nixu cybersecurity.

It WISN't me, attacking industrial wireless mesh networks

hardwear.io

Hardware Security Conference and Training

Introduction

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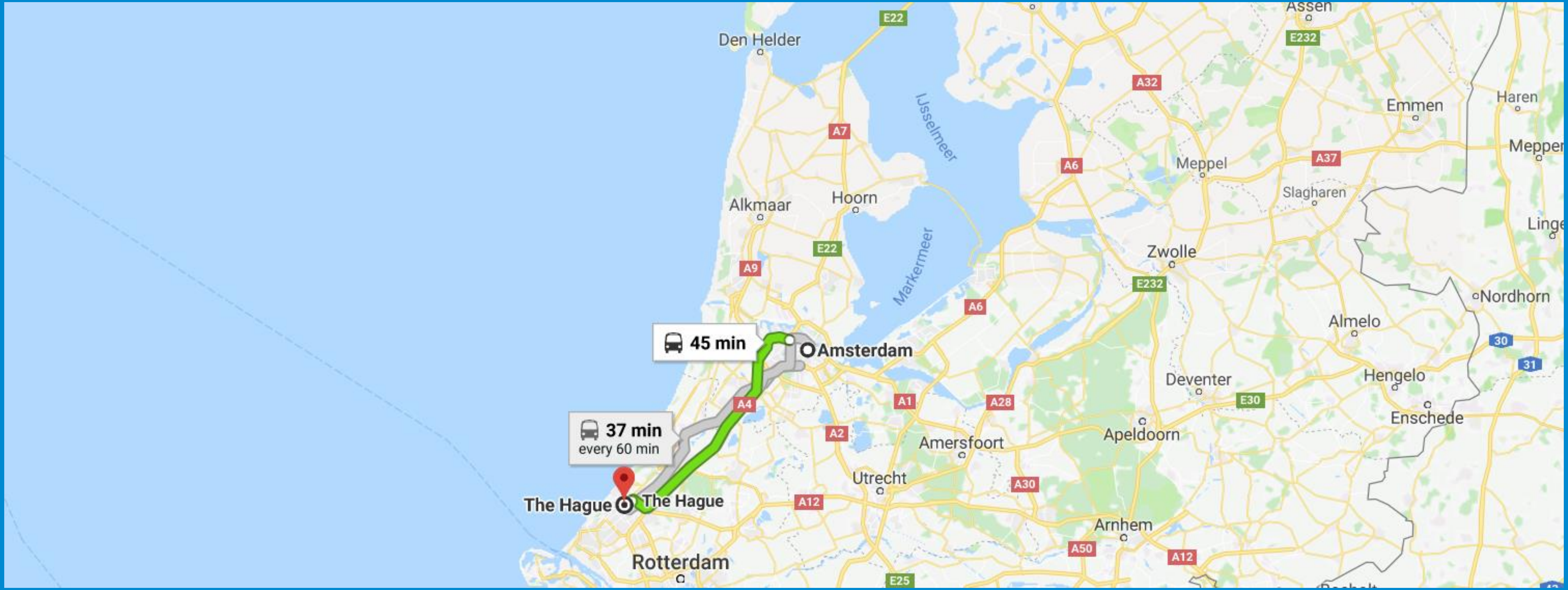

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Industrial (r)evolution

A brief history of control systems:

- ~1940: Air: Pneumatic logic systems: 3 - 15 psi
- Mid 1950: Analog: Current loop: 4 - 20 mA
- Mid 1980: Digital: HART, Fieldbus, Profibus
- Late 2000: Wireless mesh networks
  - WirelessHART (09/2007)
  - ISA 100.11a (09/2009)

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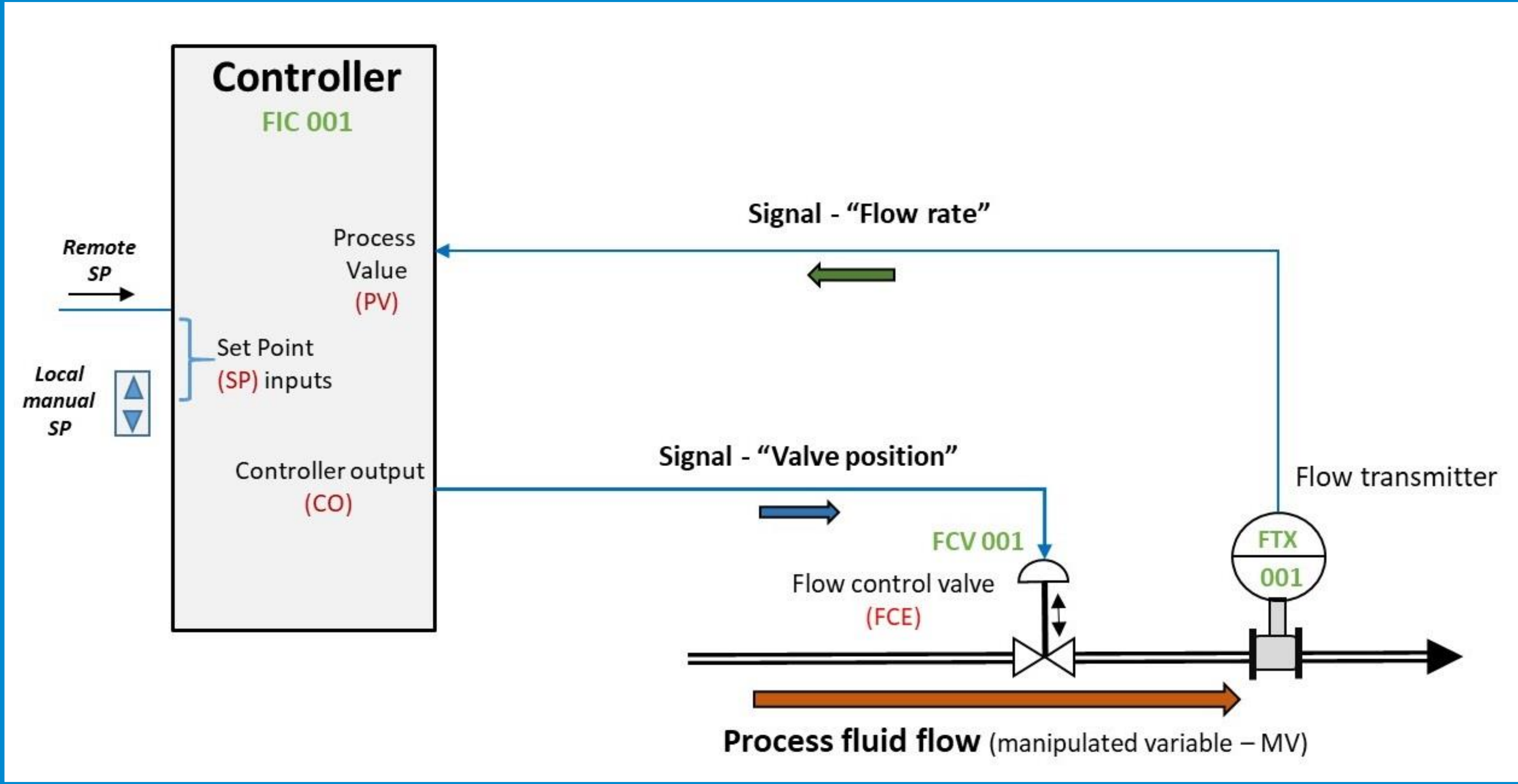
Previous research

- Security considerations for the WirelessHART protocol, Shahid Raza et al, 2009
  - https://ieeexplore.ieee.org/document/5347043/
- WirelessHART A Security Analysis, Max Duijsens, Master (2015)
  - https://pure.tue.nl/ws/files/47038470/800499-1.pdf
- Attacking the plant through WirelessHART, Mattijs & Erwin, S4 Miami (2016)
  - https://www.youtube.com/watch?v=AlEpgutwZvc
- Denial of service attacks on ICS wireless protocols, Blake Johnson, S4 Miami (2018)
  - https://github.com/voteblake/DIWI/ (video no longer available)

Wright's principle: "Security does not improve until practical tools for exploration of the attack surface are made available."

Industrial process control loop



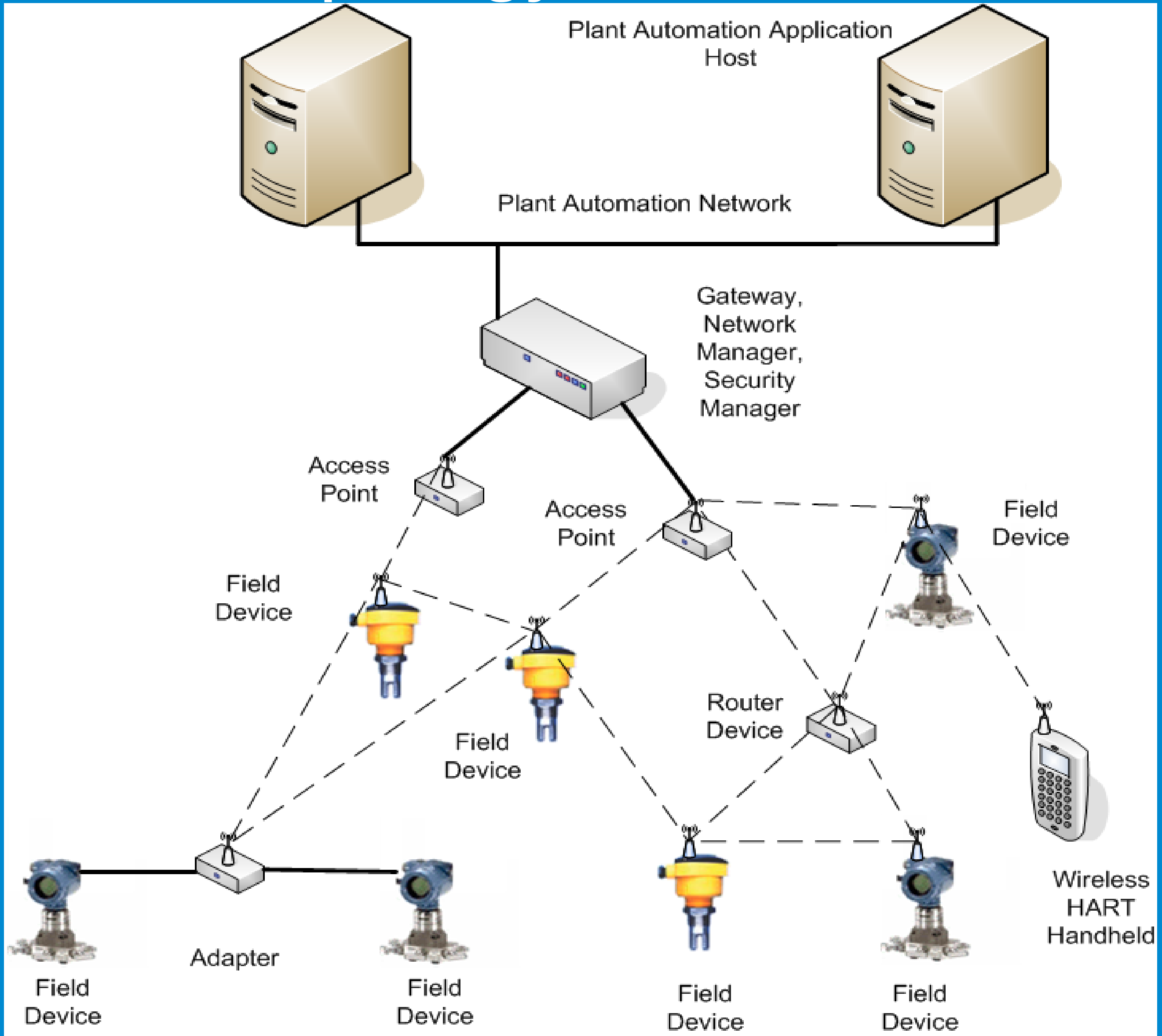
Introduction to WirelessHART

- Supports HART application layer
- Single encryption cipher/key length (AES CCM*)
- Wireless technology based on Time Synced Mesh Protocol developed by Dust Networks (now part of Analog Devices)
- Radio SoC exclusively provided by Dust Networks

Introduction to ISA 100.11a

- Relies on several standards: 6LoWPAN (IPv6/UDP)
- Ability to tunnel other protocols
- Vendor neutral application layer
- Mainly developed by Nivis
- Generic 802.15.4 chips provided by multiple vendors: STM, NXP, Texas Instruments, OKI

WISN topology



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Protocol stacks

<table>
<tr><th>OSI</th><th>HART</th><th>WirelessHART</th><th>ISA100.11a</th></tr>
<tr><td>Application</td><td colspan="2">Command oriented, predefined data types and application procedures</td><td>ISA native or legacy protocols (tunneling)</td></tr>
<tr><td>Presentation</td><td></td><td></td><td></td></tr>
<tr><td>Session</td><td></td><td></td><td></td></tr>
<tr><td>Transport</td><td colspan="2">Auto-segmented transfer of large data sets, reliable stream transport</td><td>UDP</td></tr>
<tr><td>Network</td><td></td><td>Redundant paths mesh network</td><td>6LoWPAN</td></tr>
<tr><td>Datalink</td><td>Byte oriented, token, master/slave protocol</td><td>Upper data-link sublayer
IEEE 802.15.4 MAC</td><td>Upper data-link sublayer
IEEE 802.15.4 MAC</td></tr>
<tr><td>Physical</td><td>Analog & digital signaling (4-20 mA)</td><td>IEEE 802.15.4 PHY (2.4 GHz)</td><td>IEEE 802.15.4 PHY (2.4 GHz)</td></tr>
</table>

Common denominators

- 802.15.4 MAC layer at 2.4 Ghz
- Time Slotted Channel Hopping in order to:
  - Minimize interference with other radio signals
  - Mitigate multipath fading
- Centralized network & security manager orchestrates communication between nodes
- Concluded that developing a common sniffer for both protocols should be possible

WirelessHART & ISA100.11a Security

- AES CCM* (CBC-MAC with counter mode)
  - Datalink Layer (integrity only)
  - Transport Layer (encryption)
- Join process
  - Handshake with Network Manager
    - Shared secrets
    - Certificates (ISA100.11.a only)

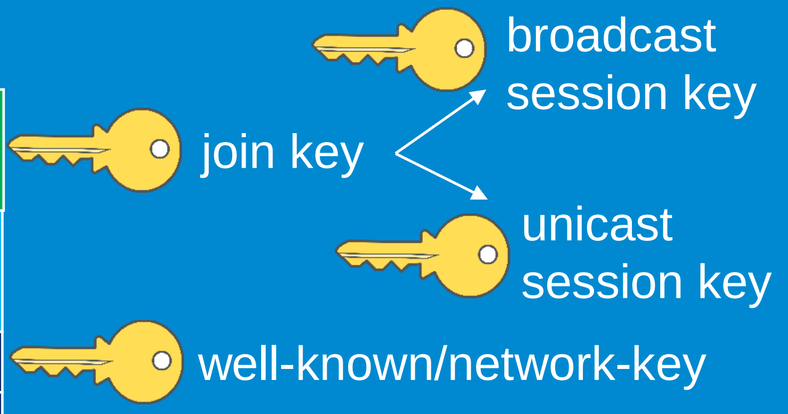
Keys galore

- ISA100.11a
  - **Global Key** – well-known
  - **K_open** – well-known
  - **K_global** – well-known
  - **Master Key** – derived during provisioning, used as KEK
  - **K_join** – Join process
  - **D-Key** – Hop-by-hop integrity
  - **T-KEY** – End-to-end encryption

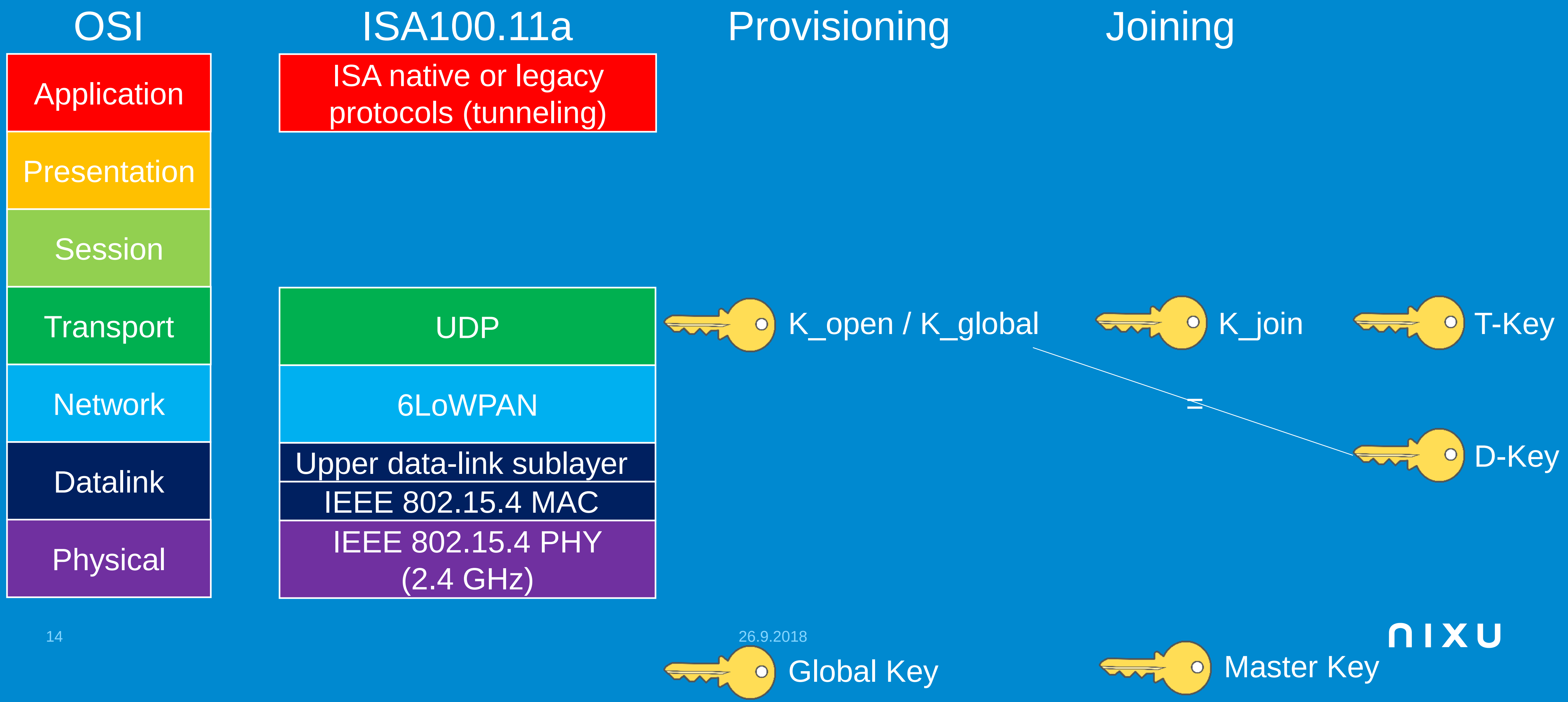
- WirelessHART
  - **Well-known Key** – Advertisements
  - **Network Key** – Hop-by-hop integrity
  - **Join Key** – Join process
  - **Broadcast Session Key** – End-to-end
  - **Unicast Session Key** – End-to-end

WirelessHART encryption keys

OSI	WirelessHART
Application	Command oriented, predefined data types and application procedures
Presentation	
Session	
Transport	Auto-segmented transfer of large data sets, reliable stream transport
Network	Redundant paths mesh network
Datalink	Upper data-link sublayer IEEE 802.15.4 MAC
Physical	IEEE 802.15.4 PHY (2.4 GHz)



ISA100.11a encryption keys



How to obtain key material

- Default keys
  - Documented, more or less
- Sniffing
  - During OTA provisioning (ISA100.11a)
- Keys stored in device NVRAM
  - Recoverable through JTAG/SPI (as demonstrated by our previous research)

WirelessHART default join keys

- **`445553544E4554574F524B53524F434B`** `– Multiple vendors`
  - DUSTNETWORKSROCK
- **`E090D6E2DADACE94C7E9C8D1E781D5ED`** `– Pepperl+Fuchs`
- **`24924760000000000000000000000000`** `– Emerson`
- **`456E647265737320B2048617573657 2`** `– Endress+Hauser`
  - Endress + Hauser

Sniffer hardware selection

- BeamLogic 802.15.4 Site Analyzer
  - 16 channels simultaneously, no injection support, Basic Wireshark dissector, Expensive (~ $1300)
- Atmel RZ Raven
  - Single channel 802.15.4 with standard firmware, no free IDE (Atmel Studio n/a), reached EOL
- NXP BeeKit
  - Single channel 802.15.4 with standard firmware (not open source), reached EOL

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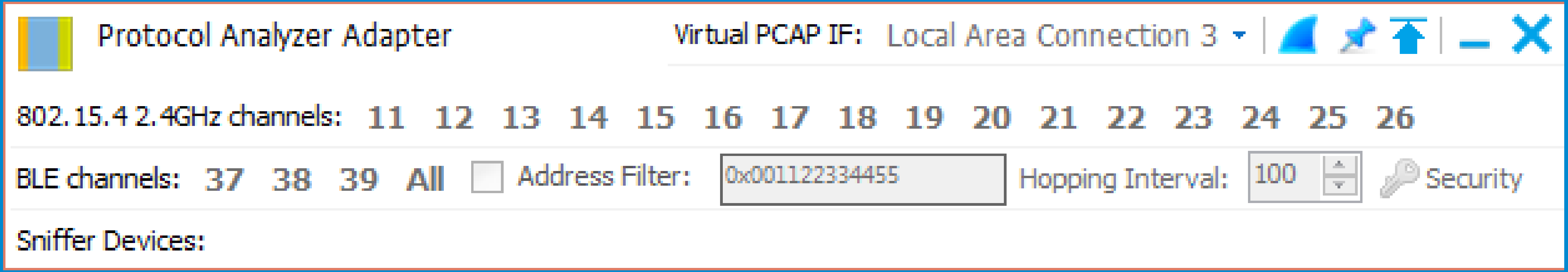
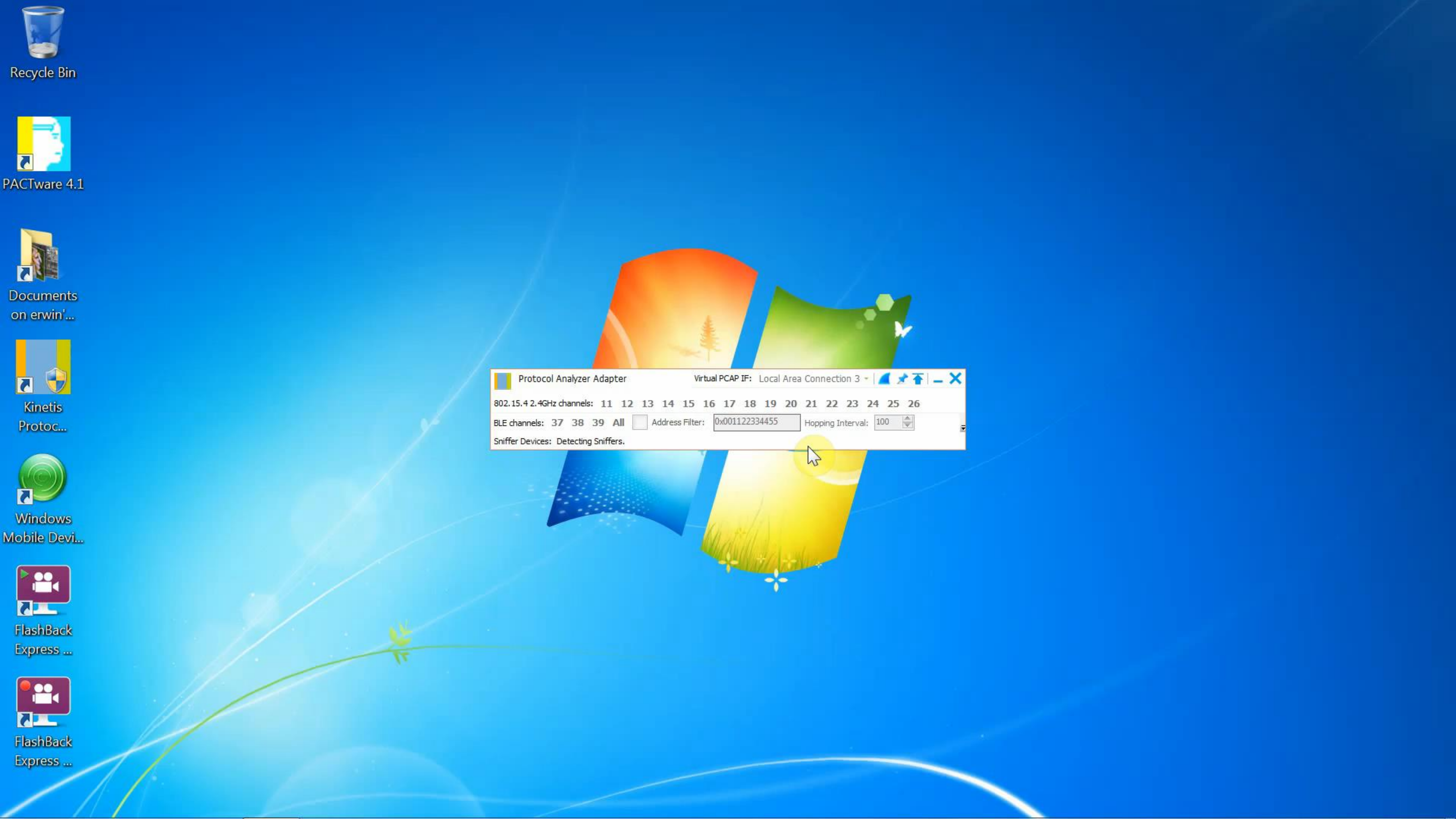
NXP USB-KW41Z

- Single channel 802.15.4 with standard firmware (not open source)
- Actively supported
- Free IDE available
- Powerful microcontroller (Cortex M0+)
- PCB ready for external antenna (Wardriving!)
- Easy firmware flashing via USB mass storage (OpenSDA)
- Documentation and examples, but with a few important omissions

Demo 1: Kinetix Protocol Analyzer Adapter (sniffer)

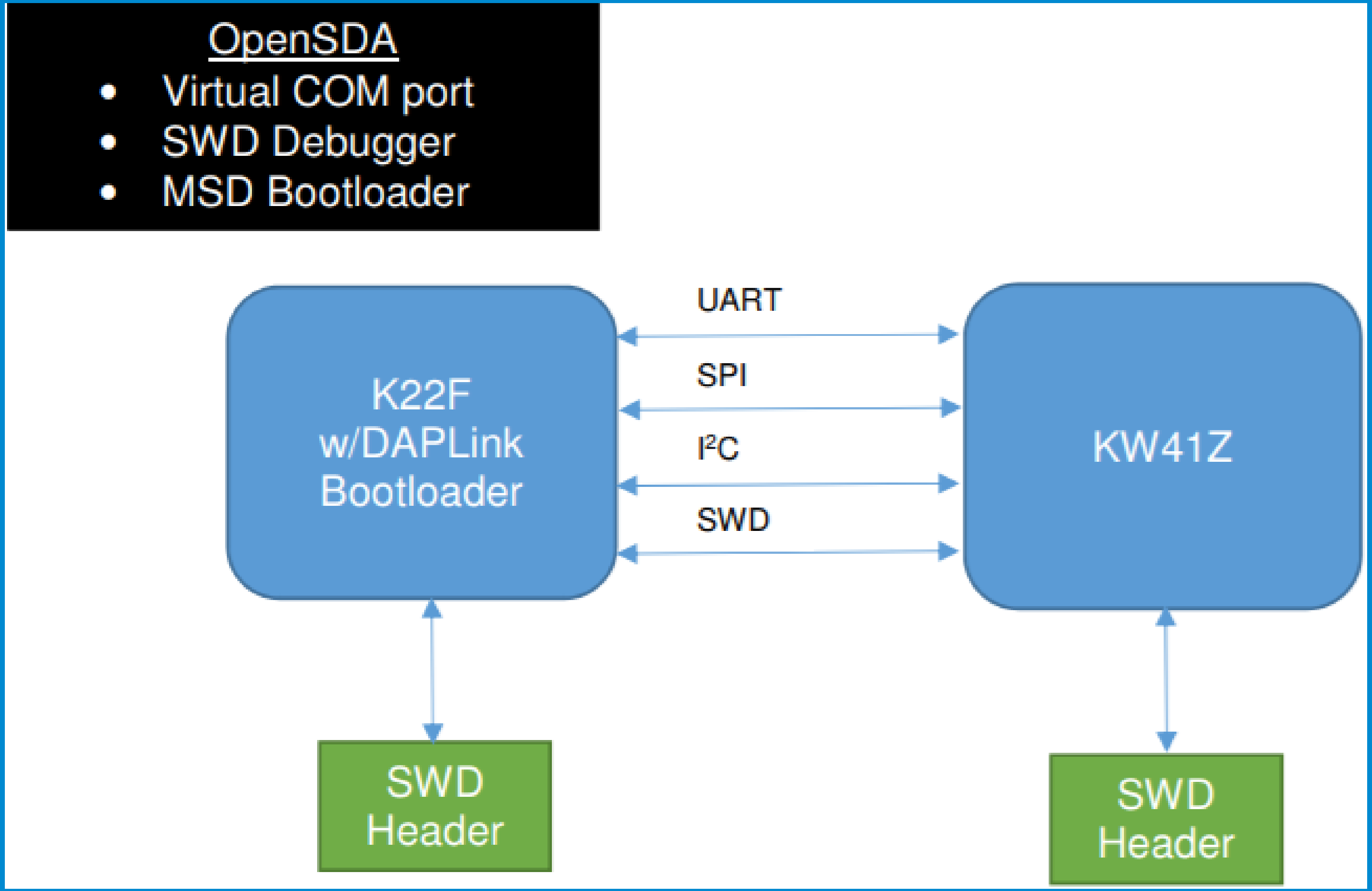



Recycle Bin
PACTware 4.1
Documents on erwin'...
Kinetis Protoc...
Windows Mobile Devi...
FlashBack Express ...
FlashBack Express ...
Protocol Analyzer Adapter
Virtual PCAP IF: Local Area Connection 3
802.15.4 2.4GHz channels: 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
BLE channels: 37 38 39 All
Address Filter: 0x001122334455
Hopping Interval: 100
Sniffer Devices: Detecting Sniffers.

USB-KW41Z <-> host communication

- Hardware is detected as virtual COM/UART port (Windows/Linux)
- Freescale Serial Communication Interface (FSCI) developed by NXP for communication between host and device firmware.
- Host SDK for FSCI is available (with Python bindings)
- FSCI protocol is fairly well documented
- Allowed us to communicate directly with the USB-KW41Z without requiring the SDK to be installed

USB-KW41Z block diagram



Building the toolset

- Extended the KillerBee framework with a driver for the USB-KW41Z
  - Allows us to comfortably capture 802.15.4 traffic into PCAP format
- Developed Scapy protocol support
  - Allows us to forge and inject packets
- Developed Wireshark dissectors for WirelessHART and ISA100.11a
  - Bringing WISN packet viewing to the masses
  - Live capture and dissecting of WISN traffic on a single channel at the time

Demo 2: Sniffing traffic with KillerBee and Wireshark

```
Resetting CPU...
Command:
0000:  02 a3 08 00 ab                                          .....

Command:
0000:  02 85 09 12 52 00 01 00 00 00 00 00 00 00 00 00        ....R..........
0010:  00 00 00 00 00 00 cd                                    .......

Response:  Packet | group: 84, opcode: 0d, crc: d8 ok:True
0000:  00 52 00                                                .R.

Set channel: 19
Channel set to: 19
Command:
0000:  02 85 09 12 21 00 13 00 00 00 00 00 00 00 00 00        ....!..........
0010:  00 00 00 00 00 00 ac                                    .......

Response:  Packet | group: 84, opcode: 0d, crc: ab ok:True
0000:  00 21 00                                                .!.

Command:
0000:  02 85 09 12 51 00 01 00 00 00 00 00 00 00 00 00        ....Q..........
0010:  00 00 00 00 00 00 ce                                    .......

Response:  Packet | group: 84, opcode: 0d, crc: db ok:True
0000:  00 51 00                                                .Q.

Command:
0000:  02 ba 01 00 bb                                          .....

Response:  Packet | group: a4, opcode: fe, crc: ac ok:True
0000:  f7                                                      .

zbwireshark: listening on '/dev/ttyACM0'
```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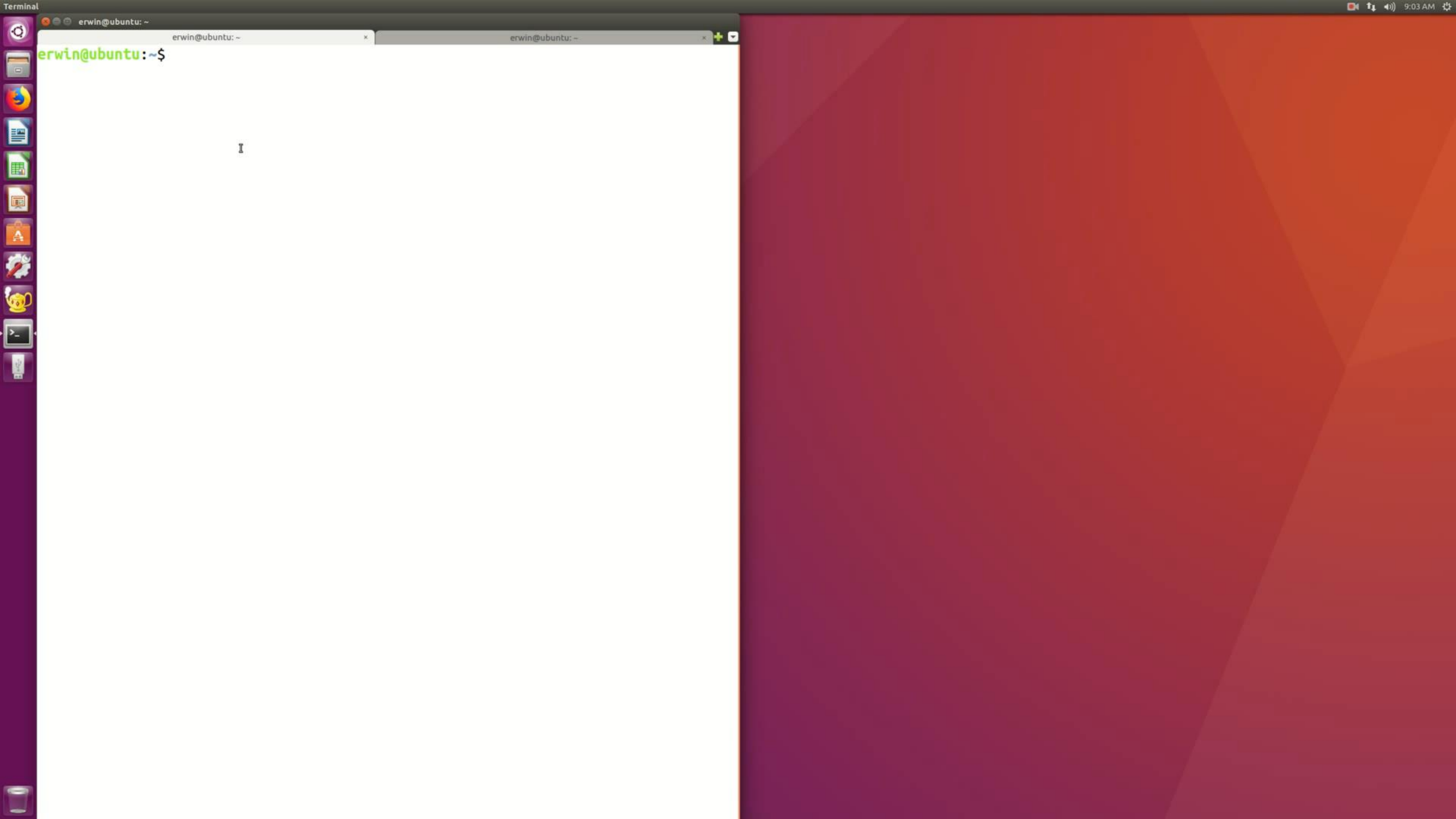
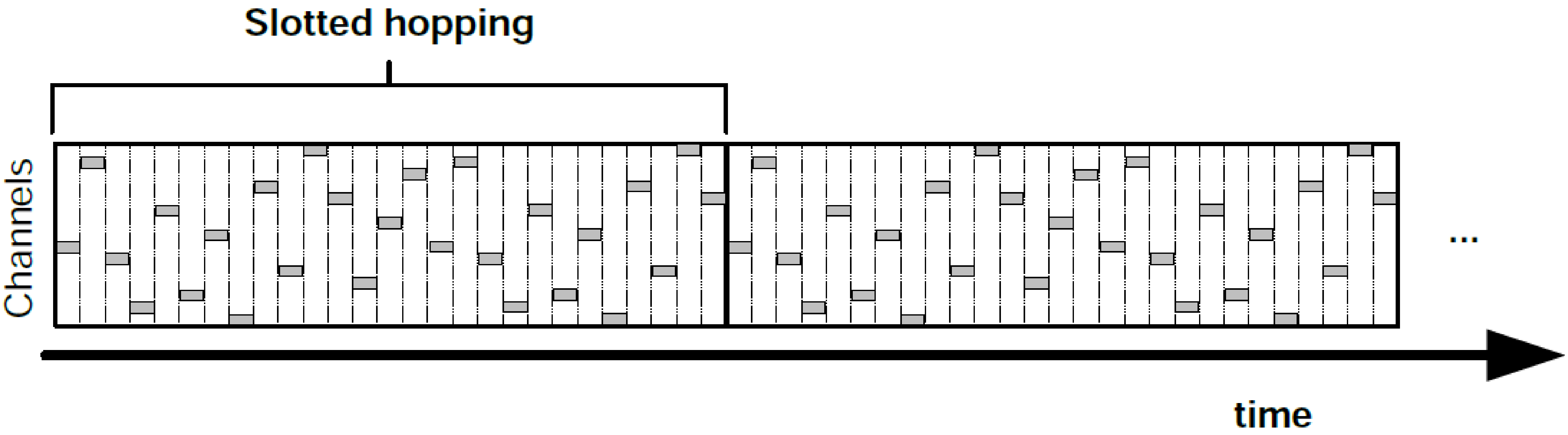
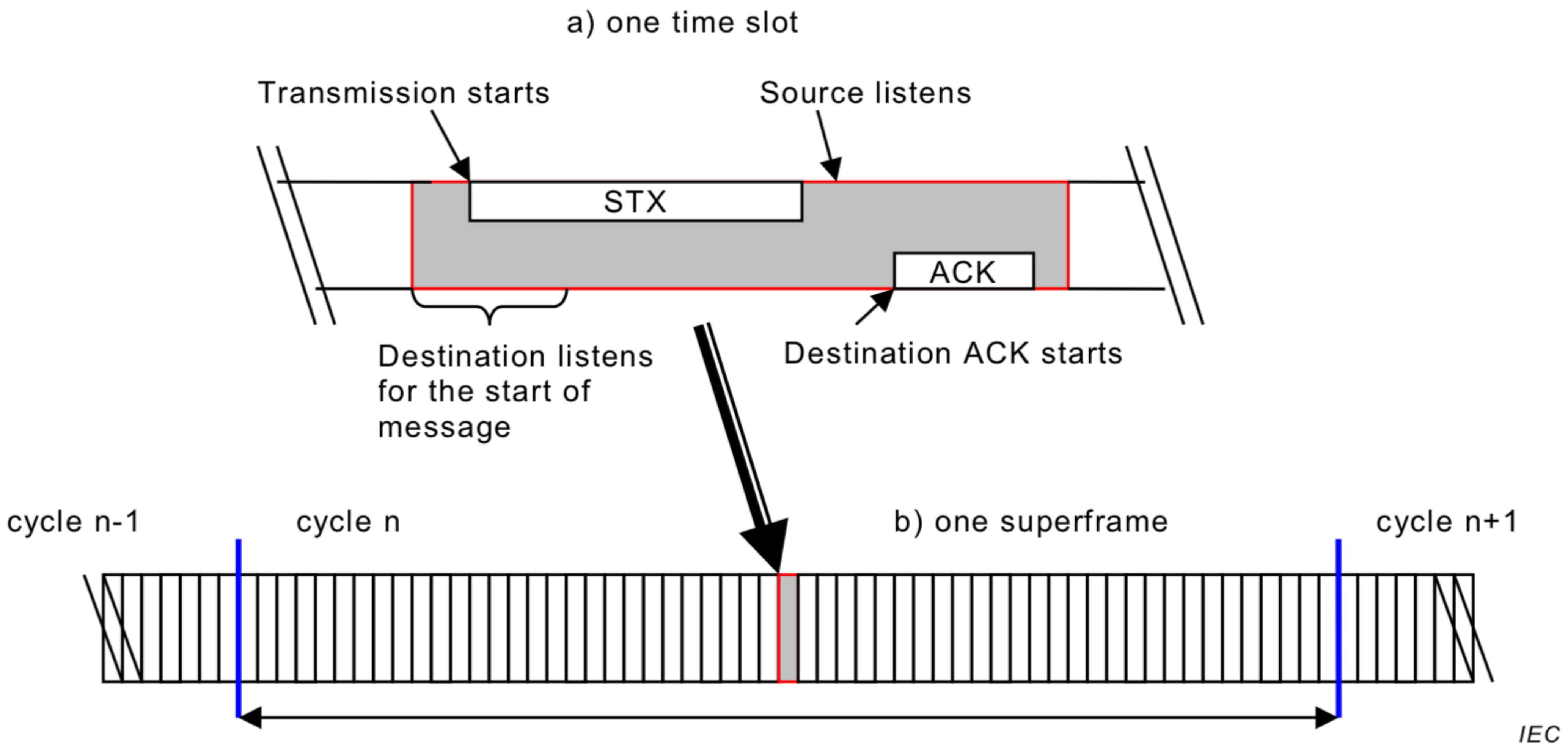

Terminal
erwin@ubuntu: ~
erwin@ubuntu: ~
erwin@ubuntu: ~
erwin@ubuntu:~$
9:03 AM

Time Slotted Channel Hopping



Superframe

- Sequence of repeating channel hopping patterns
- Period usually between 512-4096 time slots
- Time reference
  - WirelessHART: sequence number=0 (start of network manager)
  - ISA100: TAI=0 (Jan 1st 1958, 00:00:00)
- Timeslot within a superframe denotes a communication link, assigned by the Network Manager


a) one time slot
Transmission starts
Source listens
STX
ACK
Destination listens for the start of message
Destination ACK starts
cycle n-1
cycle n
b) one superframe
cycle n+1
IEC

Implementing Time Slotted Channel Hopping

- Both protocols require high speed channel hopping via predefined, but different patterns.
- FSCI communication too slow to tune into time slots (10ms)
  - **Solution: implement channel hopping in firmware**
- Two layers of encryption/authentication
  - **Solution: Implement in host software (Killerbee)**
- Ability to inject traffic
  - FSCI supports injection of arbitrary frames
  - **Solution: Implement frame injection in Killerbee, add protocol support to Scapy for crafting packets**

Firmware

Bare metal task scheduler

- Task consisting of single (endless) loop
- Blocking function waiting for events
- Once a task is running, it has full control
- Cannot run longer than ~2 ms to prevent starvation of other tasks

```
void MyTask (uint32_t param) {
    osaEventFlags_t ev;

    while(1) {
        OSA_EventWait(mAppEvent,
          osaEventFlagsAll_c, FALSE,
          osaWaitForever_c, &ev);
        if( ev && gSomeEvent) {
            /* do stuff */
            break;
        }
        break;
        ...
}
```

Bare Metal vs. RTOS

- Most RTOS use pre-emptive task scheduling
  - Nice for hard real-time requirements but:
    - Relatively large overhead
    - Context switches
    - Deal with synchronization issues
- Simple but:
  - Dependent on other tasks behaving nicely
  - Can avoid most synchronization issues
  - Faster execution

Firmware
Tasks/components

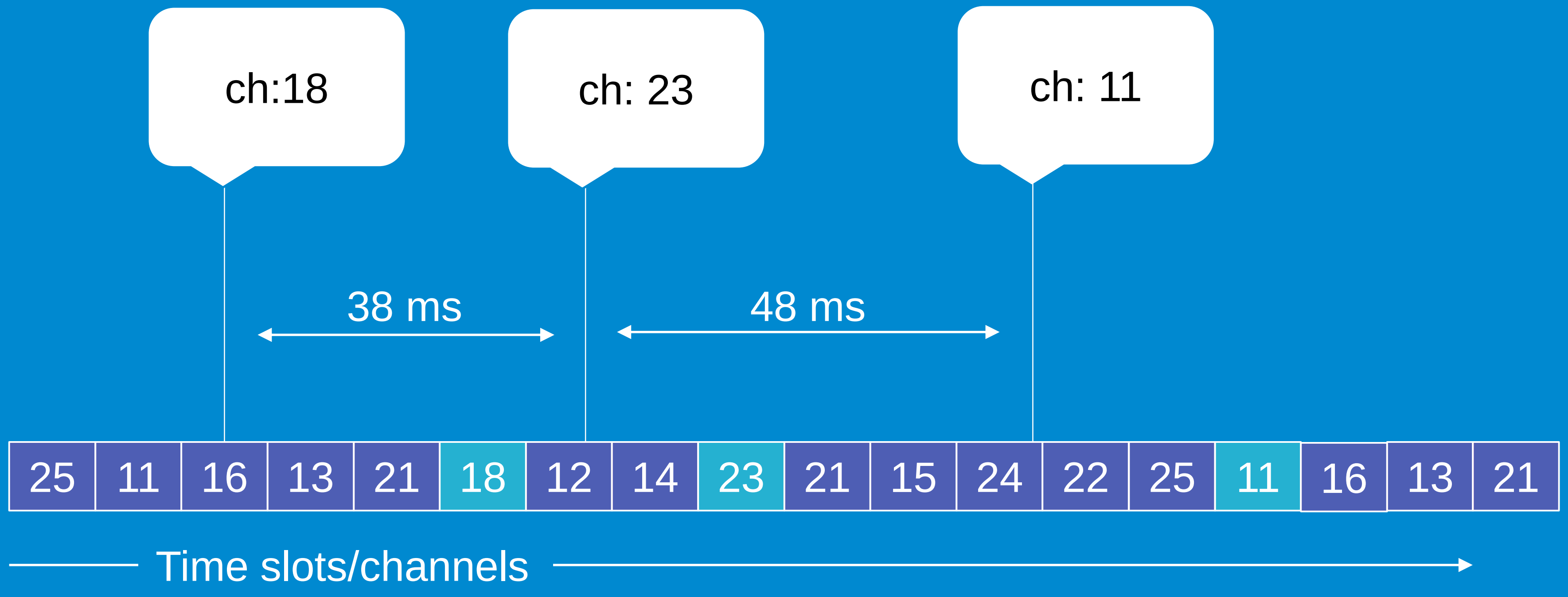
- Framework
  - Memory Manager
  - MAC/PHY
  - Serial Manager
  - Timers
  - LED driver
  - FSCI

- Application
  - 802.15.4 MAC extension layer
    - Source/destination/PAN info
  - ISA100/WirelessHART
    - Extract link information
      - Timeslots, channels
    - Timeslot synchronization
    - Channel hopping

How to synchronize?

- Both protocols support advertisement packets
- Broadcast by network manager
- Contains information about free join slots
- Timing information to synchronize on
- Hopping patterns are documented in protocol specifications

Channel hopping
Scheduling

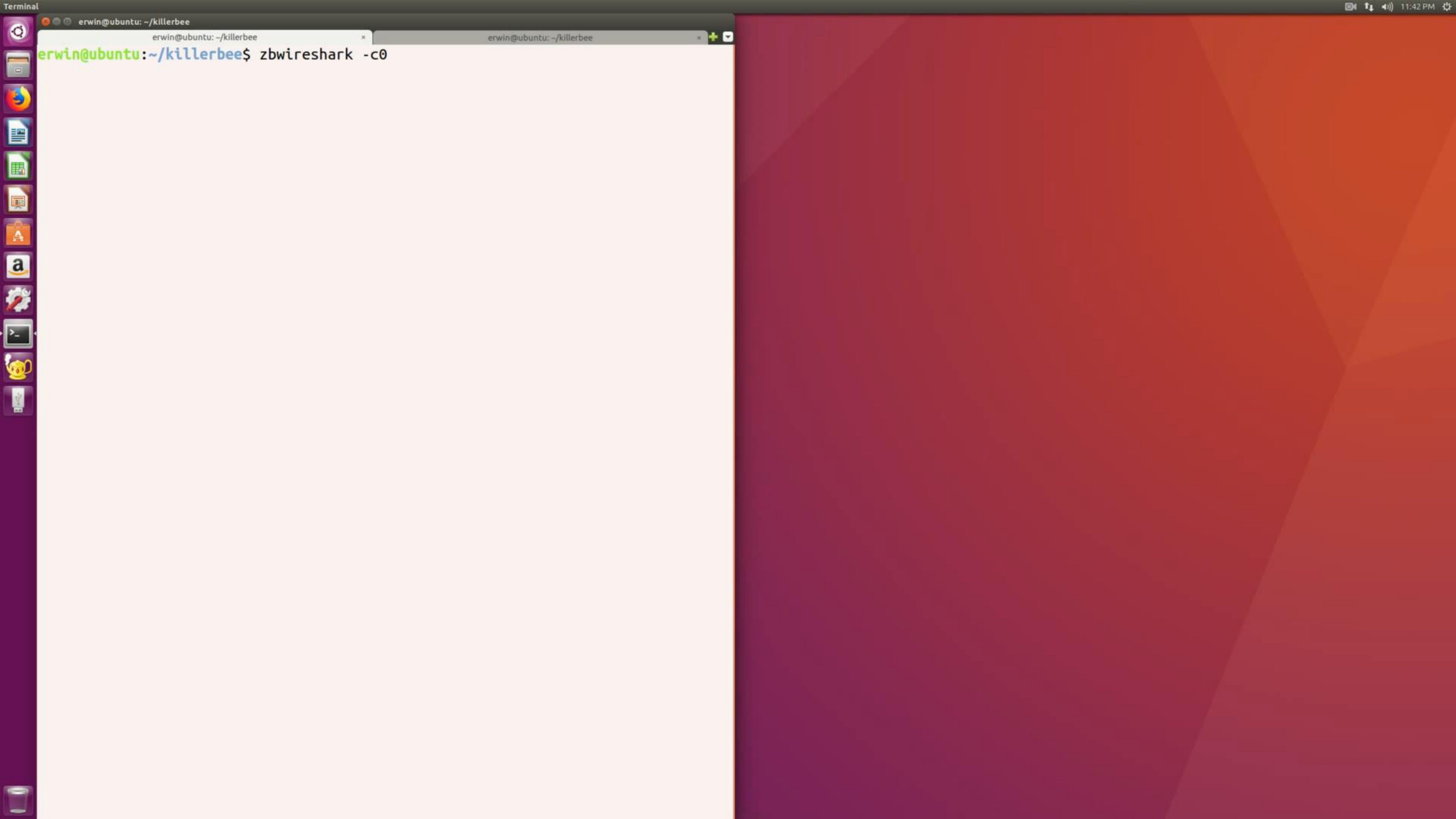


Demo 3: Sniffing with channel hopping

```
Debug: ***** WirelessHART - asn:626928 ch:12
Packet 15 | ch:0 rssi:111 time: 1388081 len: 62 crc:True
0000:  41 88 30 90 06 ff ff 01 00 31 00 00 09 91 30 11   A.0......1....0.
0010:  0f ff 7f 00 00 03 01 01 00 01 00 aa 02 00 04 00   ................
0020:  01 01 e9 45 04 00 80 06 00 12 4d 00 15 4d 00 3c   ...E......M..M.<
0030:  4d 00 42 4d 00 61 4d 00 62 4d 78 35 2a d9 1b c0   M.BM.aM.bMx5*...

Debug: ***** WirelessHART - asn:626992 ch:16
Packet 16 | ch:0 rssi:121 time: 1508080 len: 62 crc:True
0000:  41 88 f0 90 06 ff ff 01 00 31 00 00 09 91 f0 11   A........1......
0010:  0f ff 7f 00 00 03 01 01 00 01 00 aa 02 00 04 00   ................
0020:  01 01 e9 45 04 00 80 06 00 12 4d 00 15 4d 00 3c   ...E......M..M.<
0030:  4d 00 42 4d 00 61 4d 00 62 4d 6a 97 dd a5 07 47   M.BM.aM.bMj....G

Debug: ***** WirelessHART - asn:627184 ch:13
Packet 17 | ch:0 rssi:106 time: 1548079 len: 62 crc:True
0000:  41 88 30 90 06 ff ff 01 00 31 00 00 09 92 30 11   A.0......1....0.
0010:  0f ff 7f 00 00 03 01 01 00 01 00 aa 02 00 04 00   ................
0020:  01 01 e9 45 04 00 80 06 00 12 4d 00 15 4d 00 3c   ...E......M..M.<
0030:  4d 00 42 4d 00 61 4d 00 62 4d 77 ee 52 79 e4 22   M.BM.aM.bMw.Ry."
```


Terminal
11:42 PM
erwin@ubuntu: ~/killerbee
erwin@ubuntu: ~/killerbee
erwin@ubuntu: ~/killerbee
erwin@ubuntu:~/killerbee$ zbwireshark -c0

Unauthenticated attacks

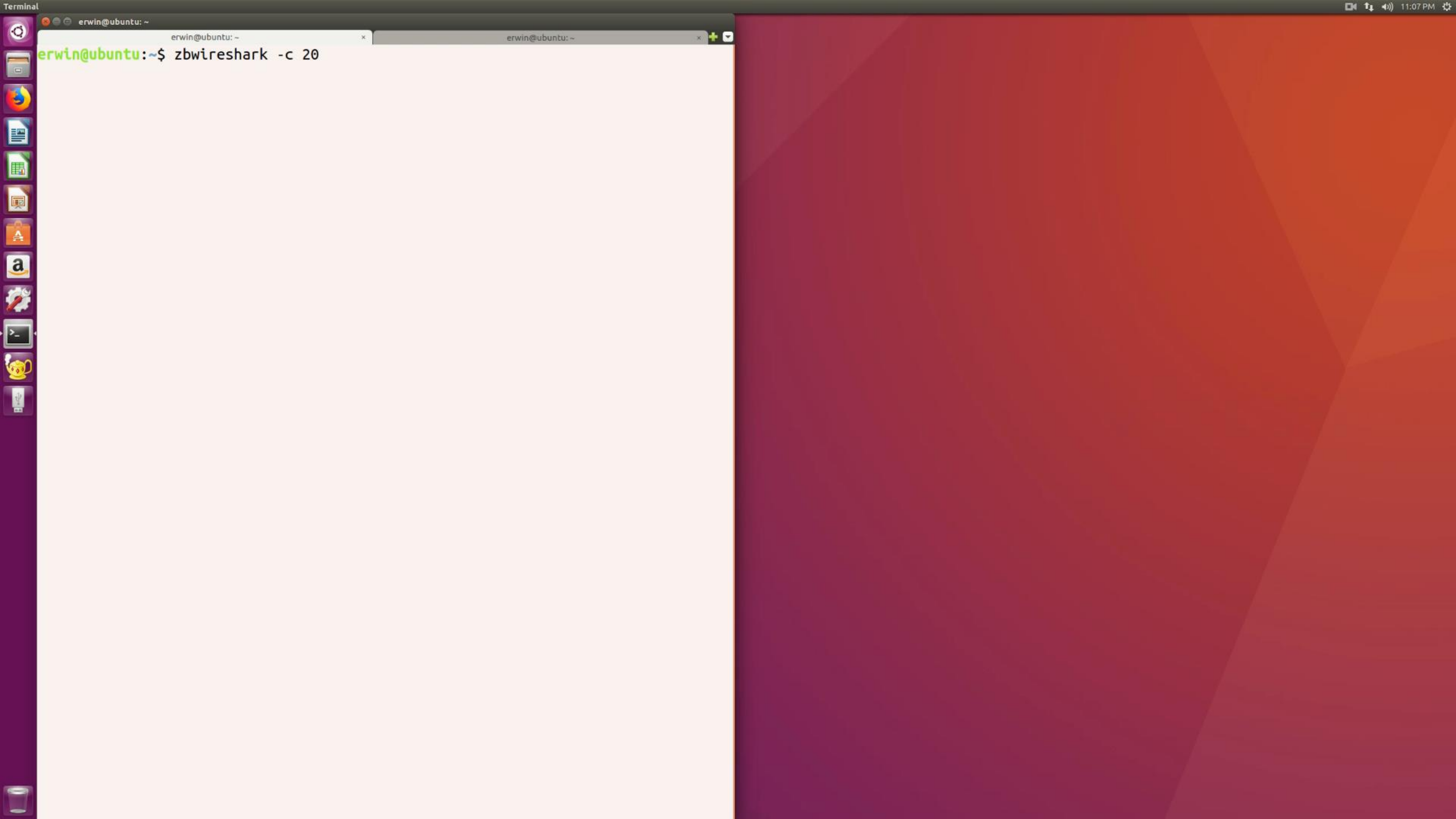
- Signal jamming through continuous power emission
- Concurrent packet transmission
  - Join slot jamming
  - Selective jamming transmitter communication
  - Transmitting fake advertisements

Demo 4: Advertisement jamming

```
mvo@mvo-virtual-machine: ~
mvo@mvo-virtual-machine:~$ whjammer -c 20
Resetting CPU...
Tuning to channel 20
Start jamming channel 20
Enabling jammer
FSCIPacket | ch: 0 group: bb, opcode: 02, crc: b9 ok:True

Packet 1 | ch:0 rssi:108 time: 385612 len: 62 crc:True
0000:  41 88 90 90 06 ff ff 01 00 31 00 00 28 d9 90 11
0010:  0f ff 7f 00 00 03 01 01 00 01 00 cc 08 00 04 00
0020:  01 03 da 48 04 00 80 06 00 03 4d 00 05 4d 00 0e
0030:  4d 00 25 4d 00 27 4d 00 51 4d 7d e4 76 71 67 ff

Debug: Tracking network PAN ID: 1680
```


Terminal
erwin@ubuntu: ~
erwin@ubuntu: ~
erwin@ubuntu: ~
erwin@ubuntu:~$ zbwireshark -c 20
11:07 PM

Authenticated attacks

- Nonce exhaustion
  - Both protocols use a semi-predictable nonce counter to feed the AES CCM* algorithm
  - A device will reject a packet if a nonce value is lower than a previously received one
  - Spoofing a packet with a maximum nonce value, causes legitimate packets to drop
- Sending spoofed measurements to influence the process

Conclusions

- Still a large unexplored attack surfaces due to complexity of the protocols
- The released tools and research will fill this gap and enable security researchers to move forward in the field of WISN research
- Using WISN technology for process control and especially functional safety applications is probably not a good idea, and should be reconsidered

Future research

- Expand tool with more theorized attacks
- Research forced rejoin triggers
- Mapping WISN locations (wardriving)
- Implementation specific vulnerabilities (transmitters, gateways)

Questions & thank you

- Our code is soon available at: https://github.com/nixu-corp

- Thanks to the following people for their help:
  - Alexander Bolshev (@dark_k3y)
  - Sake Blok (@SYNbit)