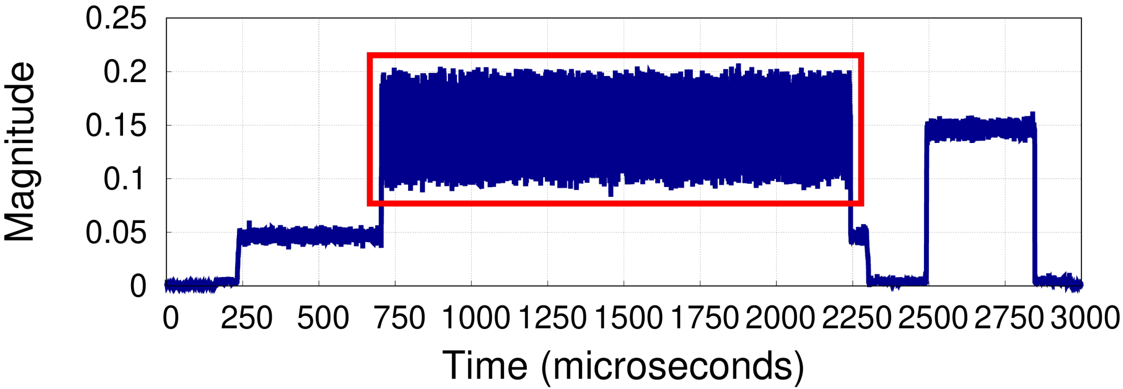

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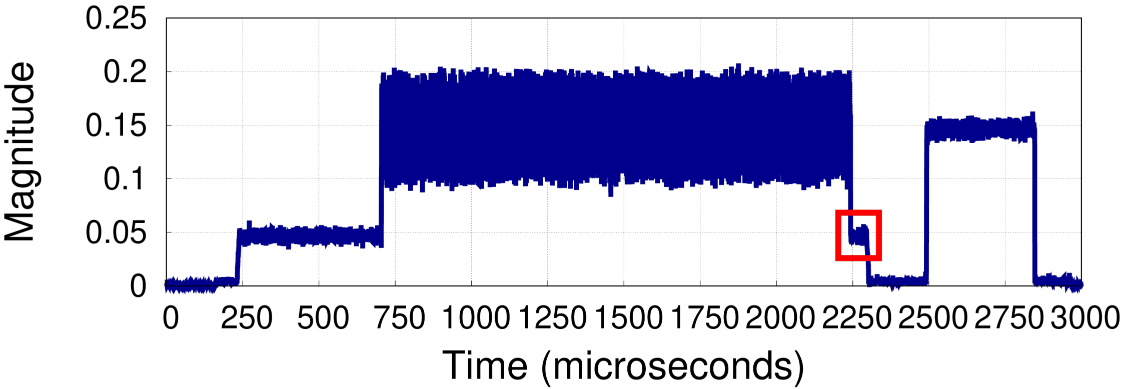

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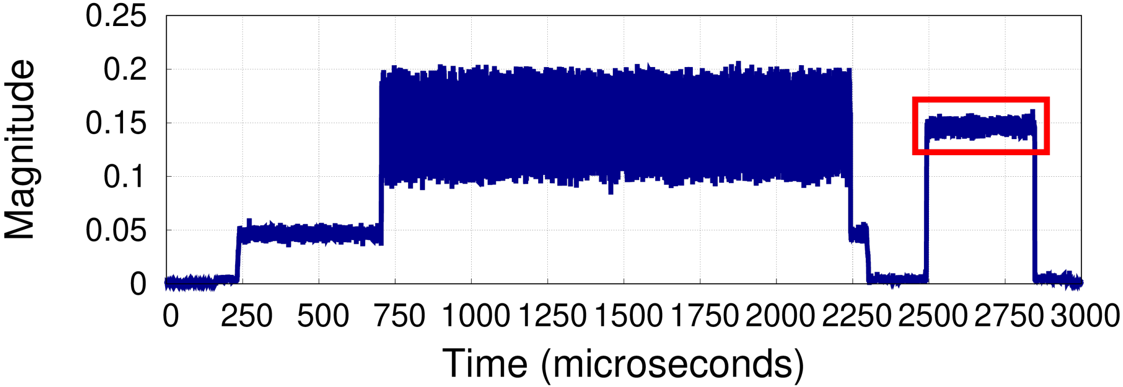
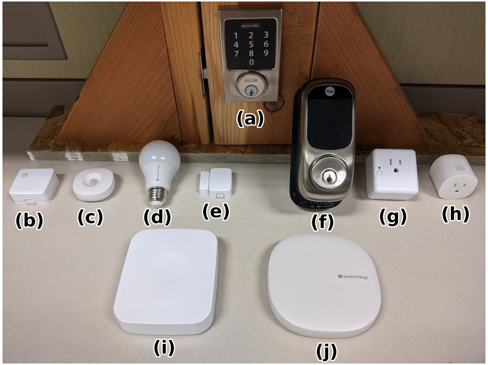


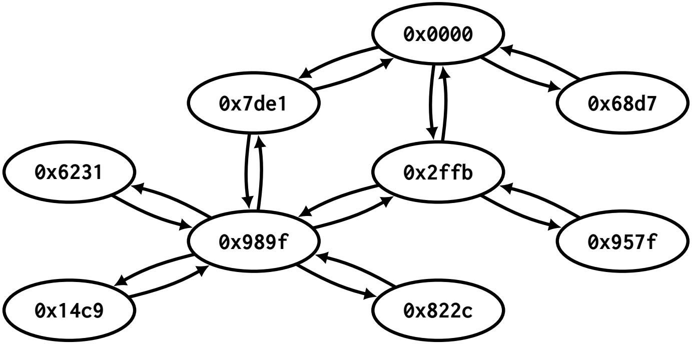
Experimental Setup

- We captured packets that were generated from **ten commercial Zigbee devices**
- We conducted **eight experiments** that differed in the smart hub that was used and the physical topology of the devices
- Our experiments lasted about 34.644 hours in total and resulted in a dataset of **571,509 valid packets**

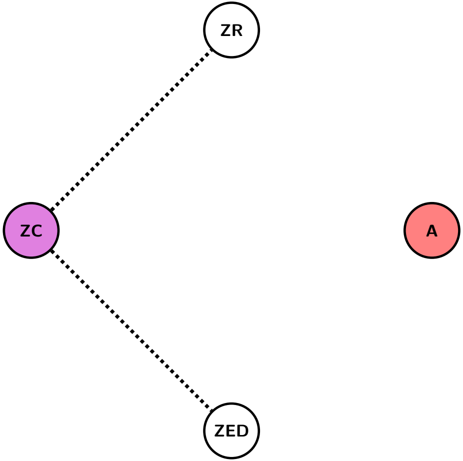


Inferring the Topology of a Zigbee Network

- Log distinct pairs of source and destination addresses
- Trivial identification of the **Zigbee Coordinator** ⇒ always `0x0000`



Identifying Logical Device Types



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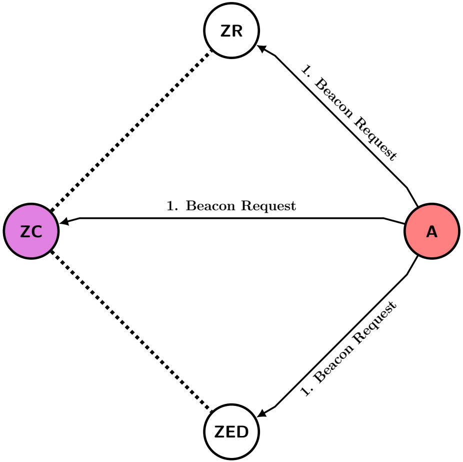

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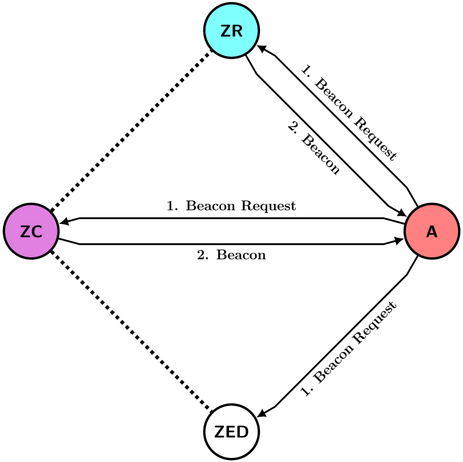

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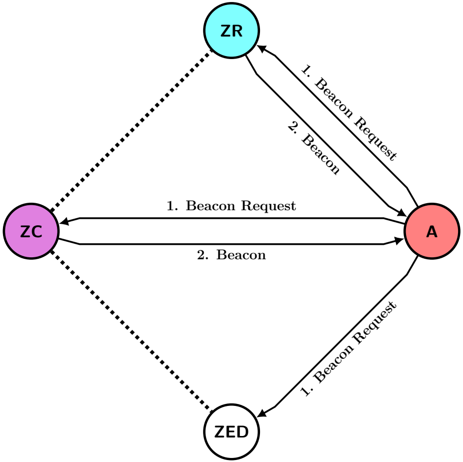

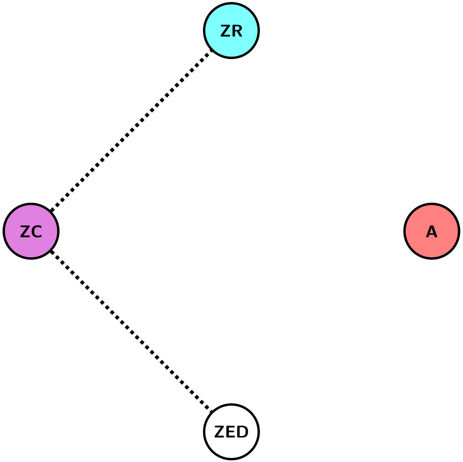

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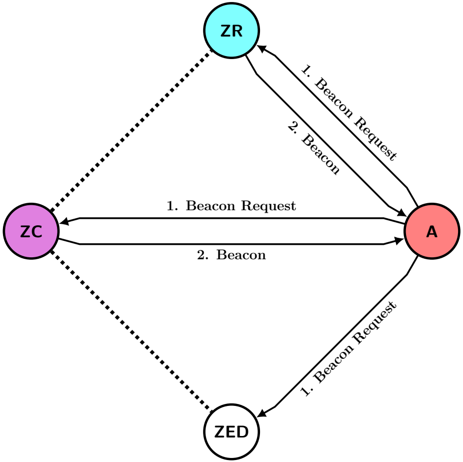

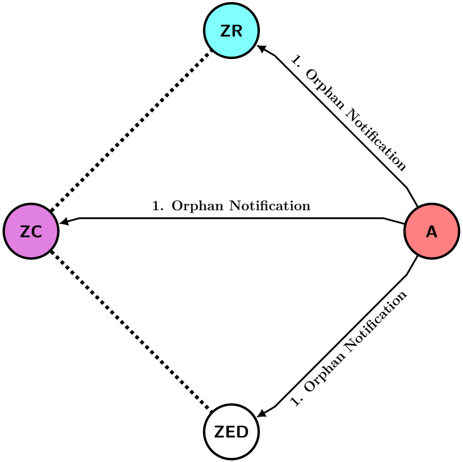

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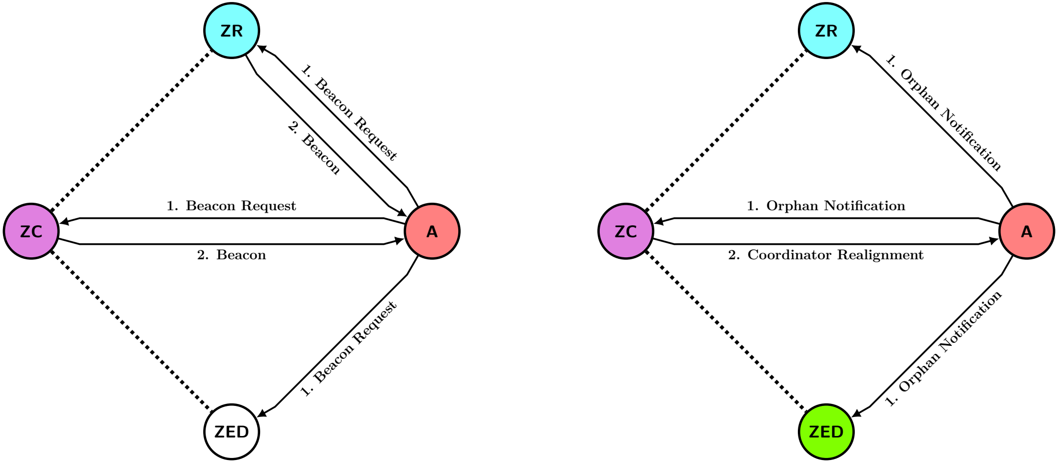

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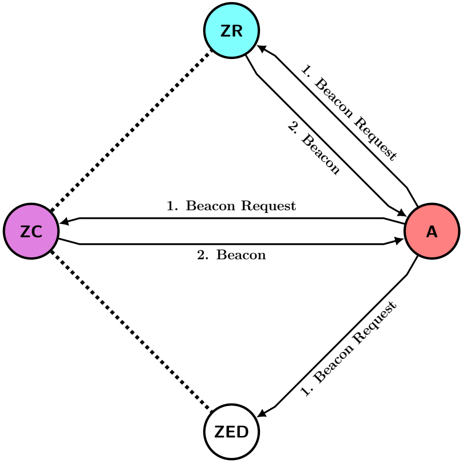

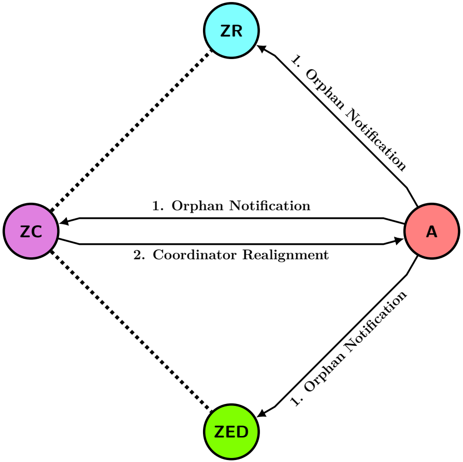

Passive identification based on **Data Request** and **Link Status** commands

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- **NWK commands** contain both the extended and the short address of their source
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  ⇒ 0x286d97
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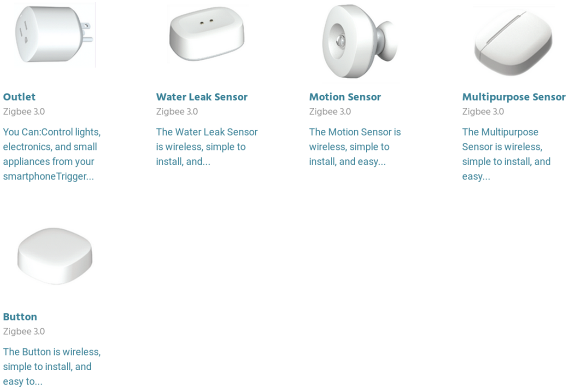

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Zigbee 3.0
You Can:Control lights, electronics, and small appliances from your smartphoneTrigger...

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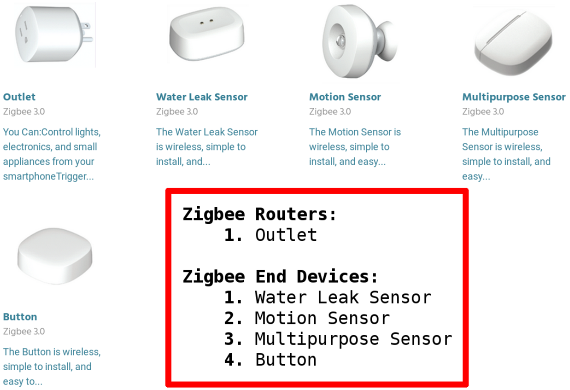

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```
Zigbee Routers:
    1. Outlet

Zigbee End Devices:
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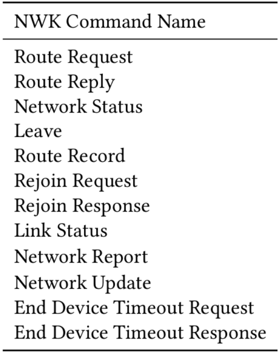
Source: https://zigbeealliance.org/product_type/certified_product/

Identifying Encrypted NWK Commands



NWK Command Name
Route Request
Route Reply
Network Status
Leave
Route Record
Rejoin Request
Rejoin Response
Link Status
Network Report
Network Update
End Device Timeout Request
End Device Timeout Response

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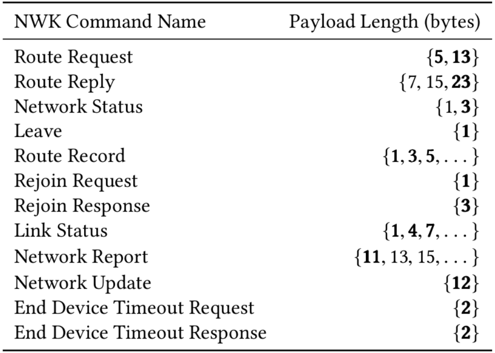

NWK Command Name	Payload Length (bytes)
Route Request	{**5**, **13**}
Route Reply	{7, 15, **23**}
Network Status	{1, **3**}
Leave	{**1**}
Route Record	{**1**, **3**, **5**, . . . }
Rejoin Request	{**1**}
Rejoin Response	{**3**}
Link Status	{**1**, **4**, **7**, . . . }
Network Report	{**11**, 13, 15, . . . }
Network Update	{**12**}
End Device Timeout Request	{**2**}
End Device Timeout Response	{**2**}

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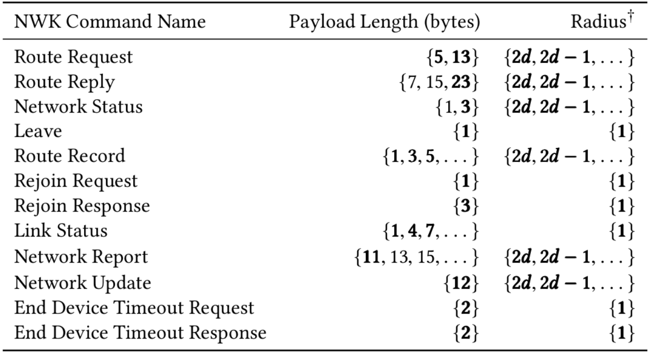

NWK Command Name	Payload Length (bytes)	Radius†
Route Request	$\{\mathbf{5}, \mathbf{13}\}$	$\{\boldsymbol{2d}, \boldsymbol{2d-1}, \ldots\}$
Route Reply	$\{7, 15, \mathbf{23}\}$	$\{\boldsymbol{2d}, \boldsymbol{2d-1}, \ldots\}$
Network Status	$\{1, \mathbf{3}\}$	$\{\boldsymbol{2d}, \boldsymbol{2d-1}, \ldots\}$
Leave	$\{\mathbf{1}\}$	$\{\mathbf{1}\}$
Route Record	$\{\mathbf{1}, \mathbf{3}, \mathbf{5}, \ldots\}$	$\{\boldsymbol{2d}, \boldsymbol{2d-1}, \ldots\}$
Rejoin Request	$\{\mathbf{1}\}$	$\{\mathbf{1}\}$
Rejoin Response	$\{\mathbf{3}\}$	$\{\mathbf{1}\}$
Link Status	$\{\mathbf{1}, \mathbf{4}, \mathbf{7}, \ldots\}$	$\{\mathbf{1}\}$
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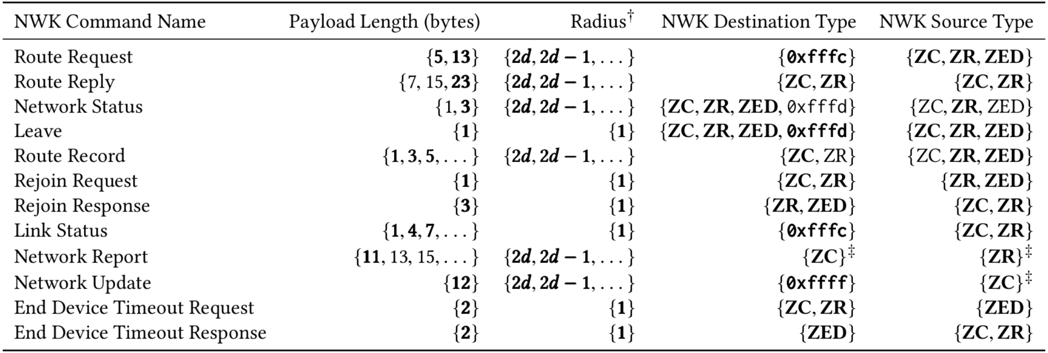

NWK Command Name	Payload Length (bytes)	Radius†	NWK Destination Type	NWK Source Type
Route Request	{**5**, **13**}	$\{\mathbf{2}\boldsymbol{d}, \mathbf{2}\boldsymbol{d}-\mathbf{1}, \ldots\}$	{**0xfffc**}	{**ZC**, **ZR**, **ZED**}
Route Reply	{7, 15, **23**}	$\{\mathbf{2}\boldsymbol{d}, \mathbf{2}\boldsymbol{d}-\mathbf{1}, \ldots\}$	{**ZC**, **ZR**}	{**ZC**, **ZR**}
Network Status	{1, **3**}	$\{\mathbf{2}\boldsymbol{d}, \mathbf{2}\boldsymbol{d}-\mathbf{1}, \ldots\}$	{**ZC**, **ZR**, **ZED**, 0xfffd}	{ZC, **ZR**, ZED}
Leave	{**1**}	{**1**}	{**ZC**, **ZR**, **ZED**, **0xfffd**}	{**ZC**, **ZR**, **ZED**}
Route Record	{**1**, **3**, **5**, . . . }	$\{\mathbf{2}\boldsymbol{d}, \mathbf{2}\boldsymbol{d}-\mathbf{1}, \ldots\}$	{**ZC**, ZR}	{ZC, **ZR**, **ZED**}
Rejoin Request	{**1**}	{**1**}	{**ZC**, **ZR**}	{**ZR**, **ZED**}
Rejoin Response	{**3**}	{**1**}	{**ZR**, **ZED**}	{**ZC**, **ZR**}
Link Status	{**1**, **4**, **7**, . . . }	{**1**}	{**0xfffc**}	{**ZC**, **ZR**}
Network Report	{**11**, 13, 15, . . . }	$\{\mathbf{2}\boldsymbol{d}, \mathbf{2}\boldsymbol{d}-\mathbf{1}, \ldots\}$	{ZC}‡	{**ZR**}‡
Network Update	{**12**}	$\{\mathbf{2}\boldsymbol{d}, \mathbf{2}\boldsymbol{d}-\mathbf{1}, \ldots\}$	{**0xffff**}	{**ZC**}‡
End Device Timeout Request	{**2**}	{**1**}	{**ZC**, **ZR**}	{**ZED**}
End Device Timeout Response	{**2**}	{**1**}	{**ZED**}	{**ZC**, **ZR**}

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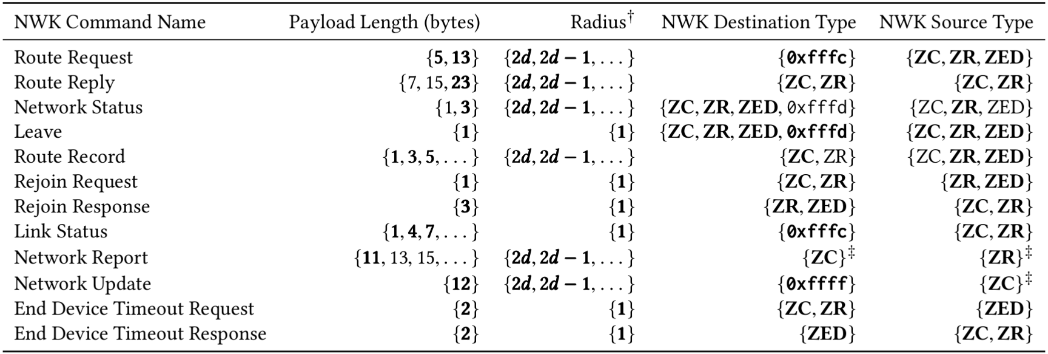

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Route Reply	{7, 15, **23**}	{***2d***, ***2d* − 1**, . . . }	{**ZC**, **ZR**}	{**ZC**, **ZR**}
Network Status	{1, **3**}	{***2d***, ***2d* − 1**, . . . }	{**ZC**, **ZR**, **ZED**, `0xfffd`}	{ZC, **ZR**, ZED}
Leave	{**1**}	{**1**}	{**ZC**, **ZR**, **ZED**, **`0xfffd`**}	{**ZC**, **ZR**, **ZED**}
Route Record	{**1**, **3**, **5**, . . . }	{***2d***, ***2d* − 1**, . . . }	{**ZC**, ZR}	{ZC, **ZR**, **ZED**}
Rejoin Request	{**1**}	{**1**}	{**ZC**, **ZR**}	{**ZR**, **ZED**}
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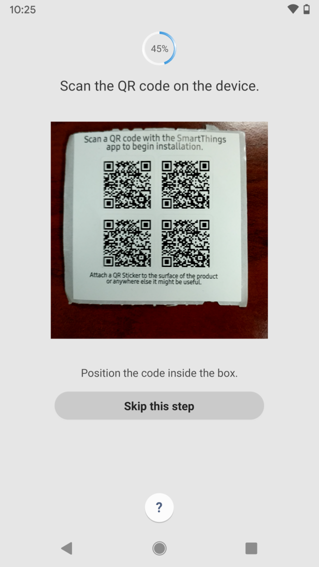
Network Report	{**11**, 13, 15, . . . }	{***2d***, ***2d* − 1**, . . . }	{**ZC**}‡	{**ZR**}‡
Network Update	{**12**}	{***2d***, ***2d* − 1**, . . . }	{**`0xffff`**}	{**ZC**}‡
End Device Timeout Request	{**2**}	{**1**}	{**ZC**, **ZR**}	{**ZED**}
End Device Timeout Response	{**2**}	{**1**}	{**ZED**}	{**ZC**, **ZR**}

The **decision tree** that we developed is included in our paper

Commissioning of Zigbee Devices

- Legacy Zigbee devices use the **default Trust Center link key** to join a network
- A Zigbee 3.0 device can join a Zigbee 3.0 network using an **install code**



Scan the QR code on the device.

Scan a QR code with the SmartThings app to begin installation.

Attach a QR Sticker to the surface of the product or anywhere else it might be useful.

Position the code inside the box.

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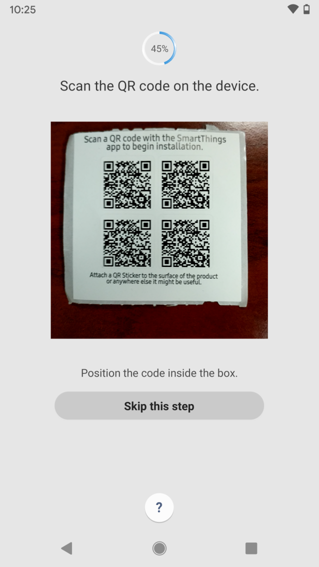
- A Zigbee 3.0 device can join a Zigbee 3.0 network using an **install code**
- The attacker's main strategy is to launch a **denial-of-service attack** that would force the end user to **factory reset** a device that uses a known Trust Center link key



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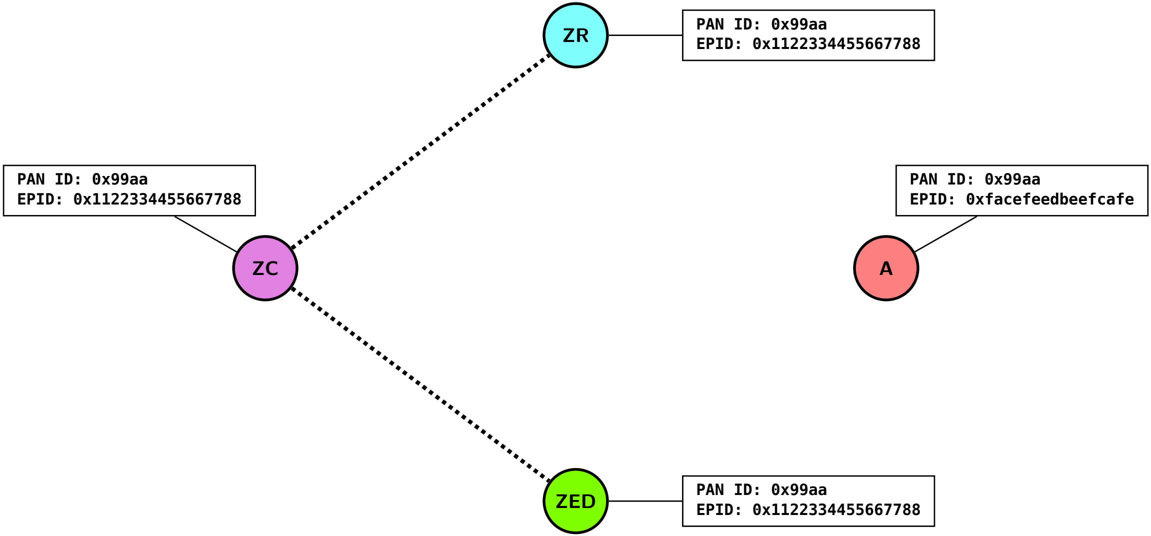
Disconnecting Zigbee Devices



PAN ID: 0x99aa
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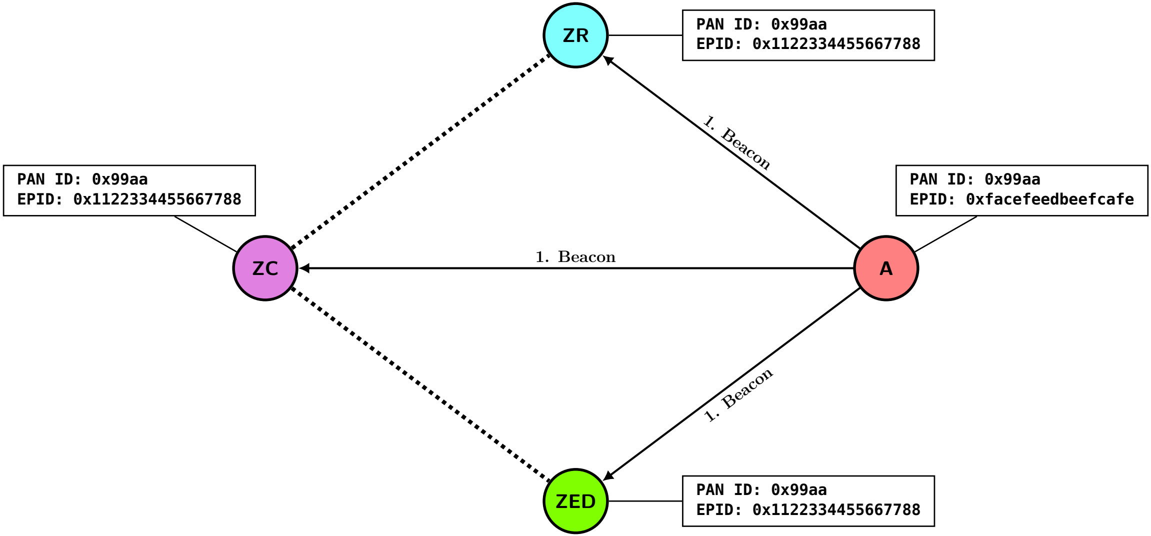
Disconnecting Zigbee Devices



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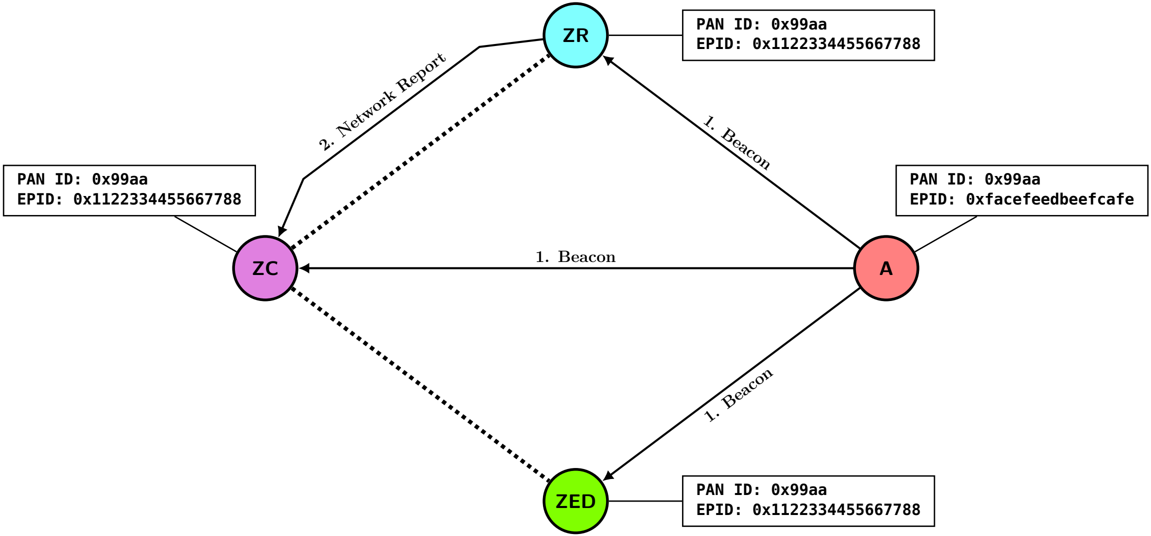

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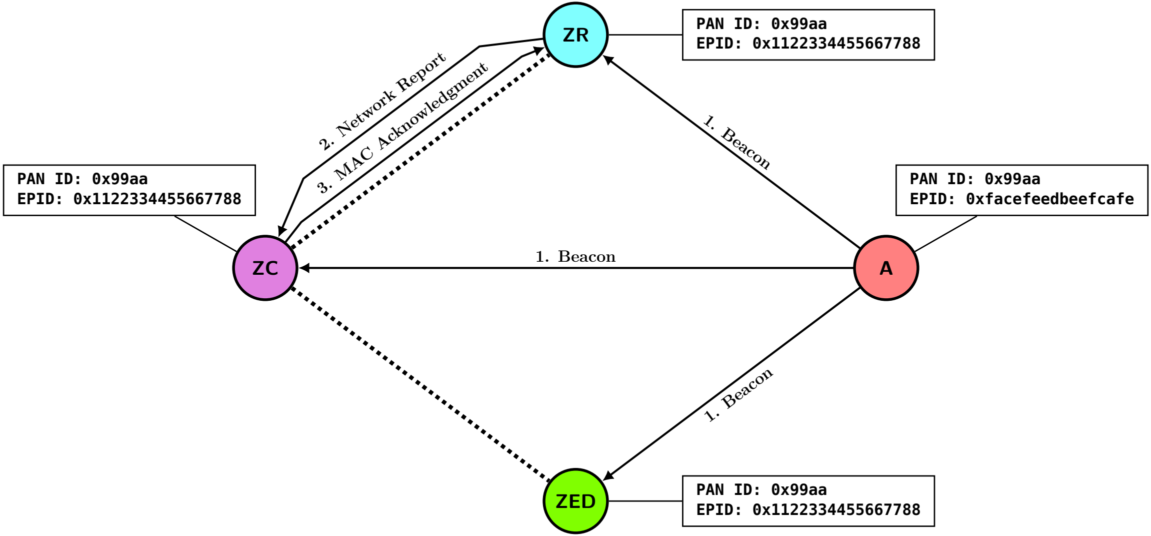

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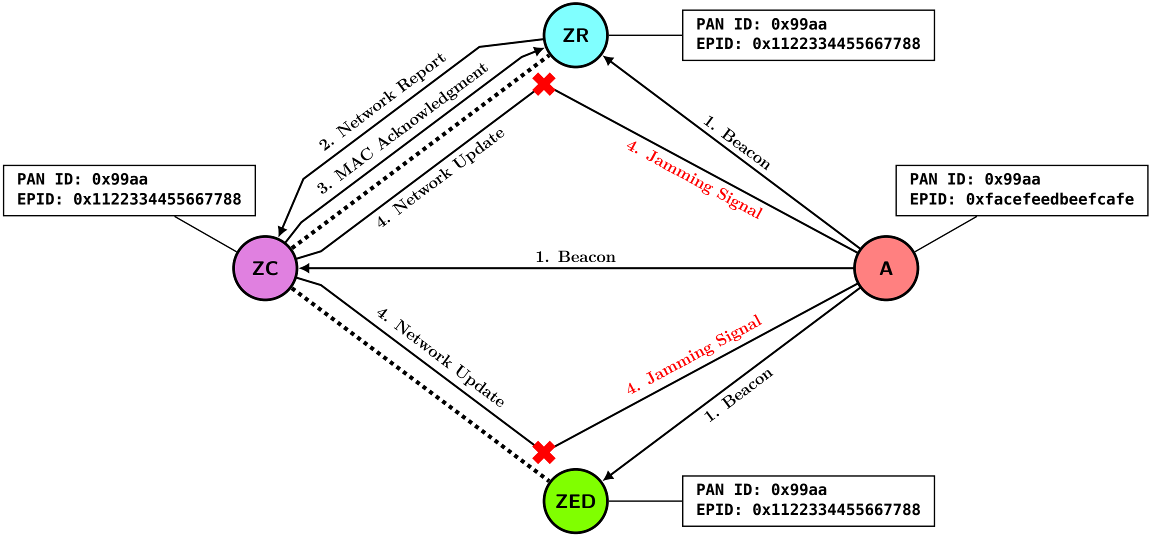

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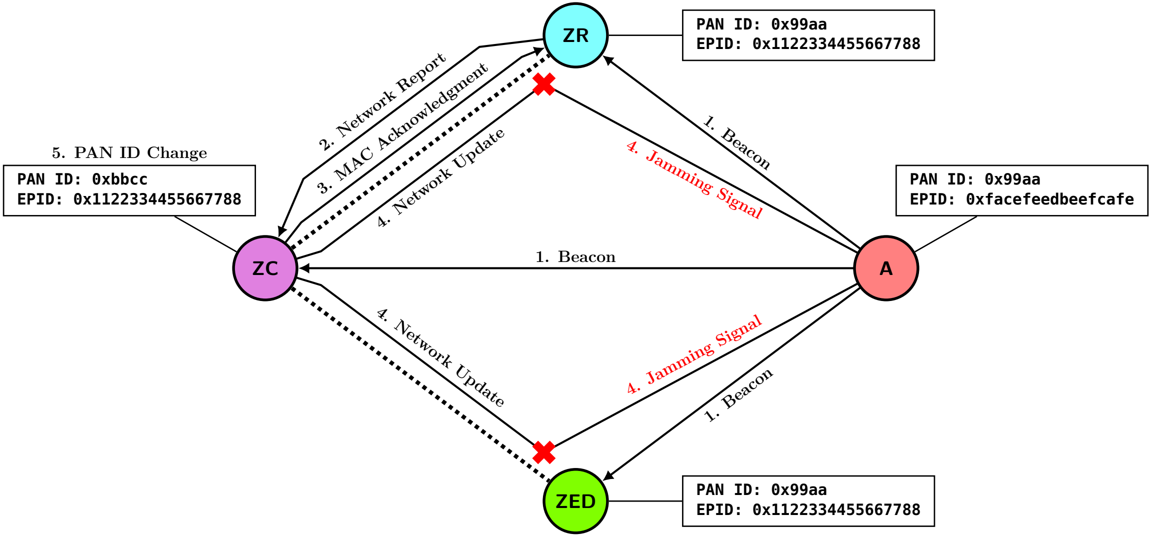

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PAN ID: 0x99aa
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PAN ID: 0x99aa
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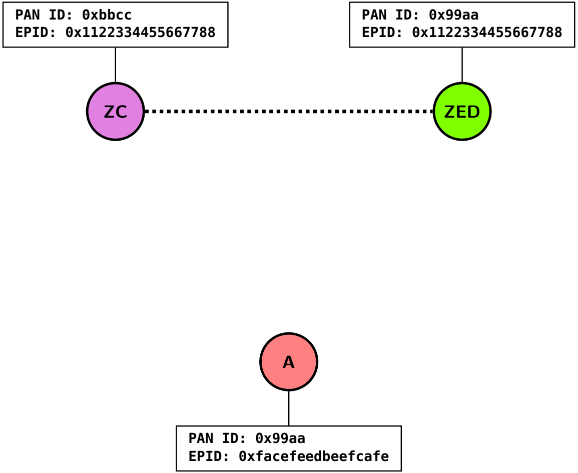
Keeping Zigbee Devices Disconnected (pt. 1)



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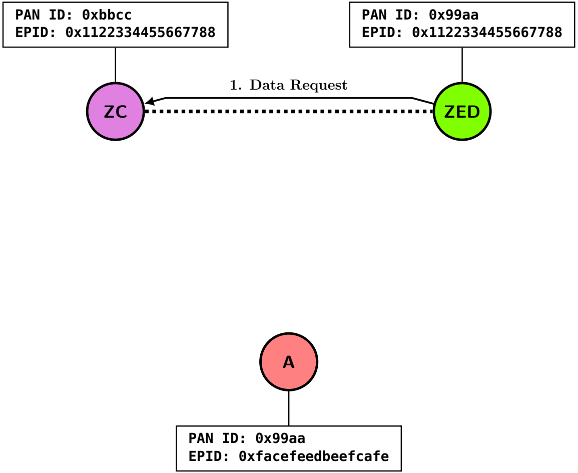

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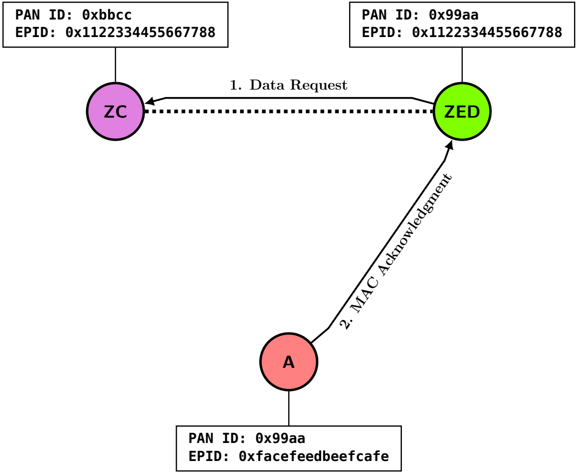

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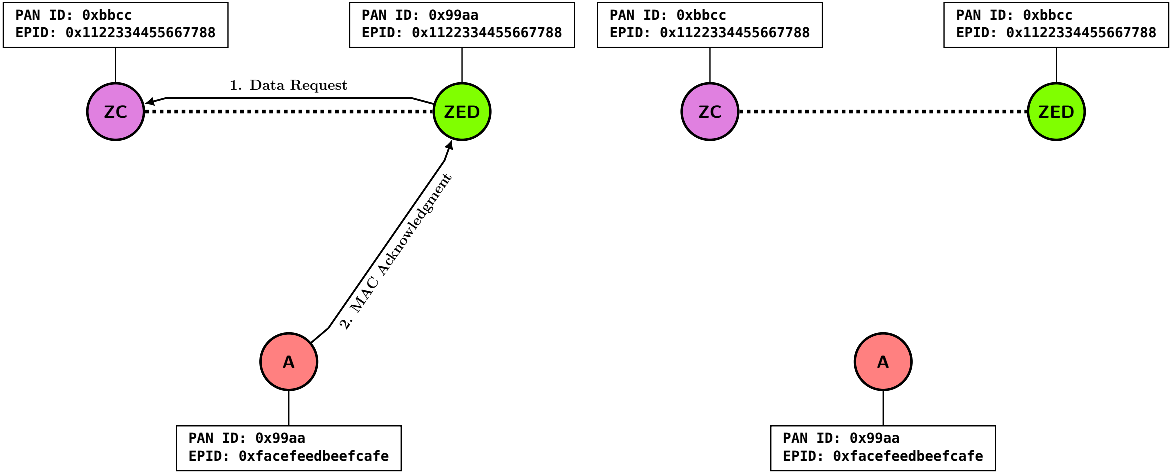

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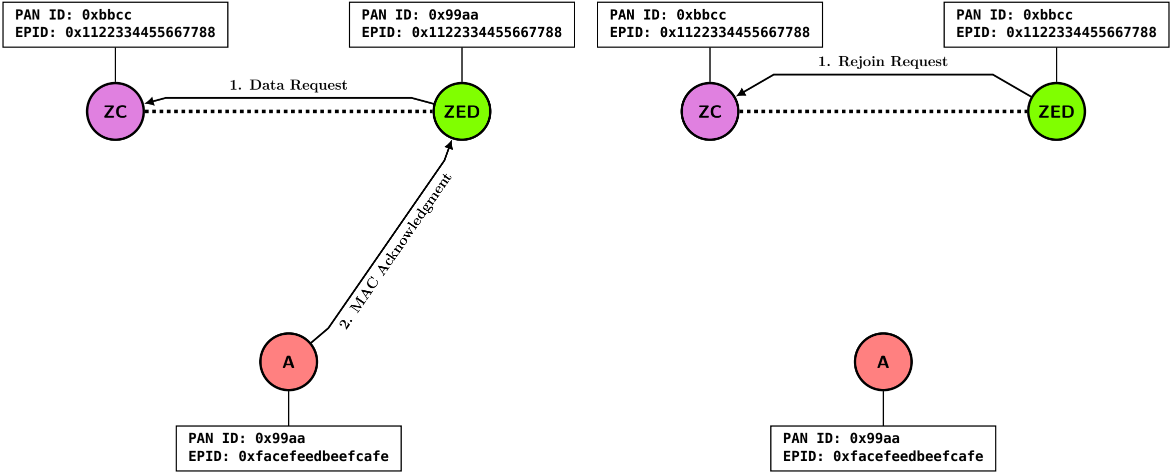

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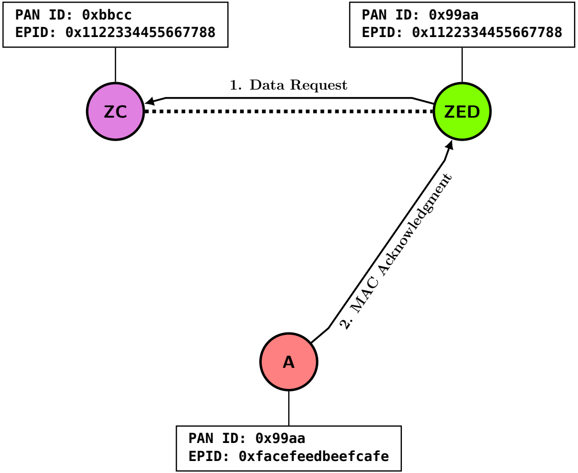

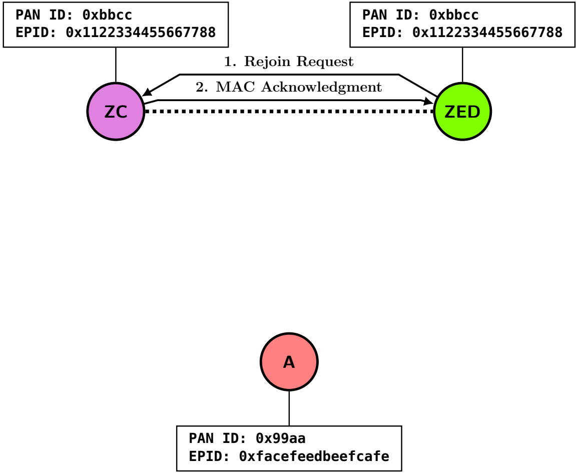

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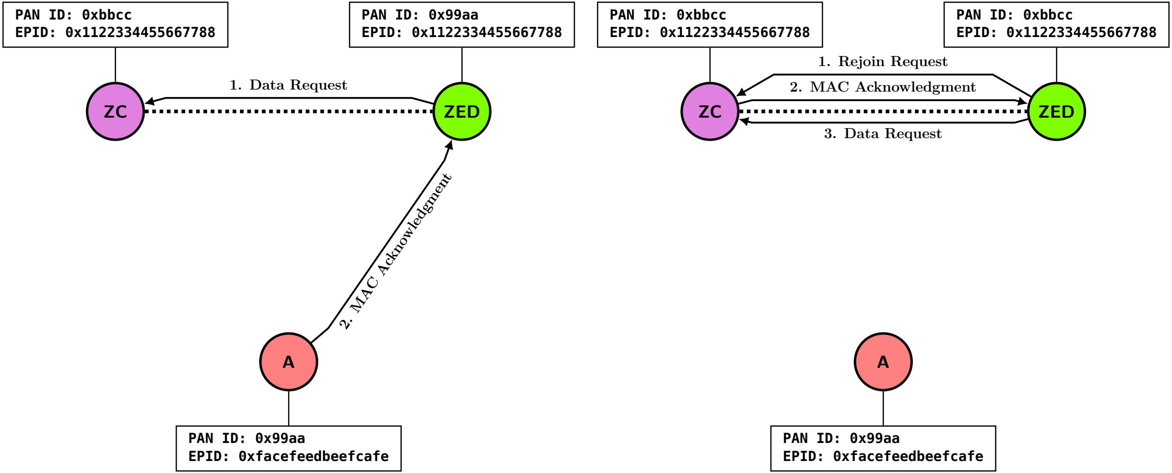

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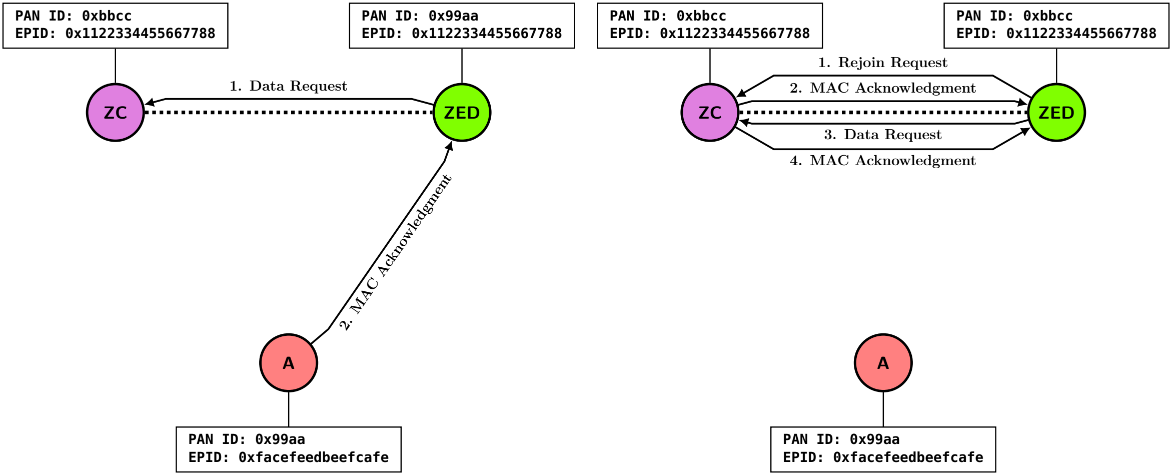

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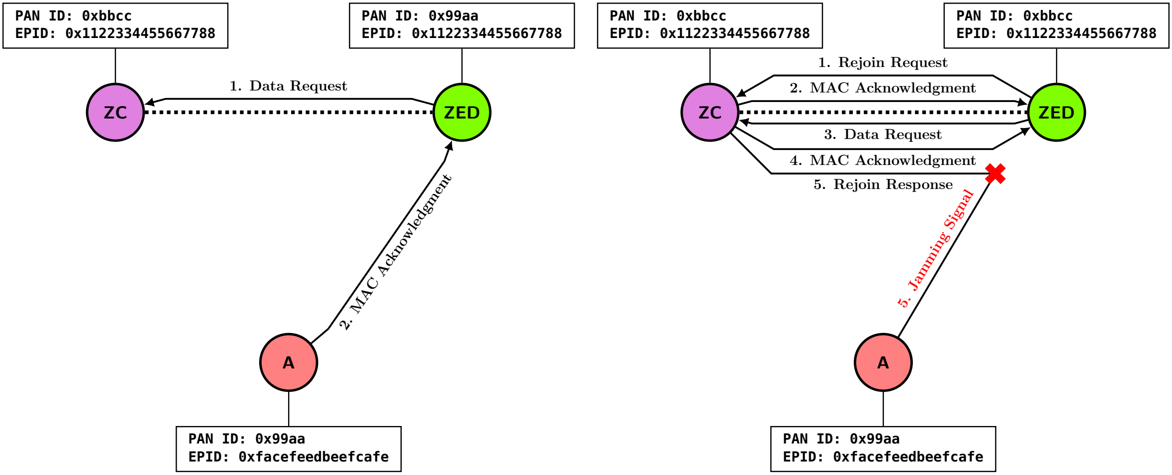


PAN ID: 0xbbcc
EPID: 0x1122334455667788

PAN ID: 0x99aa
EPID: 0x1122334455667788

1. Data Request

2. MAC Acknowledgment

PAN ID: 0x99aa
EPID: 0xfacefeedbeefcafe

PAN ID: 0xbbcc
EPID: 0x1122334455667788

PAN ID: 0xbbcc
EPID: 0x1122334455667788

1. Rejoin Request

2. MAC Acknowledgment

3. Data Request

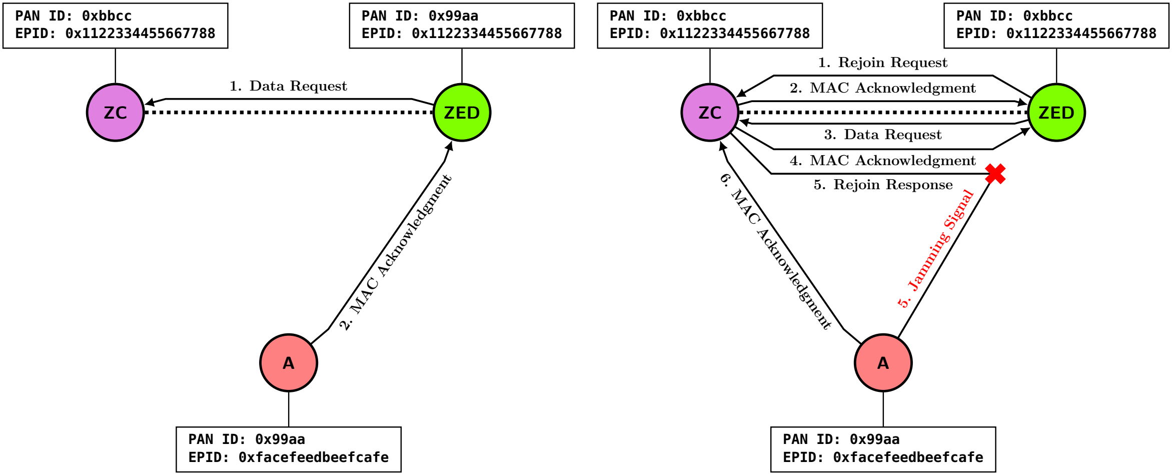
4. MAC Acknowledgment

5. Rejoin Response

5. Jamming Signal

PAN ID: 0x99aa
EPID: 0xfacefeedbeefcafe

Keeping Zigbee Devices Disconnected (pt. 1)



PAN ID: 0xbbcc
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ZC

ZED

1. Data Request

2. MAC Acknowledgment

A

PAN ID: 0x99aa
EPID: 0xfacefeedbeefcafe

PAN ID: 0xbbcc
EPID: 0x1122334455667788

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ZC

ZED

1. Rejoin Request

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4. MAC Acknowledgment

5. Rejoin Response

5. Jamming Signal

6. MAC Acknowledgment

A

PAN ID: 0x99aa
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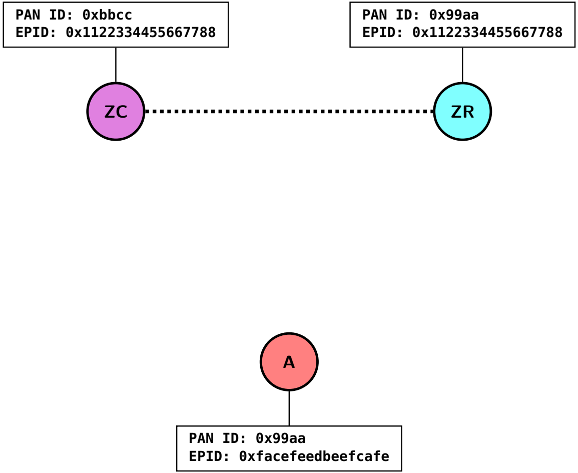
Keeping Zigbee Devices Disconnected (pt. 2)

- Some of our Zigbee devices were able to rejoin the network even if we jammed all **Rejoin Responses**
- By jamming the **beacons** with the updated PAN ID we could keep any Zigbee device disconnected



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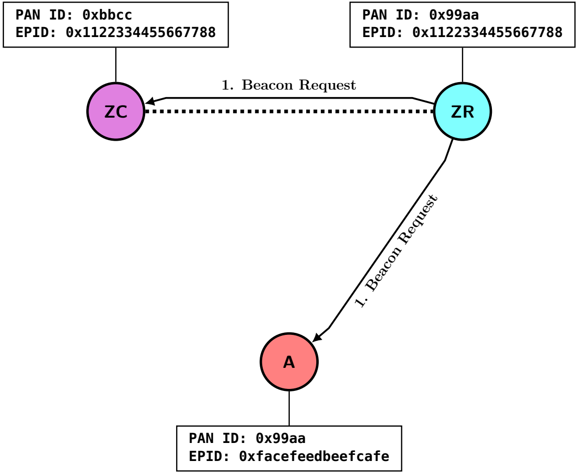

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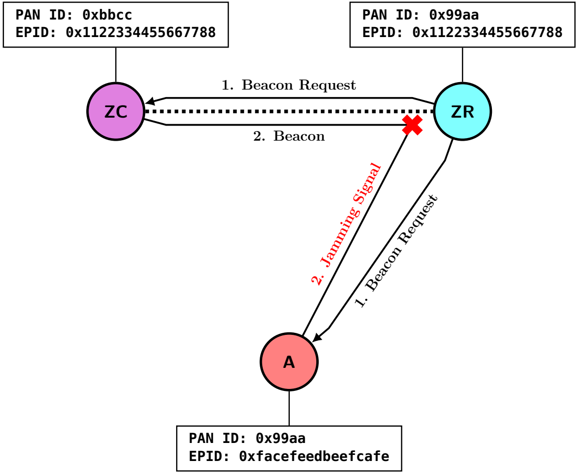

Responsible Disclosure

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- We recommend the following security enhancements:
  - The Trust Center link key should be **reconfigurable** over an out-of-band communication channel
  - The end users should be **made aware** of the security risks that the use of a legacy Zigbee device would introduce to their networks

Conclusion

- The lack of MAC-layer security exposes Zigbee networks to several passive and active attacks
- Developed software:
  - https://github.com/akestoridis/zigator
  - https://github.com/akestoridis/atusb-attacks
  - https://github.com/akestoridis/grc-ieee802154
  - https://github.com/akestoridis/wireshark-zigbee-profile
- CRAWDAD dataset cmu/zigbee-smarthome:
  - https://doi.org/10.15783/c7-nvc6-4q28
- Additional resources:
  - http://mews.sv.cmu.edu/research/zigator/