TROOPERS17

MARC NEWLIN // MATT KNIGHT // BASTILLE NETWORKS

SO YOU WANT TO HACK RADIOS

A PRIMER ON WIRELESS REVERSE ENGINEERING

WHO ARE THESE GUYS

- Marc “mou$e whisperer” Newlin
  - Security Researcher @ **Bastille**
  - Discovered Mousejack vulnerability in 2016
  - Finished 2rd in DARPA Spectrum Challenge in 2013
  - Finished 3nd in DARPA Shredder Challenge in 2011

marc@**Bastille**.net
@marcnewlin

- Matt Knight
  - Software Engineer and Security Researcher @ **Bastille**
  - Reverse engineered the LoRa wireless protocol in 2016
  - BE & BA from Dartmouth

matt@**Bastille**.net
@embeddedsec

WHO IS THIS FOR?

WHY SHOULD YOU CARE?

WIRELESS SYSTEMS ARE EVERYWHERE

MOBILE

WIRELESS SYSTEMS
ARE EVERYWHERE

MOBILE

WIRELESS SYSTEMS
ARE EVERYWHERE

IOT

MOBILE

WIRELESS SYSTEMS ARE EVERYWHERE

IOT

Fewer wires every year!

ABOUT THE INTERNET OF THINGS…

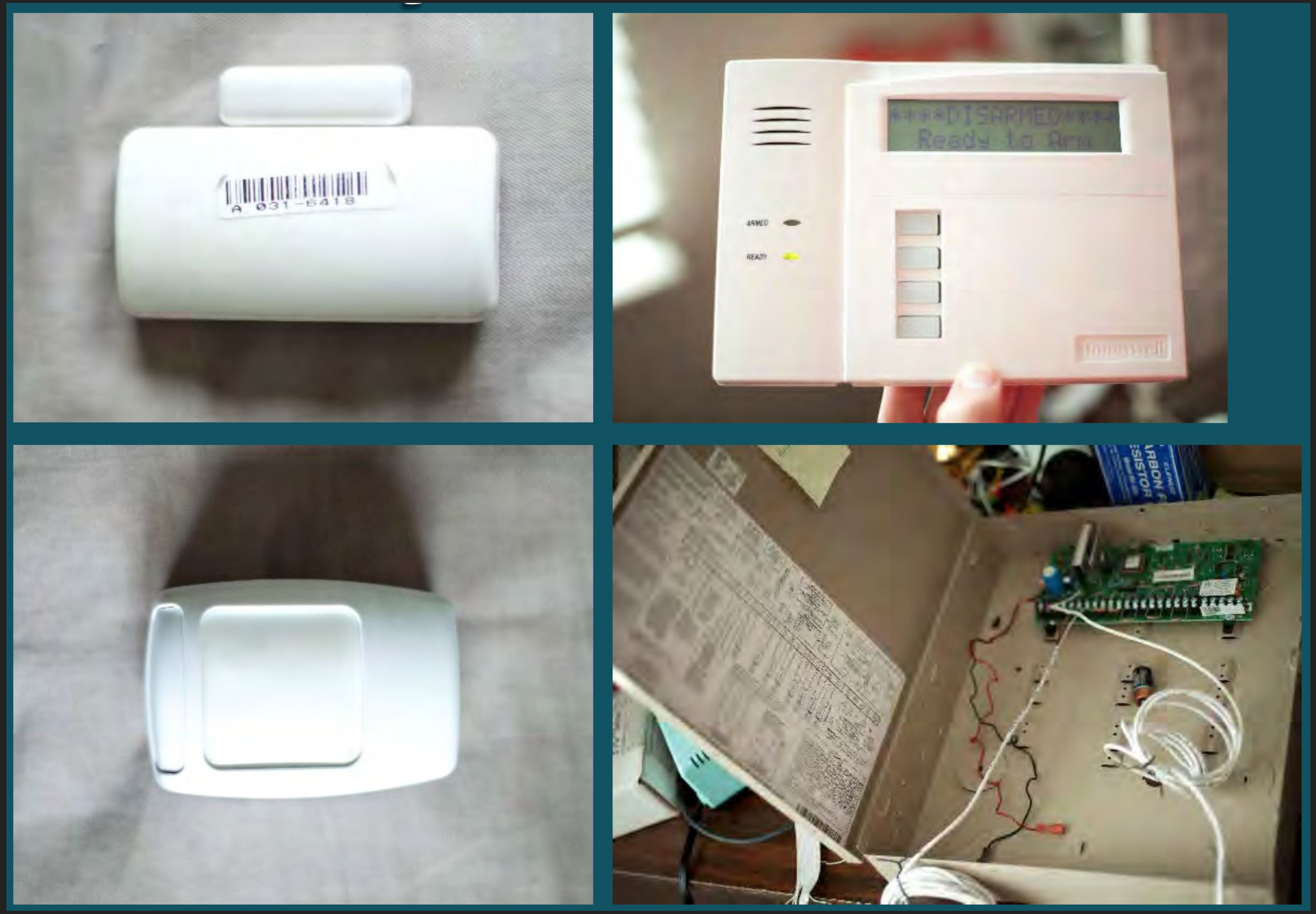
- Everyone’s Favorite Buzzword™
- What is it, actually?
  - Sales and marketing speak for “connected embedded devices”
  - “Smart” devices are usually pretty stupid

EMBEDDED REALITIES

- Embedded systems are built on compromise
  - Size and cost constraints
  - Battery powered
  - Challenging deployment scenarios
  - Difficult to patch

Vulnerable by Virtue of Being Constrained

ALARM SYSTEM VULNERABILITIES



- Discovered by **Bastille**'s Logan Lamb in 2014
- Legacy RF link between home alarm system sensors and control panel is vulnerable to:
  - Jamming (denying alarm reporting)
  - Command injection (trigger false alarms)
  - Eavesdropping (detect occupancy, monitor movement)

Image credit: Logan Lamb

MOUSEJACK

- Discovered by **Bastille**'s Marc Newlin in 2015
- RF link between non-Bluetooth wireless keyboards and mice (100MMs of devices) vulnerable to:
  - Command injection (running arbitrary commands at current permissions level)
  - Eavesdropping (sniffing passwords, credit card #s, etc.)

@krystalmead

IOT VILLAGE FEEDBACK

- Interest in Software Defined Radio and RF systems is high
- RF is intimidating!
  - Too much EE for software people
  - Too academic!

NO PHD?

NO PROBLEM!

AGENDA

1. So you want to hack RF…
2. Introduce essential RF concepts
3. Introduce RF reverse engineering workflow that applies to all systems
4. Do it live!
    1. Z-Wave home automation protocol
    2. Wireless doorbell
    3. HP wireless keyboard

This is what it’s all about

WHAT WE WON'T COVER

Digital Signal Processing

SO YOU WANT TO

HACK WIRELESS

BARRIERS TO ENTRY

- Lower than ever before
- Commodity hardware is:
  - Really powerful
  - Increasingly cheap
- Free (beer && liberty) software is abundant!

HARDWARE TOOLS

- Dedicated Radio Chipset (Hardware Defined Radio)
  - Does 1 protocol really well
  - Pros: single-protocol performance, cost, simplicity, low power
  - Cons: lack of flexibility
- Examples:
  - Ubertooth ($200)
  - RFCat / Yardstick One ($100)
  - nRF24 dongles ($35)
  - ApiMote ($90)

HARDWARE TOOLS

- Software Defined Radio (SDR)
  - Swiss army knife for most-things RF
  - Pros: flexibility (can implement any protocol)
  - Cons: cost, complexity, power, performance (software and RF)
- Examples:
  - Ettus USRP ($686—>$$$$$)
  - HackRF ($300)
  - BladeRF ($420-$650)

FREE SOFTWARE

- SDR:
  - GNU Radio: open source digital signal processing suite
  - GNU Radio OOT Modules: third party plugins
    - gr-lora, gr-nordic
  - Baudline, Inspectrum, Fosphor: powerful analysis tools
- HDR:
  - Bluez, libubertooth, Killerbee
  - Marc’s nRF24 library

TOOLS ARE RIDICULOUS

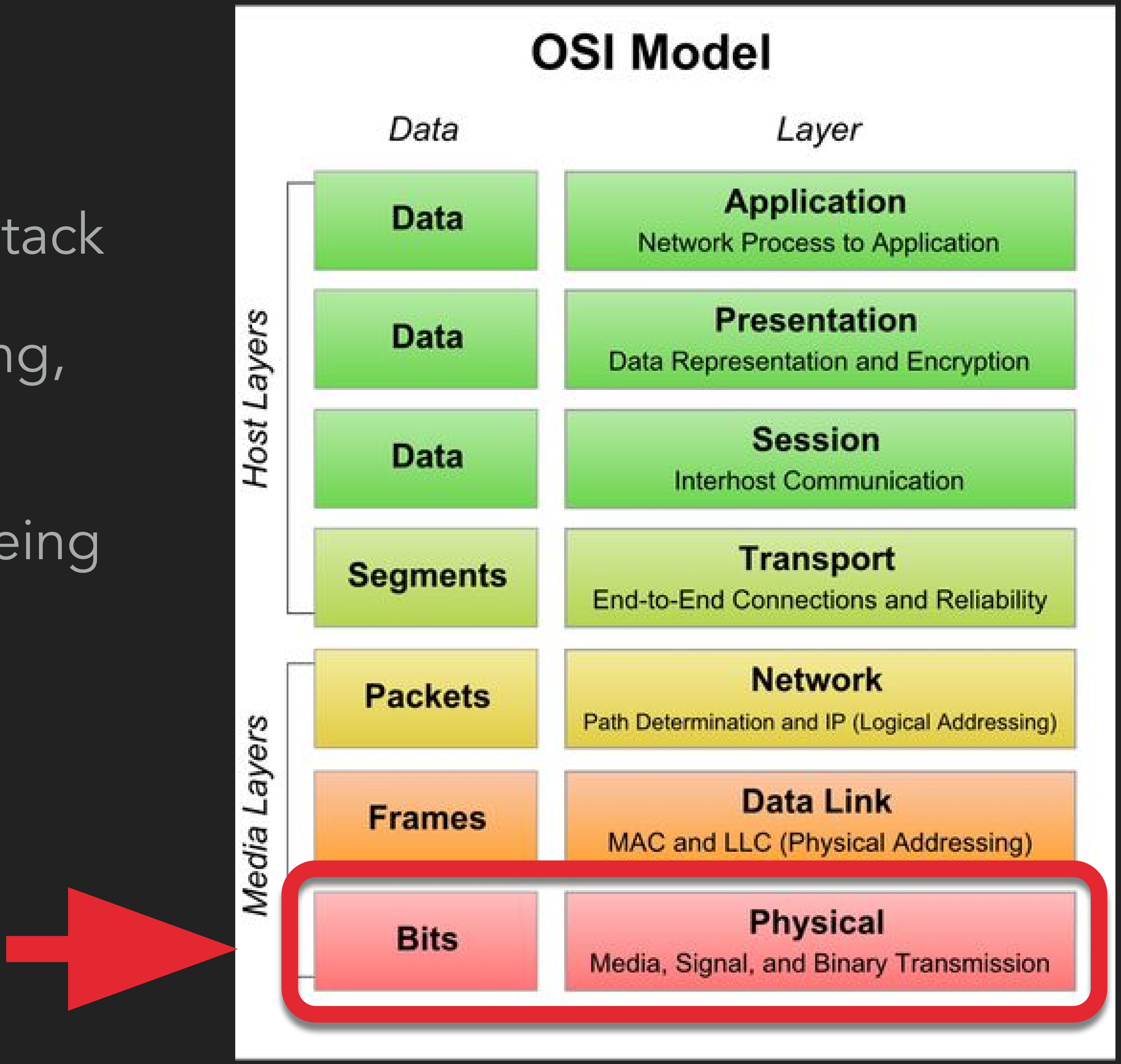
OFFENSIVELY

~~OBSCENELY~~ SHORT

RADIO CRASH COURSE

PHY LAYER

- Lowest layer in communication stack
- In wired protocols: voltage, timing, and wiring defining 1s and 0s
- In wireless: patterns of energy being sent over RF medium



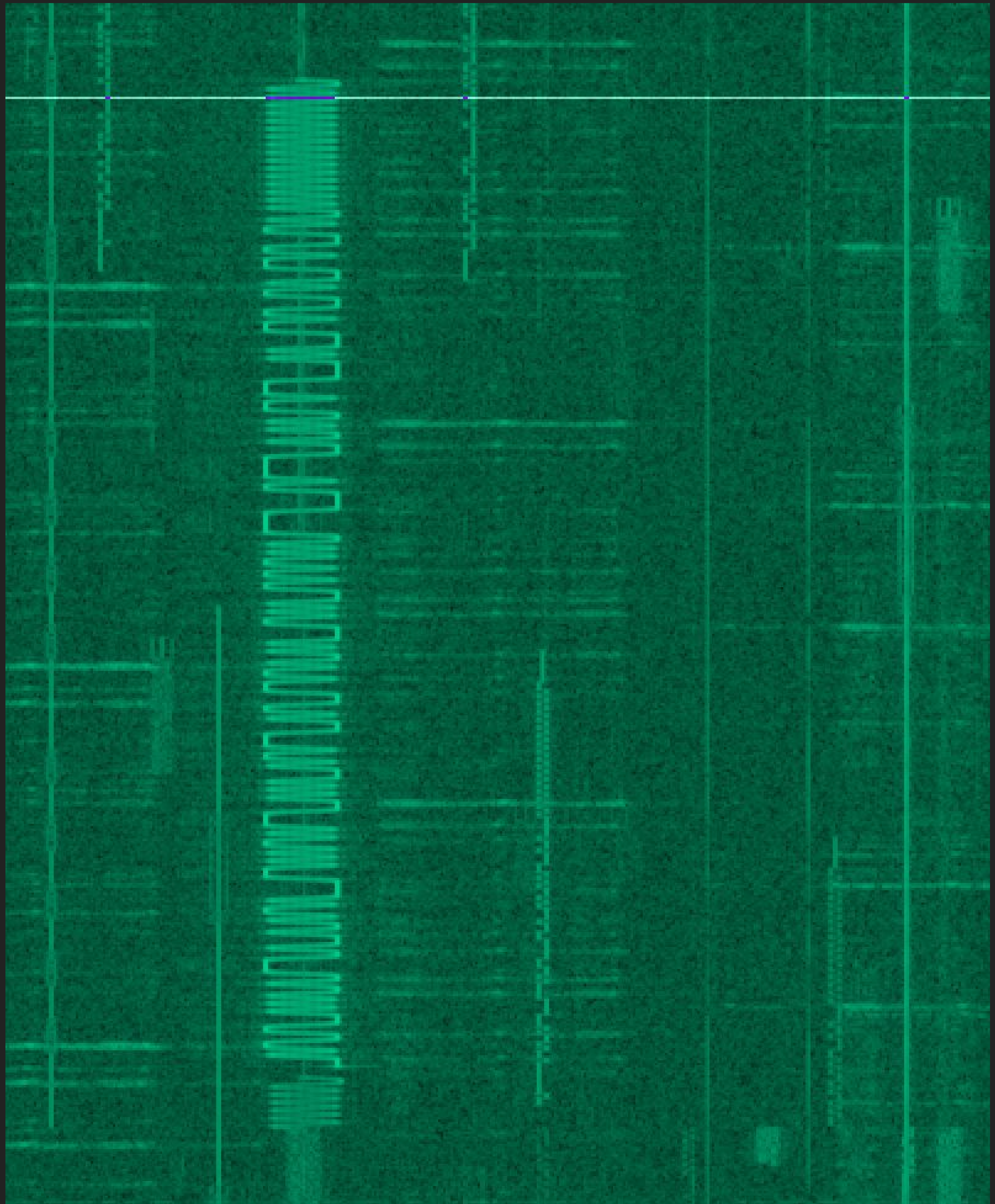
OSI Model

Data	*Layer*
Data	**Application** Network Process to Application
Data	**Presentation** Data Representation and Encryption
Data	**Session** Interhost Communication
Segments	**Transport** End-to-End Connections and Reliability
Packets	**Network** Path Determination and IP (Logical Addressing)
Frames	**Data Link** MAC and LLC (Physical Addressing)
Bits	**Physical** Media, Signal, and Binary Transmission

http://www.tech-faq.com/wp-content/uploads/2009/01/osimodel.png

WHAT IS RF?

- “One of the four fundamental forces of the universe” — Tom Rondeau, DARPA Program Manager, former GNU Radio lead
- “Radio Frequency”
- Electromagnetic waves
- Energy

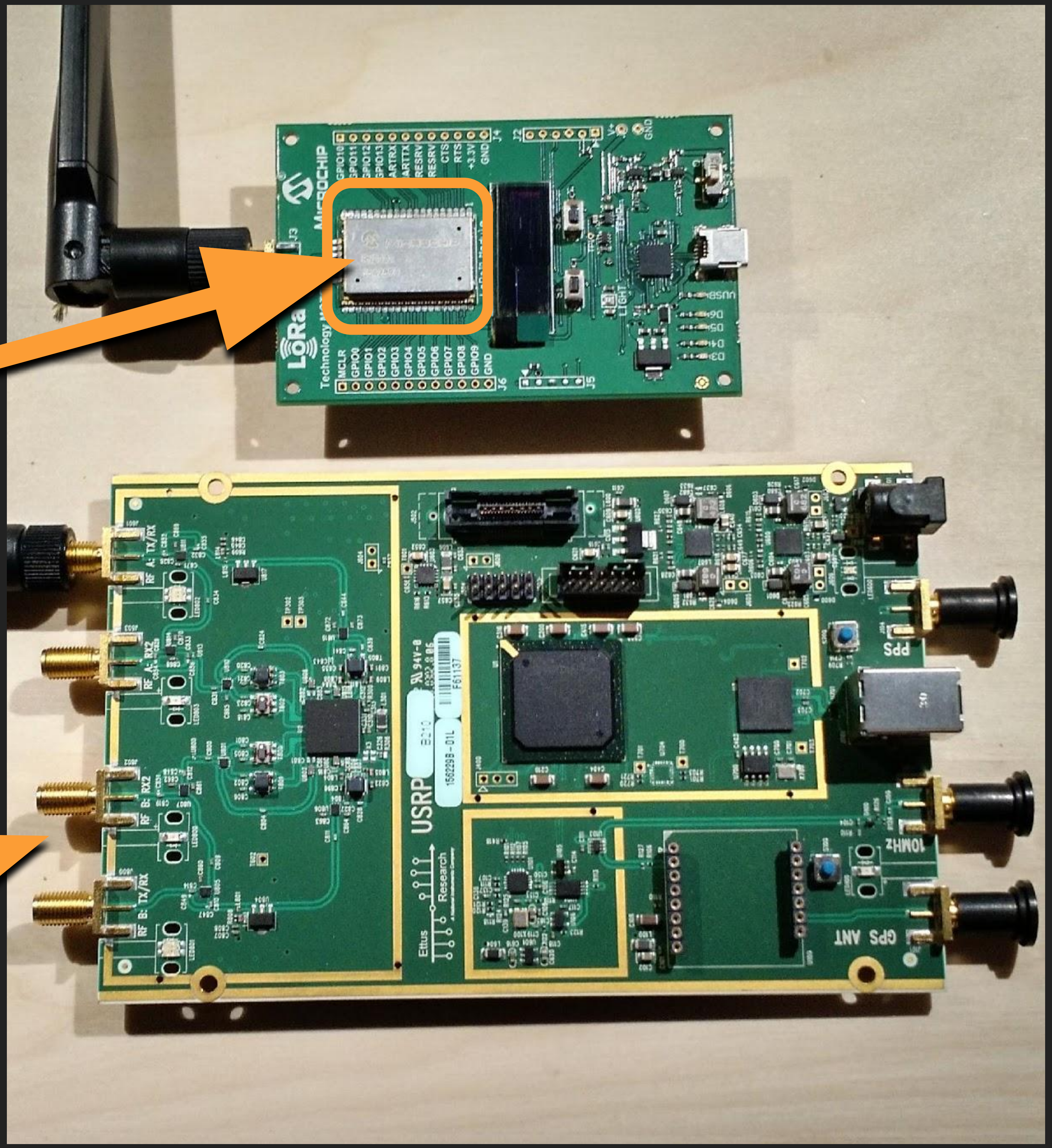


Spectrogram

a.k.a. “waterfall”

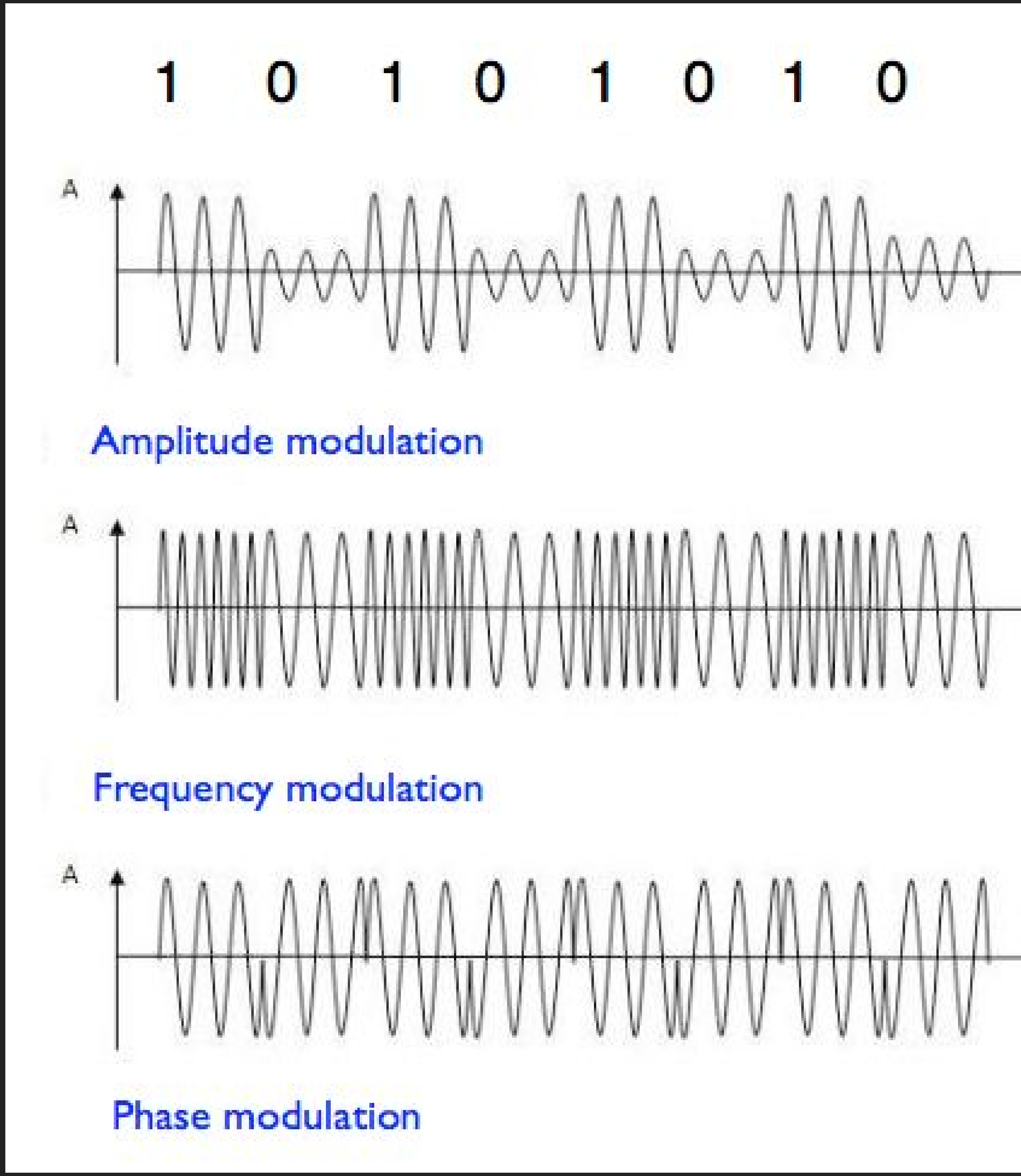
MANIPULATING RF

- Done with a radio
- Hardware defined
  - RF and protocol in silicon
- Software defined radio (SDR)
  - Flexible silicon handles RF
  - Protocol-specific components implemented in software (CPU or FPGA)



PHY COMPONENTS

- Modulation
  - How digital values are mapped to RF energy
- RF parameters that can be modulated:
  - Amplitude
  - Frequency
  - Phase
  - some combination of the above



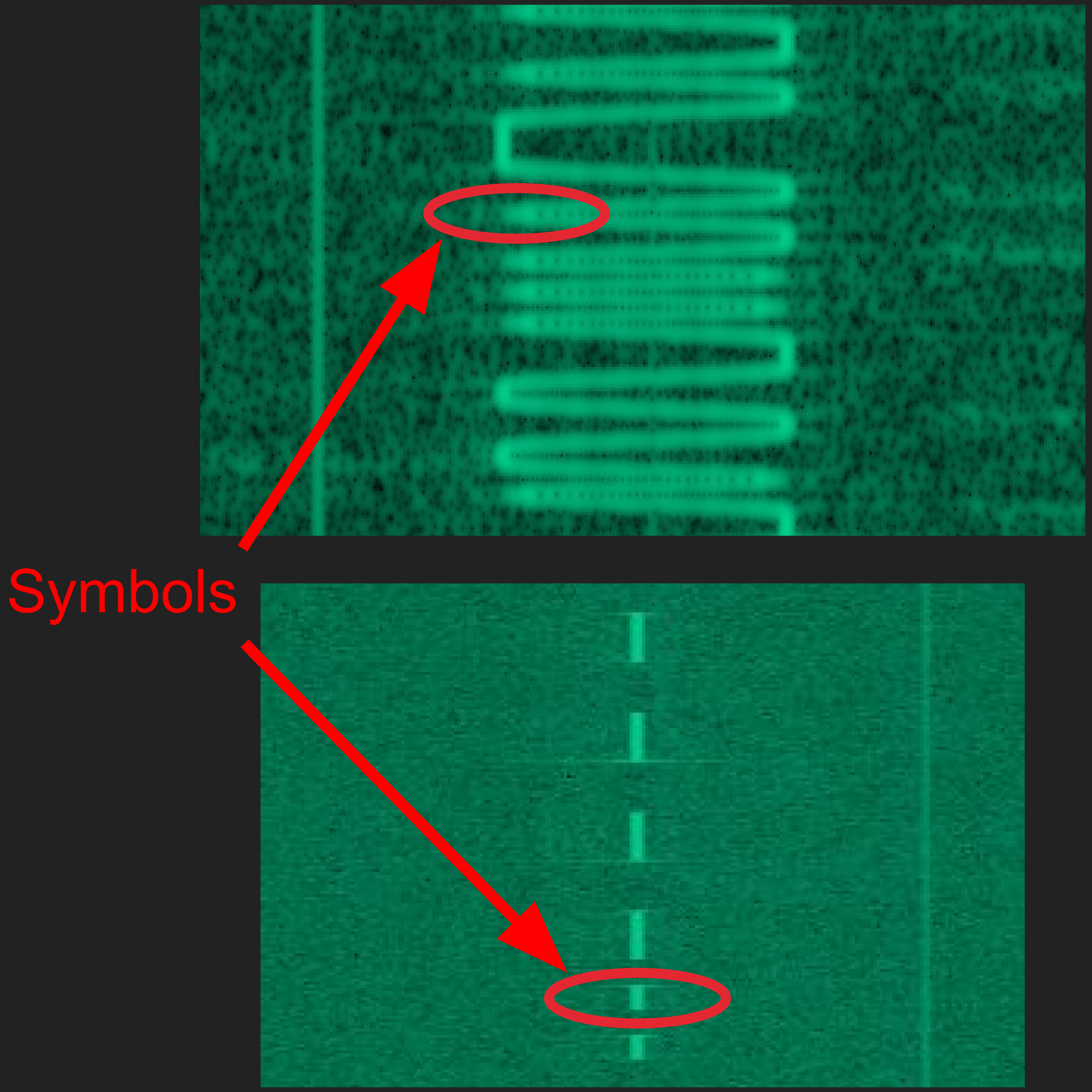
http://xenon.colorado.edu/spotlight/kb/gps_basics/modulations.001.png

MODULATION

- Modulators can modulate analog or digital information
- Digital modulation
  - Symbols: discrete RF energy state representing some quantity of information

COMMON IOT PHYS

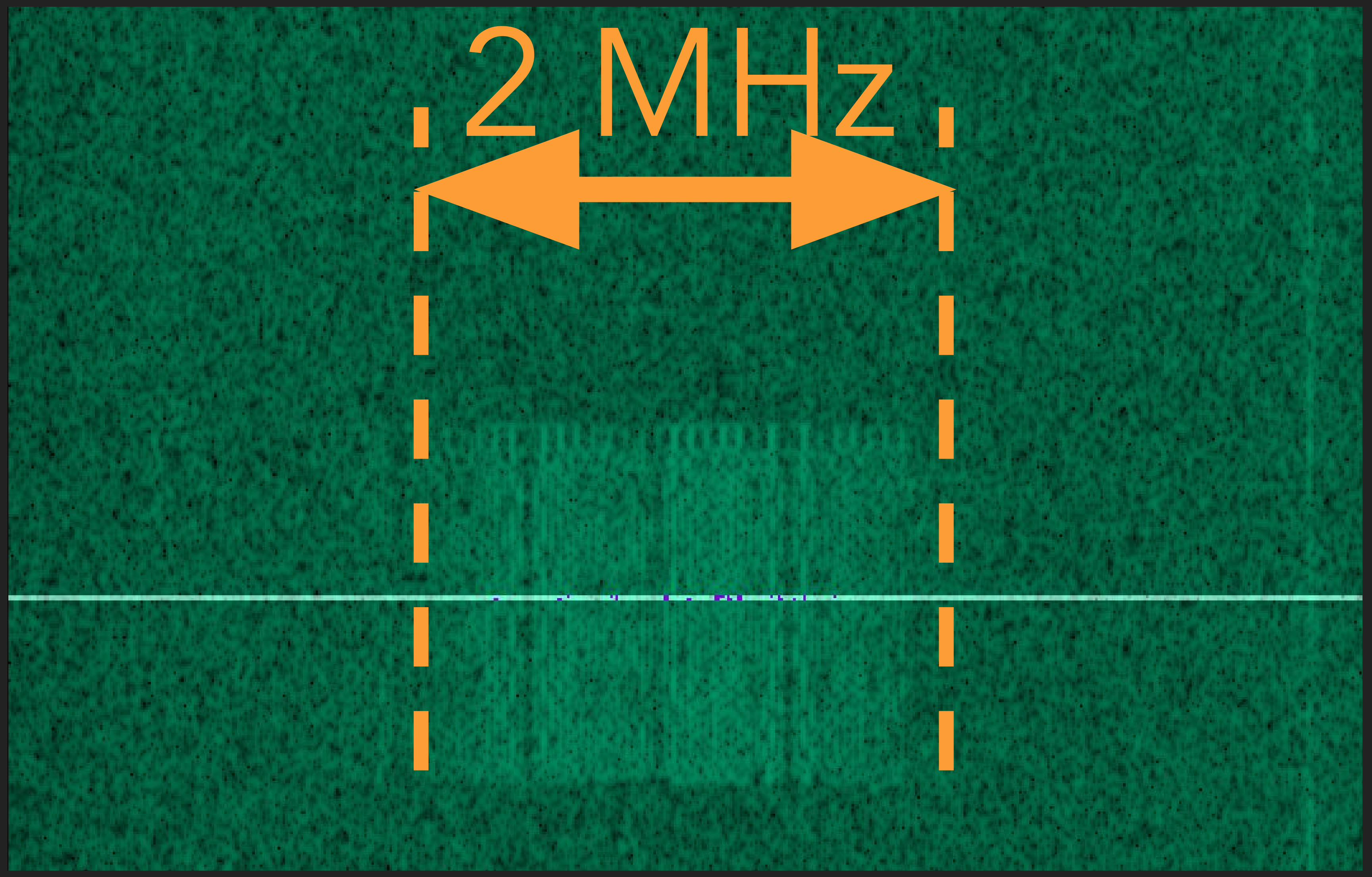
- Frequency Shift Keying: FSK, GFSK
    - RF energy alternates between two frequencies to signify digital values
- Amplitude Shift Keying: ASK, OOK
    - Changes in RF power on a certain frequency signify digital values

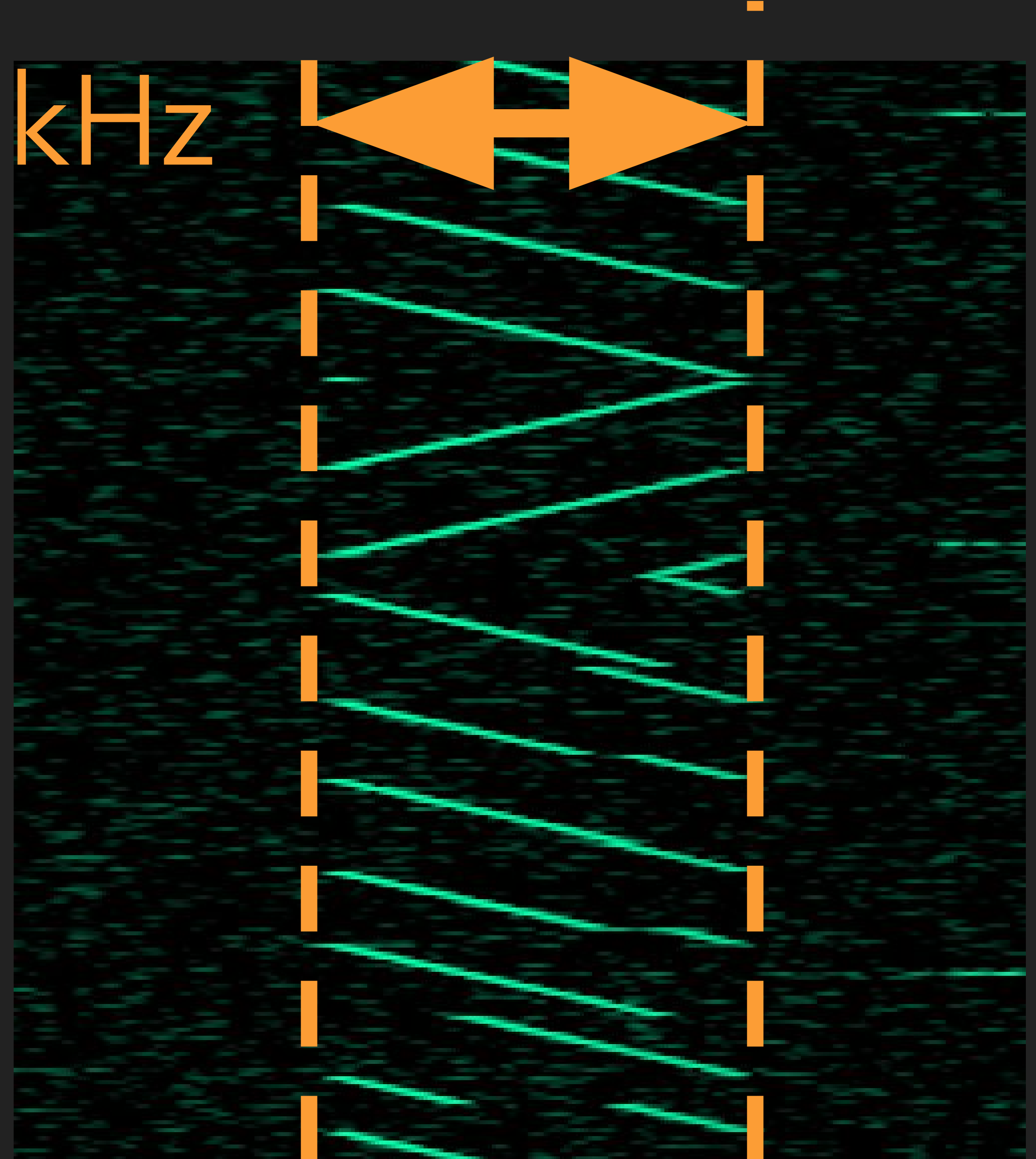


http://3.bp.blogspot.com/-w66qwKucSJI/UgWKKmPUP2I/AAAAAAAADYA/B9NMGYzqJVk/s1600/Screenshot-2013-08-03-04-41-52.png

MORE COMPLICATED IOT PHYS

- Spread spectrum
  - Data bits are encoded at a higher rate and occupy more spectrum
  - Resilient to RF noise
- Examples:
  - 802.15.4 (top)
  - LoRa (bottom)





RADIOS CONTINUED

- Radios can have two functions:
  - Transmitting
  - Receiving

- If a radio can do both it is dubbed a transceiver

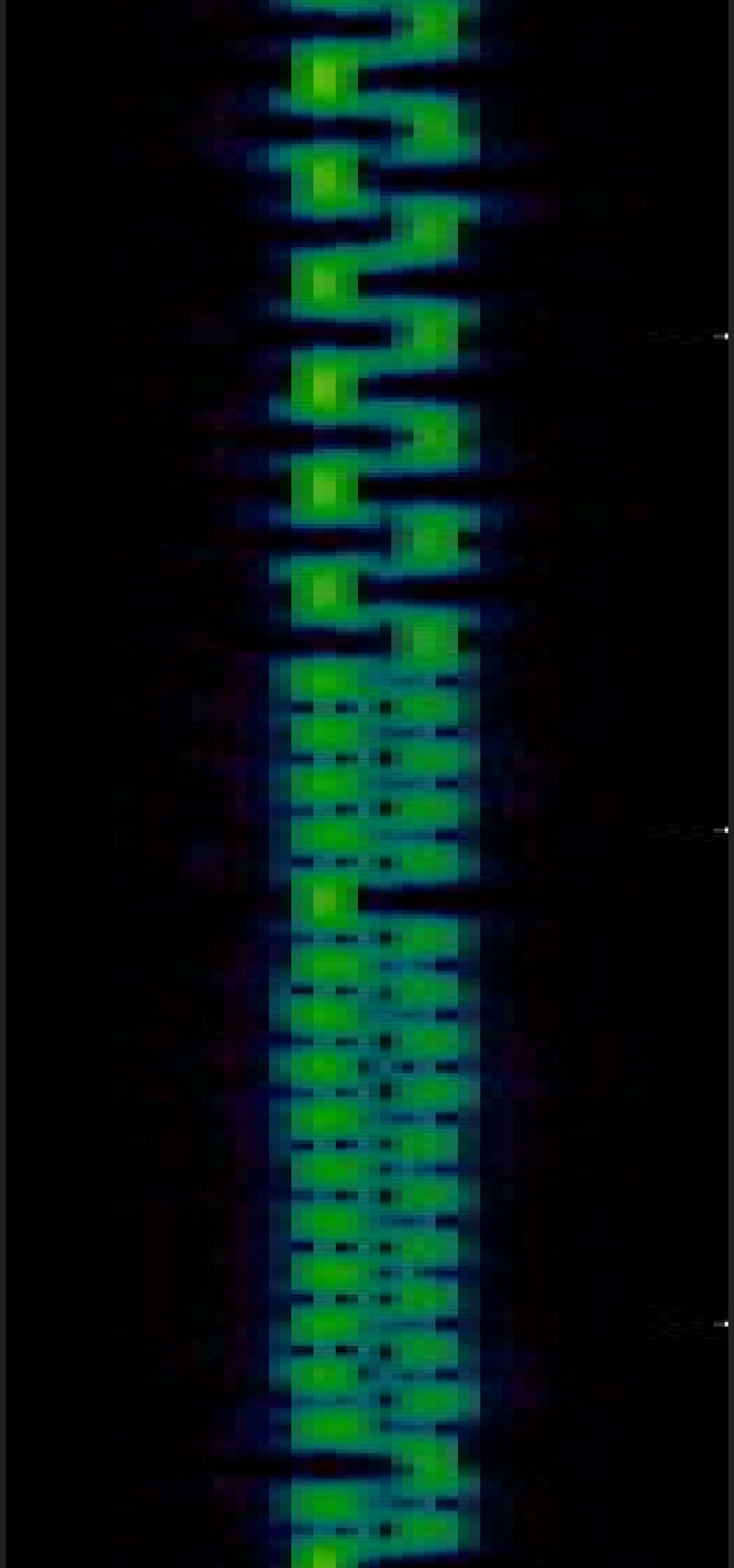
ON REVERSE ENGINEERING

- How does one reverse engineer an arbitrary wireless system?
- Main objective: figure out how data is mapped to symbols
- Reverse engineering boils down to building receivers

WIRELESS REVERSE ENGINEERING

METHODOLOGY

[INTERACTIVE]



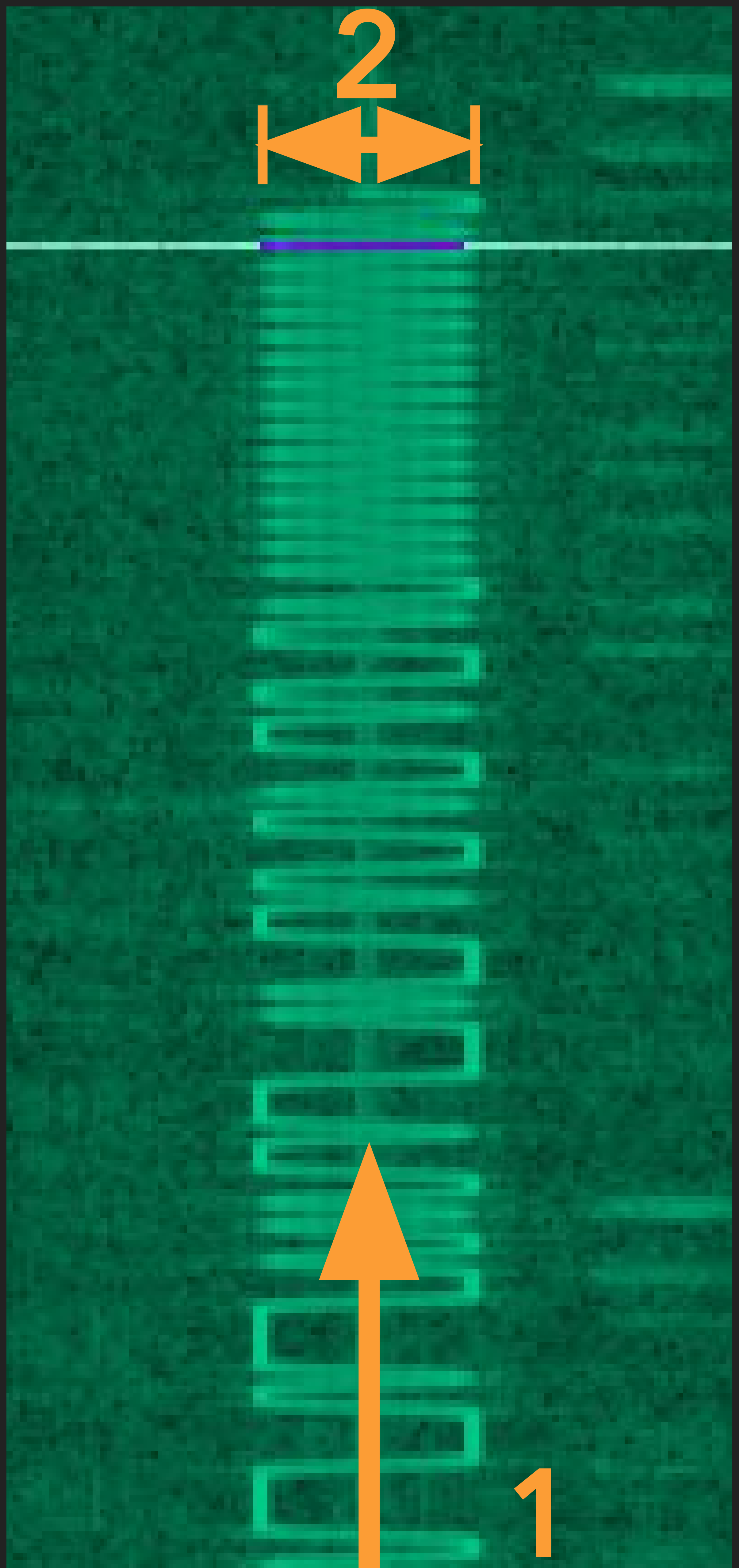
LET’S FORMALIZE THIS

RF REVERSE ENGINEERING METHODOLOGY

1. Characterize the channel

1. CHANNEL CHARACTERIZATION

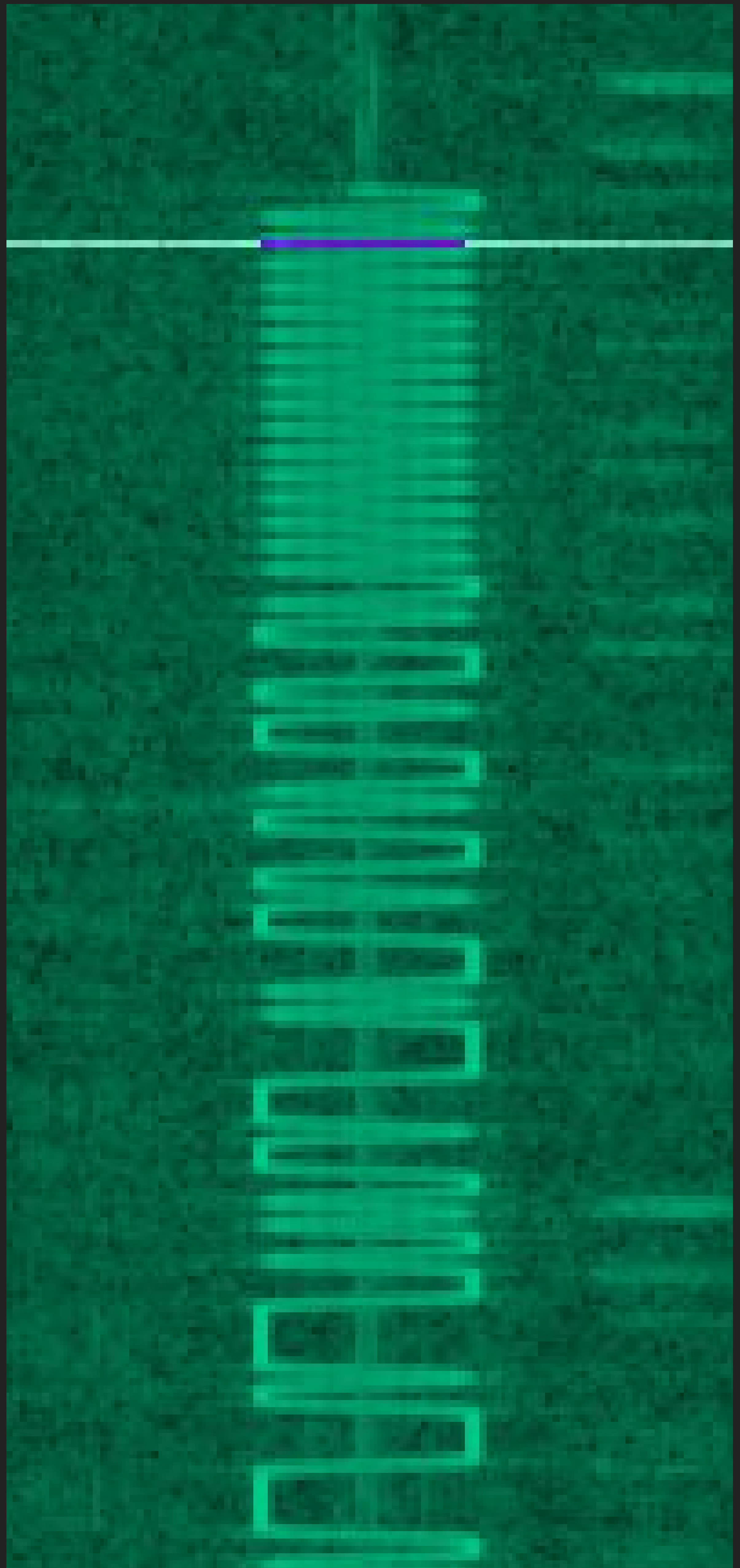
- Things to identify:
  1. Where on the spectrum is it? i.e. what is its Center Frequency?
  2. How wide is the channel? (kHz or MHz)
  3. Is the channel static or does it hop? If latter, what pattern/timing?



RF REVERSE ENGINEERING METHODOLOGY

1. Characterize the channel
2. Identify the modulation

2. IDENTIFY THE MODULATION



- Defines how data is mapped to RF energy
- This is the scariest part!
- …until you realize that most modulations are variations on a theme
- How to identify:
  1. OSINT/Documentation
  2. Intuition!

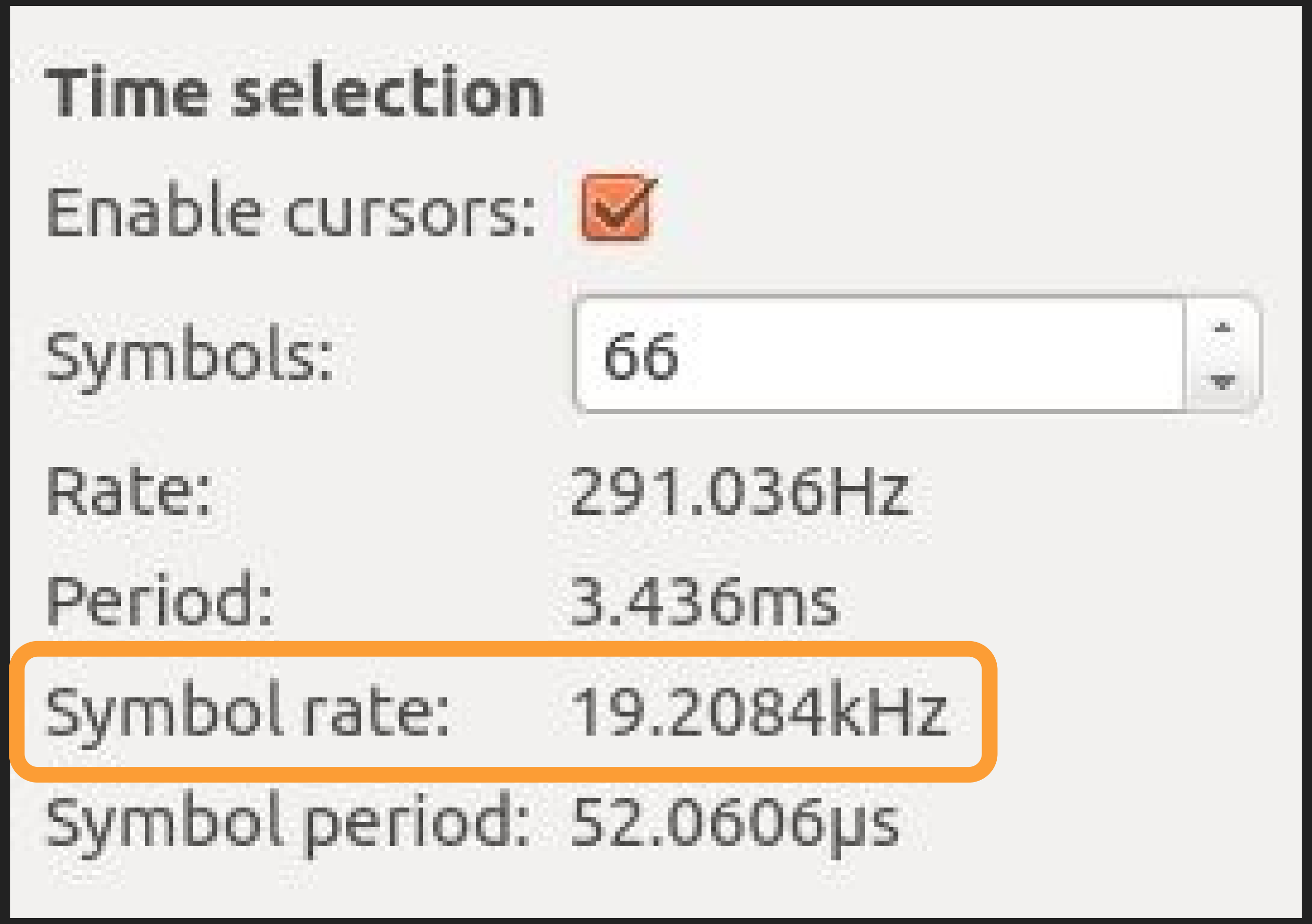
RF REVERSE ENGINEERING METHODOLOGY

1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate

3. DETERMINE SYMBOL RATE

- How often does the symbol state change?

- How to identify:
  - OSINT/Documentation
  - Measurement (Baudline, Inspectrum)



Time selection

Enable cursors: ☑

Symbols: 66

Rate: 291.036Hz

Period: 3.436ms

Symbol rate: 19.2084kHz

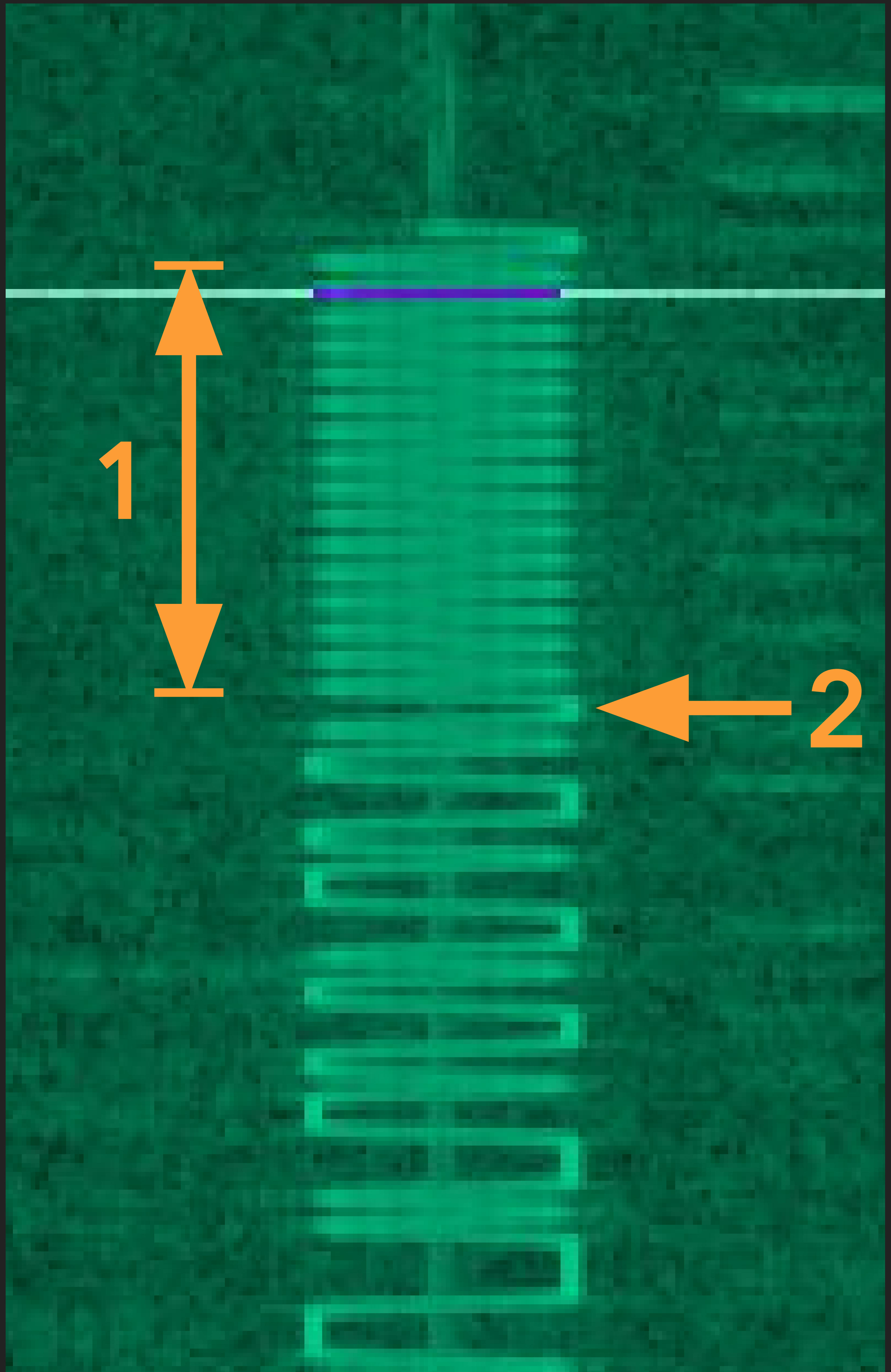
Symbol period: 52.0606μs

RF REVERSE ENGINEERING METHODOLOGY

1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate
4. Synchronize

4. SYNCHRONIZE

- Things to identify:
  1. **Preamble**: pattern that tells receivers "data to follow", clock recovery
  2. **Start of Frame Delimiter (SFD)**: tells receiver "preamble is over, data follows from here on out"
- These are present in essentially ALL digital communication schemes!



RF REVERSE ENGINEERING METHODOLOGY

1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate
4. Synchronize
5. Extract symbols

5. EXTRACT SYMBOLS

- De-map symbols into data based on the expected modulation topology
- Profit! (more on this later)

RF REVERSE ENGINEERING METHODOLOGY

1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate
4. Synchronize
5. Extract symbols

LET’S SEE IT IN ACTION

BUT FIRST

A word on

OPEN SOURCE INTELLIGENCE

OPEN SOURCE INTELLIGENCE (OSINT)

- Information gleaned from public sources:
  - FCC/regulatory filing documents
  - Technical documentation (datasheets, application notes)
  - Patents
  - etc.

- See Marc's prior talks on OSINT from FCC filings

RF REVERSE ENGINEERING METHODOLOGY

0. Open-source intelligence research
1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate
4. Synchronize
5. Extract symbols

Frequency Shift Keying

Z-WAVE

HOME AUTOMATION PROTOCOL

Z-WAVE HOME AUTOMATION SYSTEM

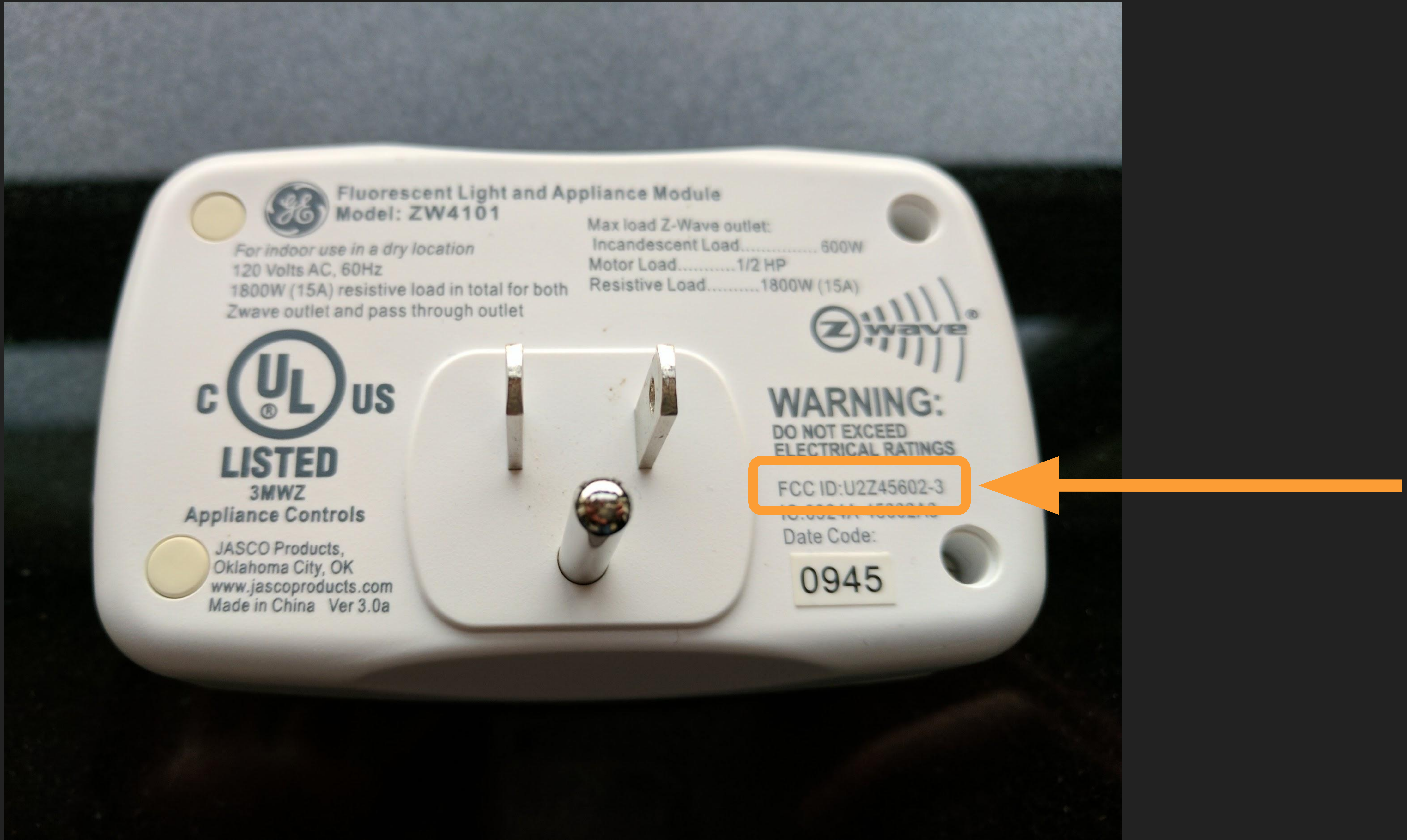
- Competes with ZigBee Home Automation cluster library
- Perfect example of a low-complexity IoT PHY

- Let’s build a PHY to enable analysis of the upper layers

Z-WAVE: RF REVERSE ENGINEERING METHODOLOGY

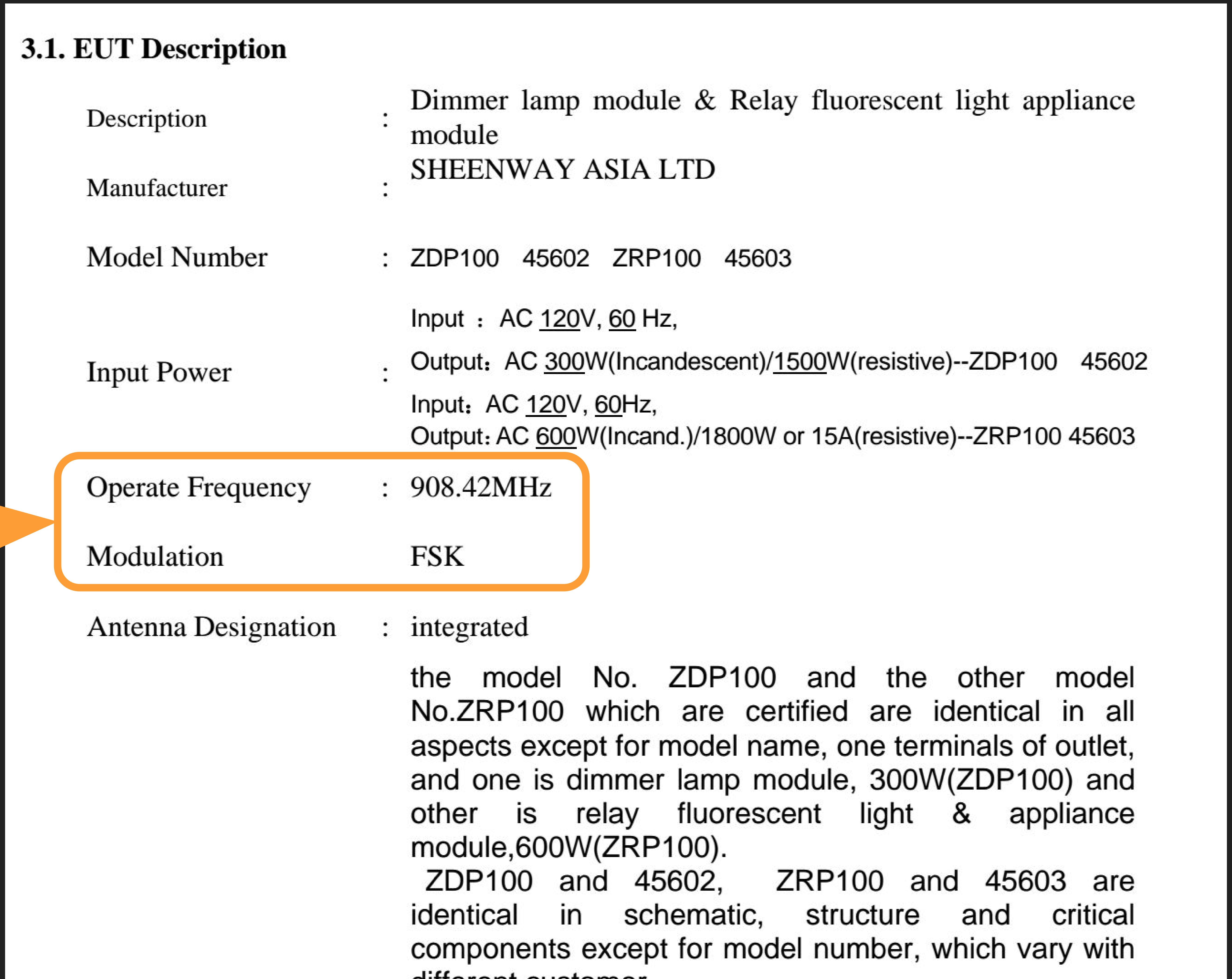
0. Open-source intelligence research
1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate
4. Synchronize
5. Extract symbols

Z-Wave Device FCCID



FCC ID U2Z45602-3 Test Photos

FCC Test Report EUT Description



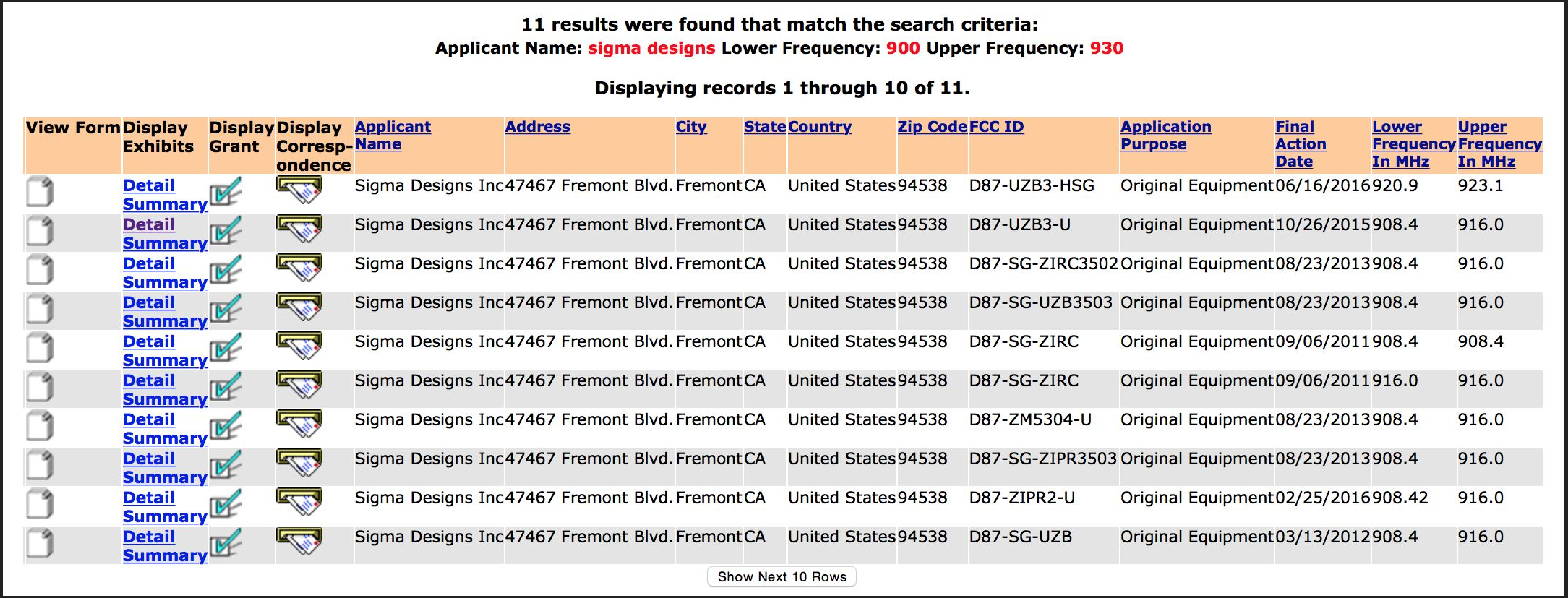
3.1. EUT Description

Description	:	Dimmer lamp module & Relay fluorescent light appliance module
Manufacturer	:	SHEENWAY ASIA LTD
Model Number	:	ZDP100 45602 ZRP100 45603
Input Power	:	Input ：AC 120V, 60 Hz, Output：AC 300W(Incandescent)/1500W(resistive)--ZDP100 45602 Input：AC 120V, 60Hz, Output：AC 600W(Incand.)/1800W or 15A(resistive)--ZRP100 45603
Operate Frequency	:	908.42MHz
Modulation		FSK
Antenna Designation	:	integrated
		the model No. ZDP100 and the other model No.ZRP100 which are certified are identical in all aspects except for model name, one terminals of outlet, and one is dimmer lamp module, 300W(ZDP100) and other is relay fluorescent light & appliance module,600W(ZRP100). ZDP100 and 45602, ZRP100 and 45603 are identical in schematic, structure and critical components except for model number, which vary with

Channel and modulation clues

Good start…
Let’s see what else we can find

FCC Reports from Z-Wave IC Manufacturer

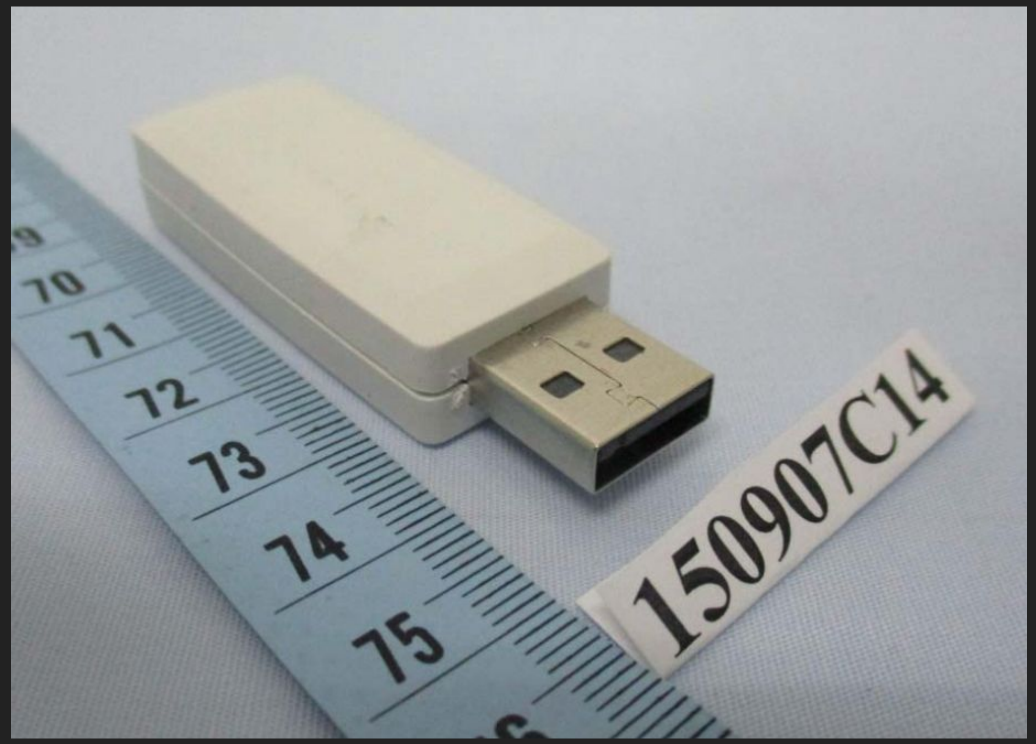


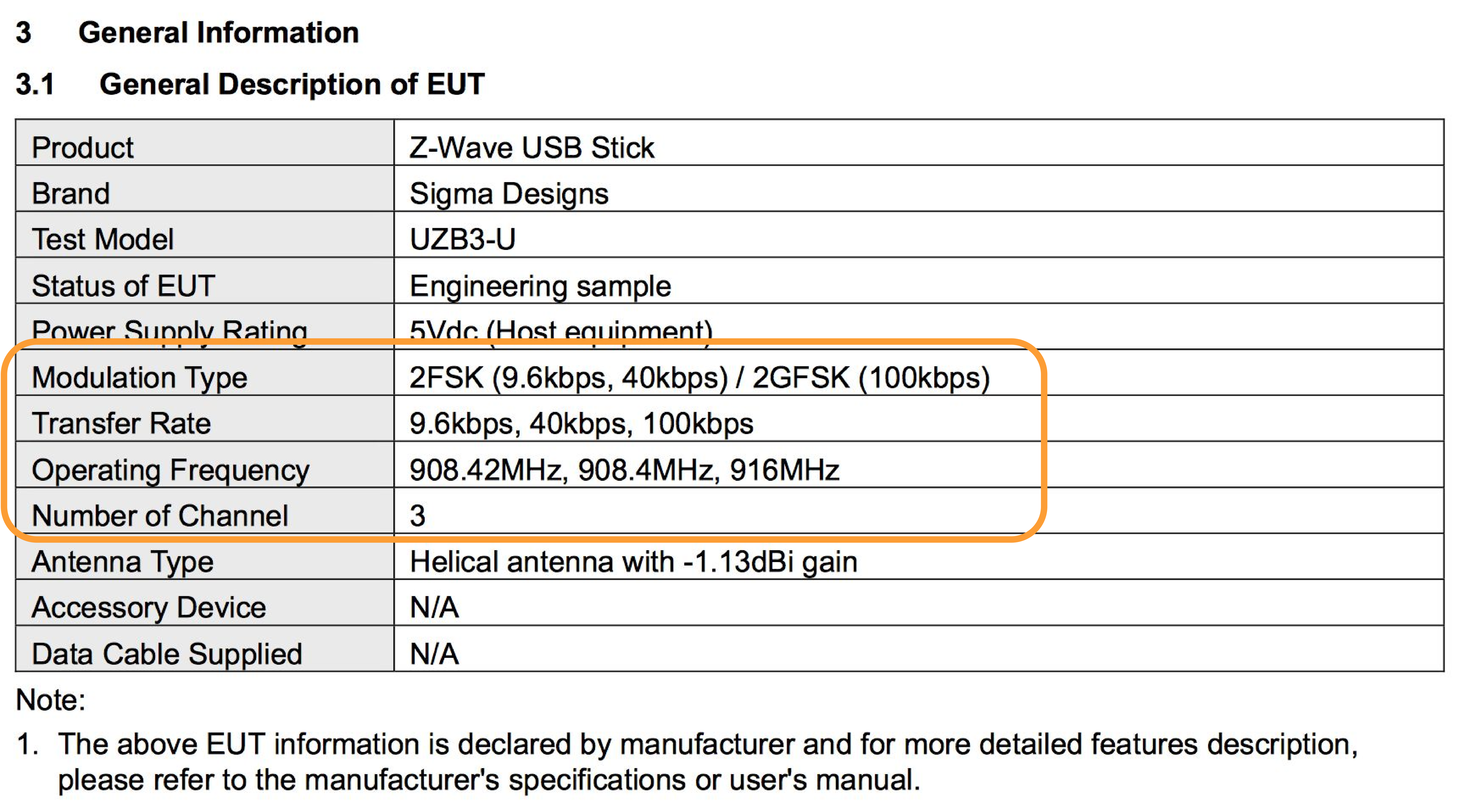
11 results were found that match the search criteria:
Applicant Name: sigma designs Lower Frequency: 900 Upper Frequency: 930

Displaying records 1 through 10 of 11.

View Form	Display Exhibits	Display Grant	Display Corresp-ondence	Applicant Name	Address	City	State	Country	Zip Code	FCC ID	Application Purpose	Final Action Date	Lower Frequency In MHz	Upper Frequency In MHz
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-UZB3-HSG	Original Equipment	06/16/2016	920.9	923.1
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-UZB3-U	Original Equipment	10/26/2015	908.4	916.0
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-SG-ZIRC3502	Original Equipment	08/23/2013	908.4	916.0
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-SG-UZB3503	Original Equipment	08/23/2013	908.4	916.0
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-SG-ZIRC	Original Equipment	09/06/2011	908.4	908.4
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-SG-ZIRC	Original Equipment	09/06/2011	916.0	916.0
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-ZM5304-U	Original Equipment	08/23/2013	908.4	916.0
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-SG-ZIPR3503	Original Equipment	08/23/2013	908.4	916.0
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-ZIPR2-U	Original Equipment	02/25/2016	908.42	916.0
	Detail Summary			Sigma Designs Inc	47467 Fremont Blvd.	Fremont	CA	United States	94538	D87-SG-UZB	Original Equipment	03/13/2012	908.4	916.0

Pick an arbitrary one





3 General Information

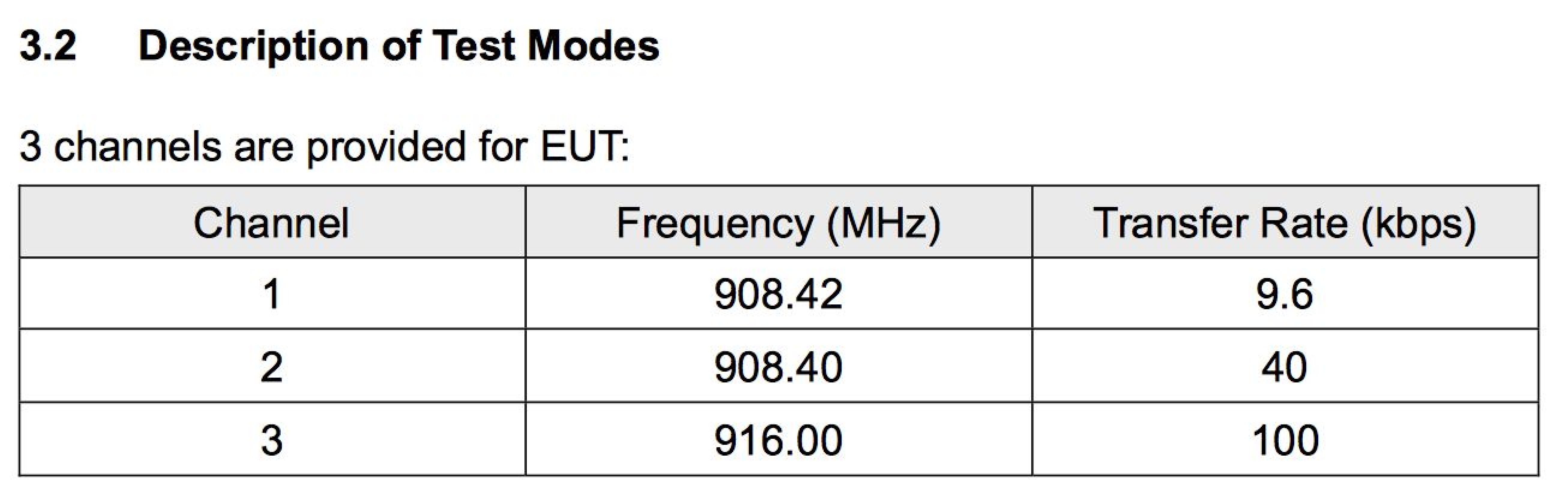
3.1 General Description of EUT

Product	Z-Wave USB Stick
Brand	Sigma Designs
Test Model	UZB3-U
Status of EUT	Engineering sample
Power Supply Rating	5Vdc (Host equipment)
Modulation Type	2FSK (9.6kbps, 40kbps) / 2GFSK (100kbps)
Transfer Rate	9.6kbps, 40kbps, 100kbps
Operating Frequency	908.42MHz, 908.4MHz, 916MHz
Number of Channel	3
Antenna Type	Helical antenna with -1.13dBi gain
Accessory Device	N/A
Data Cable Supplied	N/A

Note:

1. The above EUT information is declared by manufacturer and for more detailed features description, please refer to the manufacturer's specifications or user's manual.

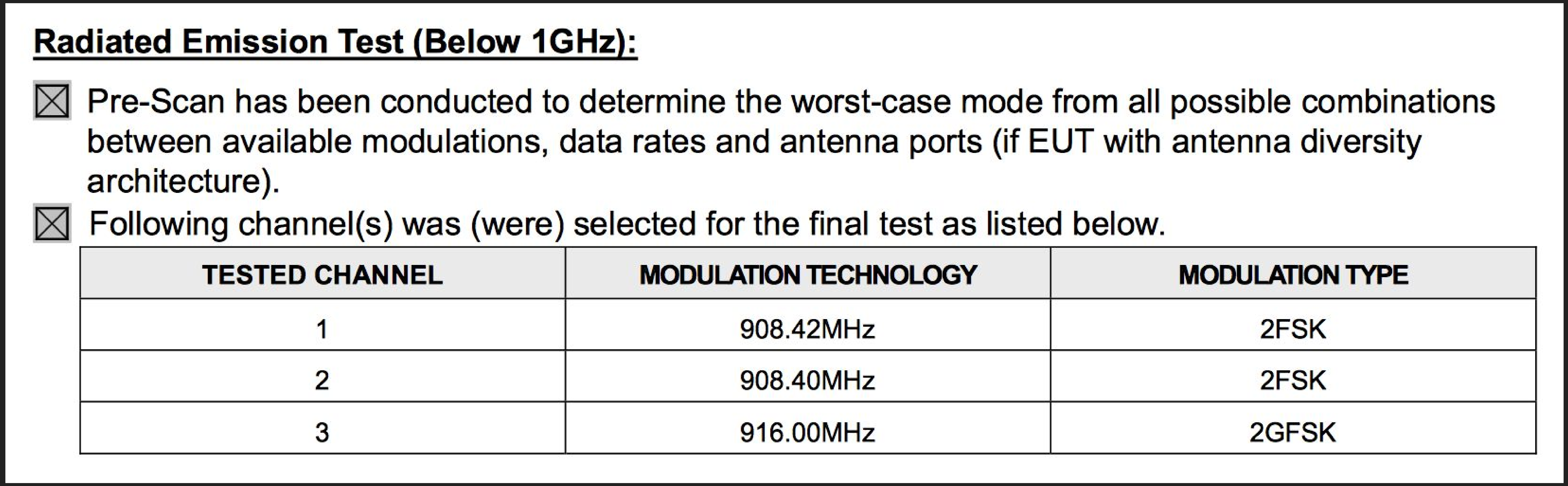
Z-Wave Channel Mapping



3.2 Description of Test Modes

3 channels are provided for EUT:

Channel	Frequency (MHz)	Transfer Rate (kbps)
1	908.42	9.6
2	908.40	40
3	916.00	100



Radiated Emission Test (Below 1GHz):

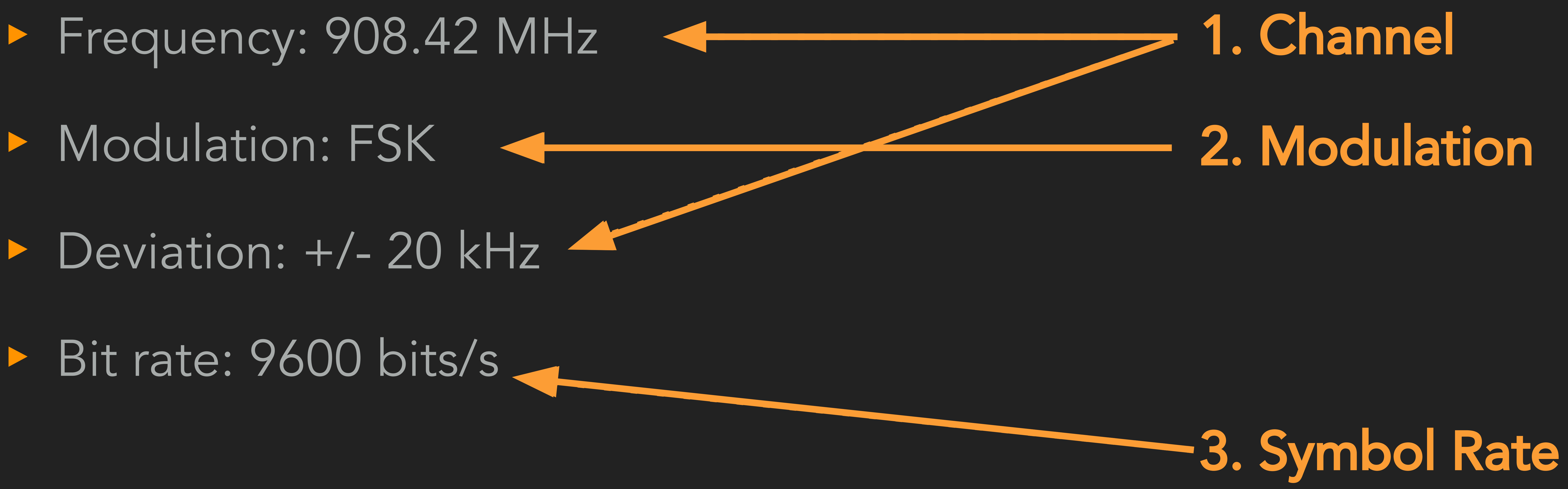
☒ Pre-Scan has been conducted to determine the worst-case mode from all possible combinations between available modulations, data rates and antenna ports (if EUT with antenna diversity architecture).

☒ Following channel(s) was (were) selected for the final test as listed below.

TESTED CHANNEL	MODULATION TECHNOLOGY	MODULATION TYPE
1	908.42MHz	2FSK
2	908.40MHz	2FSK
3	916.00MHz	2GFSK

0. OSINT

Looking at the 9.6 kbps @ 908.42 MHz channel



- Frequency: 908.42 MHz
- Modulation: FSK
- Deviation: +/- 20 kHz
- Bit rate: 9600 bits/s

1. Channel

2. Modulation

3. Symbol Rate

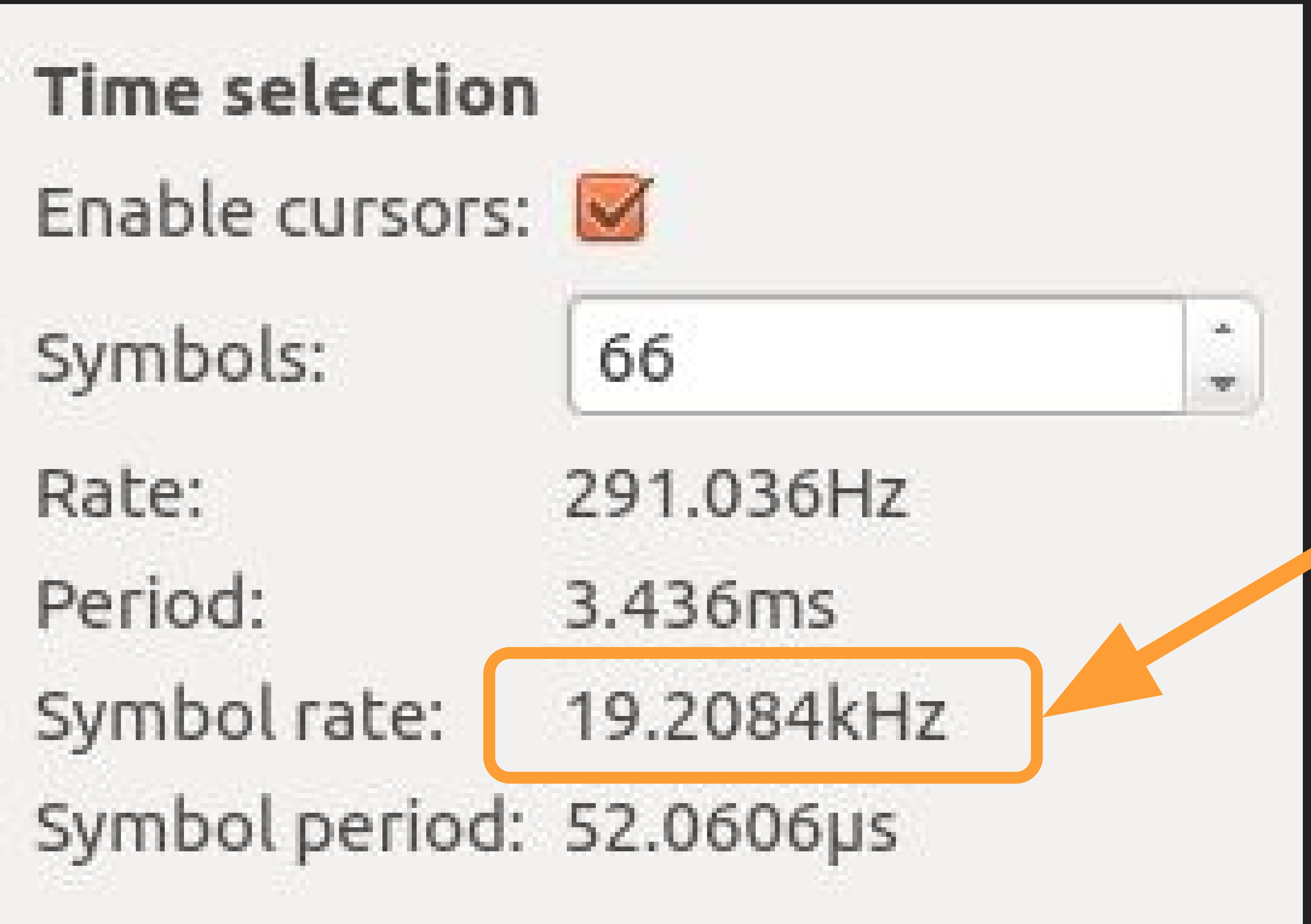
OSINT leads to clues for first 3 steps

Validating OSINT

- Frequency: 908.42 MHz → Measure center frequency
- Modulation: FSK → Visually confirm
- Deviation: +/- 20 kHz → Measure width of channel
- Bit rate: 9600 bits/s → Measure symbol timing

Validating Symbol Rate

Inspectrum



Time selection

Enable cursors: ☑

Symbols: 66

Rate: 291.036Hz

Period: 3.436ms

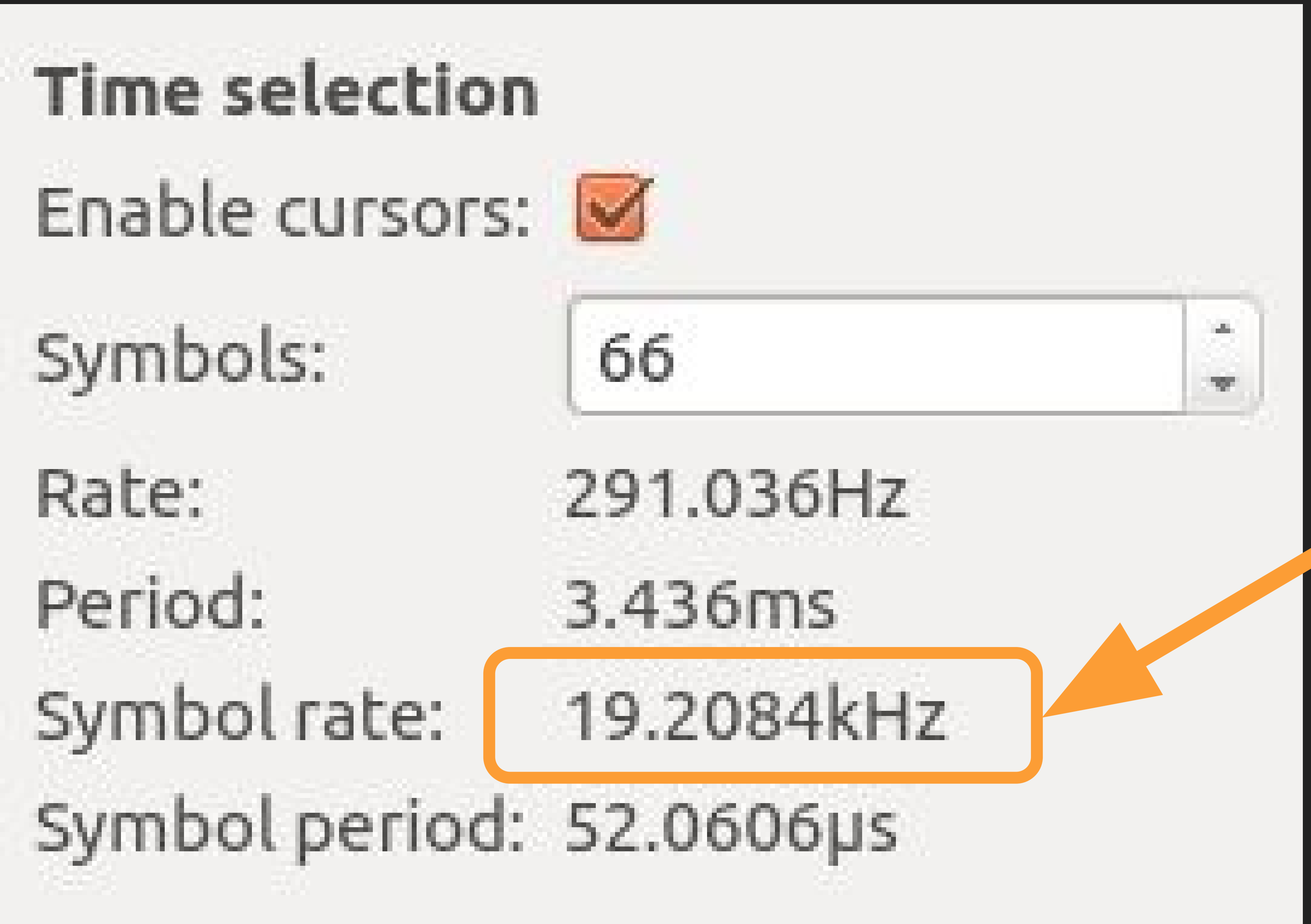
Symbol rate: 19.2084kHz

Symbol period: 52.0606μs

2x expected bit rate (9600 bits/s)

Validating Symbol Rate

Inspectrum



Time selection

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Symbols: 66

Rate: 291.036Hz

Period: 3.436ms

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2x expected bit rate (9600 bits/s)

Manchester encoding!

Manchester Encoding

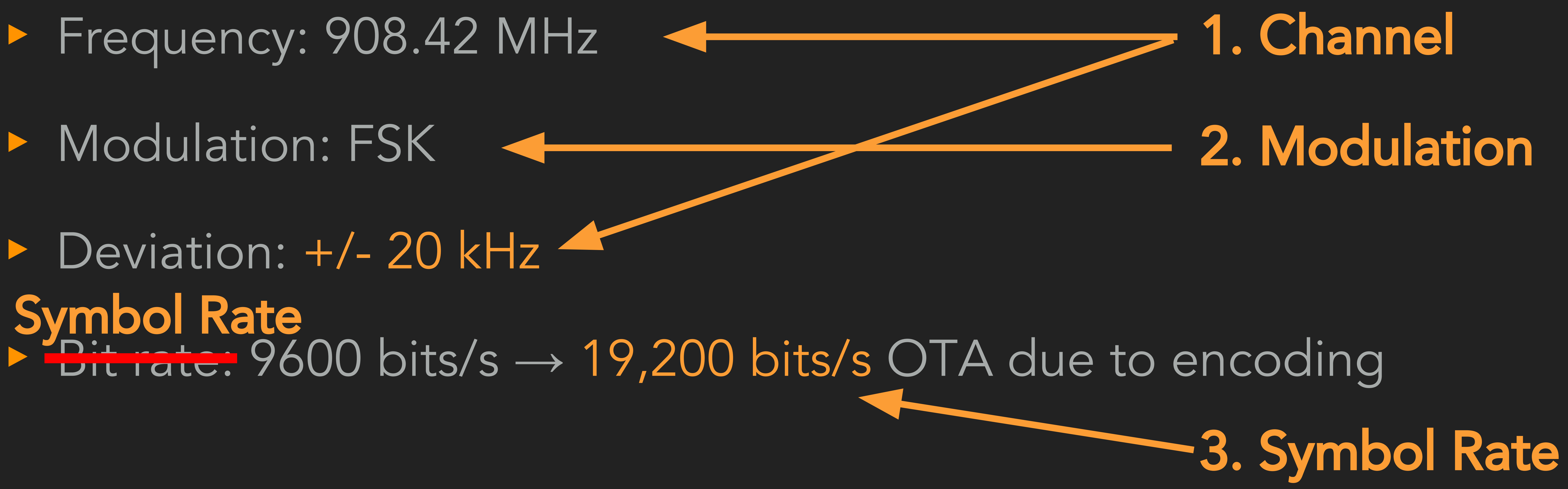
Data Bits (un-encoded)	**Manchester Bits (encoded)**
0b0	0b01
0b1	0b10
(illegal state)	0b00
(illegal state)	0b11

Result: encoded bitstream has no more than 2 adjacent symbols with the same value
0b0000 → 0b01010101
0b1111 → 0b10101010

Benefit: lots of symbol changes for receivers to perform clock recovery/synchronization against

Cost: restricts bit rate to ½ baud rate (symbol rate)

0. OSINT



- Frequency: 908.42 MHz
- Modulation: FSK
- Deviation: +/- 20 kHz

Symbol Rate

- ~~Bit rate:~~ 9600 bits/s → 19,200 bits/s OTA due to encoding

1. Channel

2. Modulation

3. Symbol Rate

Z-WAVE: RF REVERSE ENGINEERING METHODOLOGY

0. ✓ Open-source intelligence research
1. ✓ Characterize the channel
2. ✓ Identify the modulation
3. ✓ Determine the symbol rate
4. Synchronize
5. Extract symbols

GNU Radio Flowgraph to produce a stream of symbols

Python scripting to parse symbols into data

Translate OSINT into GNU Radio Flowgraph

Options
ID: top_block
Generate Options: WX GUI

Import
Import: math

Note
Note: 9.6 kHz channel

Variable
ID: samp_rate
Value: 1M

Variable
ID: resamp_rate_9600
Value: 614.4k

Note
Note: 'freq' i...-target freq

Variable
ID: freq
Value: 908.3M

Variable
ID: offset_9600
Value: -120k

Note
Note: 'deviati...NT research.

Variable
ID: deviation
Value: 20k

Variable
ID: symbol_rate_9600
Value: 19.2k

UHD: USRP Source
Device Arguments: nu...e=4096
Samp Rate (Sps): 1M
Ch0: Center Freq (Hz): 908.3M
Ch0: Gain Value: 0
Ch0: Antenna: TX/RX

Note
Note: The 'rot... FSK signal.

Rotator
Phase Increment: -753.982m

Polyphase Arbitrary Resampler
Resampling Rate: 614.4m
Taps:
Number of Filters: 32
Stop-band Attenuation: 100

Low Pass Filter
Decimation: 1
Gain: 1
Sample Rate: 614.4k
Cutoff Freq: 40k
Transition Width: 10k
Window: Hamming
Beta: 6.76

Note: 'Clock R...oversampled.

Note
Note: The 'Qua...INT sources.

Quadrature Demod
Gain: 39.1139

Clock Recovery MM
Omega: 32
Gain Omega: 7.65625m
Mu: 500m
Gain Mu: 175m
Omega Relative Limit: 10m

Binary Slicer

File Sink
File: /mnt/ramdisk/z9600.fifo
Unbuffered: On
Append file: Append

1. Channel

2. Demodulation

3. Symbol Rate

4. Synchronization and 5. Symbol Extraction

1. Look for preamble
2. Look for SFD to synchronize
3. Read out frame and de-Manchester. Frame length determined by:
   a. Preconfigured MTU size
   b. Power squelch (FSK is constant envelope)
   c. Decoding failure (i.e. Manchester decoding hits an illegal state)
   d. Decoded length field
4. Parse frame

Demo Time!

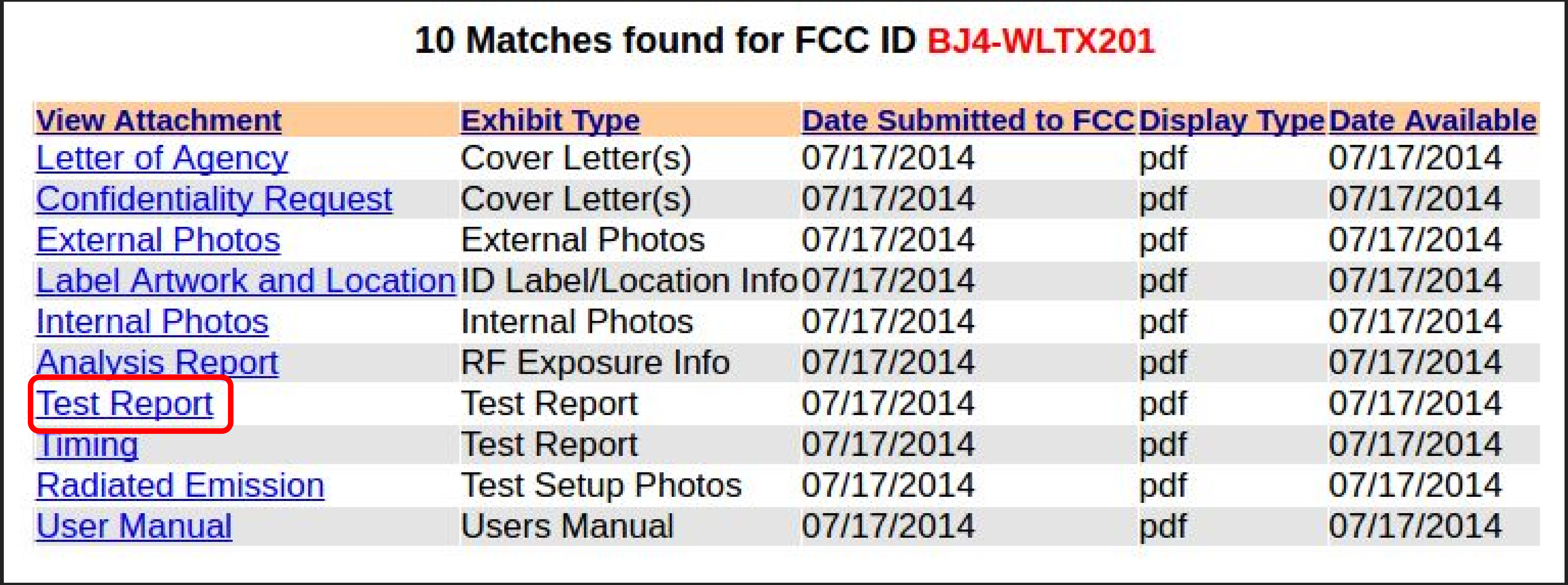
On-Off Keying / Pulse-Width Modulation

WIRELESS DOORBELL

HeathZenith SL-7762

- Wireless Doorbell
  - Battery operated
  - Two transmitters (buttons)
    - FCC ID BJ4-WLTX201
  - One receiver (chime)
    - Receive-only, no FCC ID

DOORBELL FCC EXHIBITS

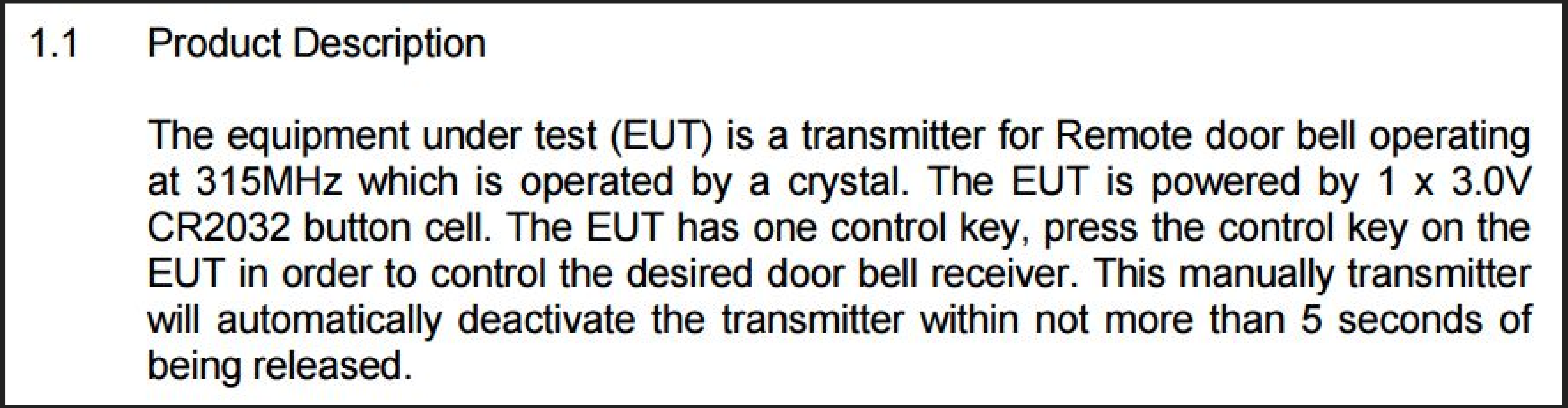


10 Matches found for FCC ID BJ4-WLTX201

View Attachment	Exhibit Type	Date Submitted to FCC	Display Type	Date Available
Letter of Agency	Cover Letter(s)	07/17/2014	pdf	07/17/2014
Confidentiality Request	Cover Letter(s)	07/17/2014	pdf	07/17/2014
External Photos	External Photos	07/17/2014	pdf	07/17/2014
Label Artwork and Location	ID Label/Location Info	07/17/2014	pdf	07/17/2014
Internal Photos	Internal Photos	07/17/2014	pdf	07/17/2014
Analysis Report	RF Exposure Info	07/17/2014	pdf	07/17/2014
Test Report	Test Report	07/17/2014	pdf	07/17/2014
Timing	Test Report	07/17/2014	pdf	07/17/2014
Radiated Emission	Test Setup Photos	07/17/2014	pdf	07/17/2014
User Manual	Users Manual	07/17/2014	pdf	07/17/2014

DOORBELL FCC TEST REPORT

- 315MHz center frequency



1.1 Product Description

The equipment under test (EUT) is a transmitter for Remote door bell operating at 315MHz which is operated by a crystal. The EUT is powered by 1 x 3.0V CR2032 button cell. The EUT has one control key, press the control key on the EUT in order to control the desired door bell receiver. This manually transmitter will automatically deactivate the transmitter within not more than 5 seconds of being released.

DOORBELL FCC TEST REPORT

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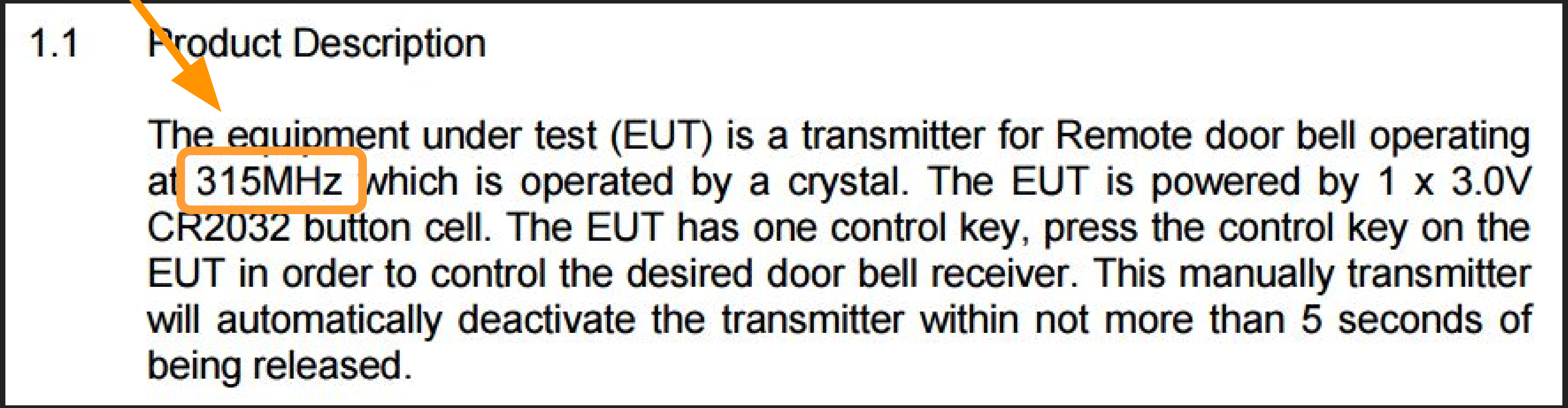

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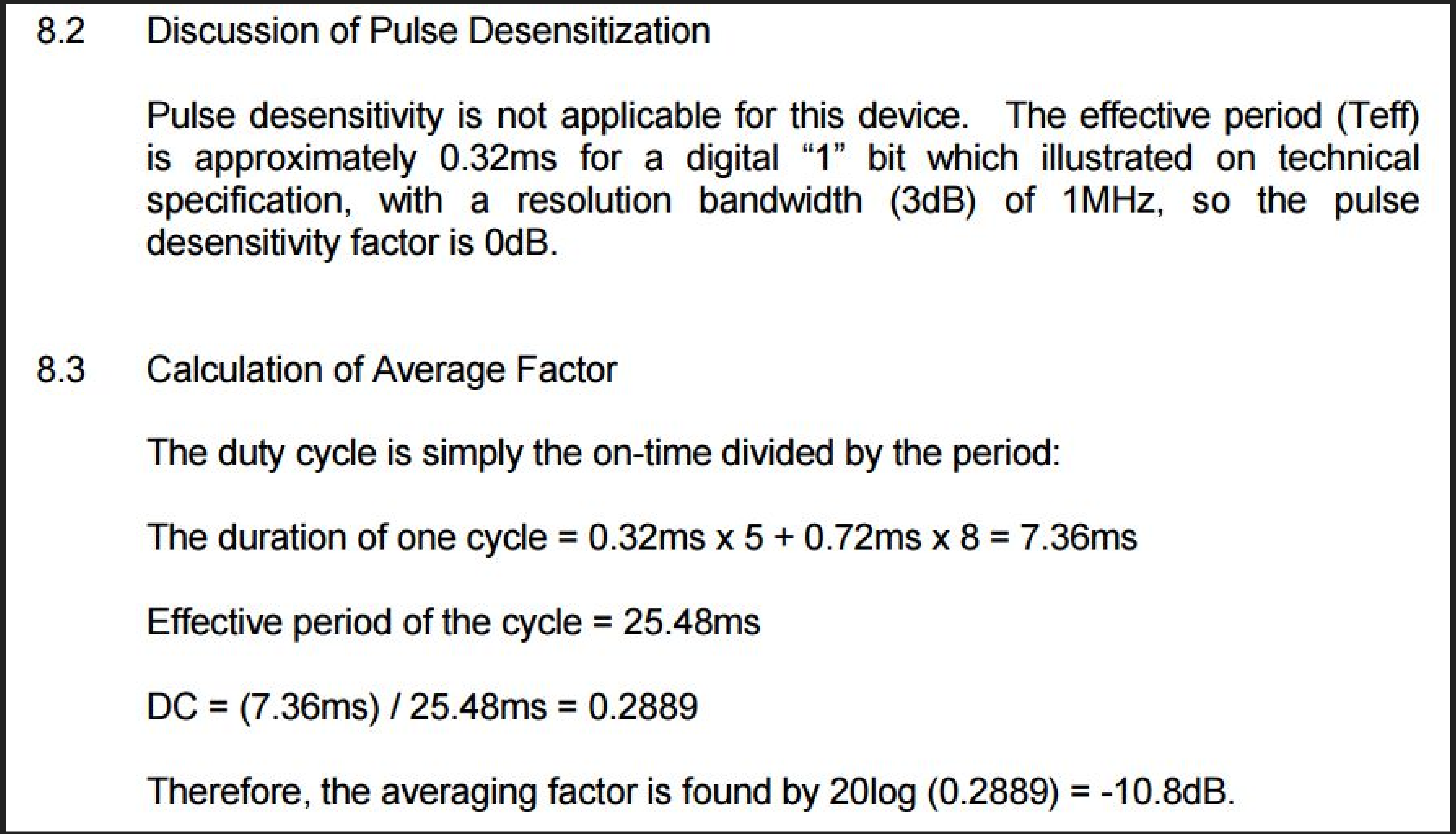
DOORBELL FCC TEST REPORT

- 320us duration bit 1
- 13 bits per packet
- 25.48ms packet spacing
- ~30% duty cycle



8.2 Discussion of Pulse Desensitization

Pulse desensitivity is not applicable for this device. The effective period (Teff) is approximately 0.32ms for a digital “1” bit which illustrated on technical specification, with a resolution bandwidth (3dB) of 1MHz, so the pulse desensitivity factor is 0dB.

8.3 Calculation of Average Factor

The duty cycle is simply the on-time divided by the period:

The duration of one cycle = 0.32ms x 5 + 0.72ms x 8 = 7.36ms

Effective period of the cycle = 25.48ms

DC = (7.36ms) / 25.48ms = 0.2889

Therefore, the averaging factor is found by 20log (0.2889) = -10.8dB.

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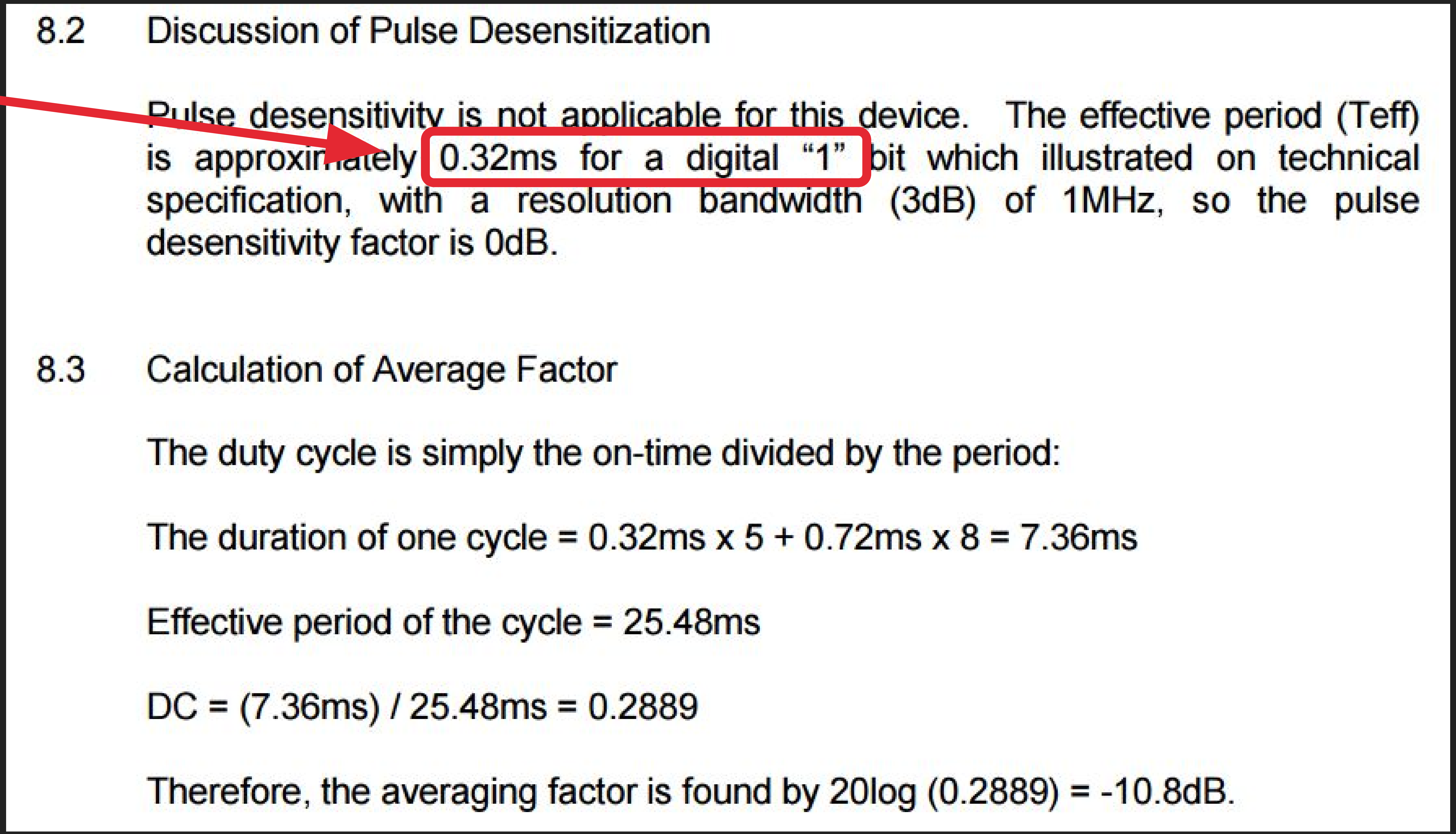

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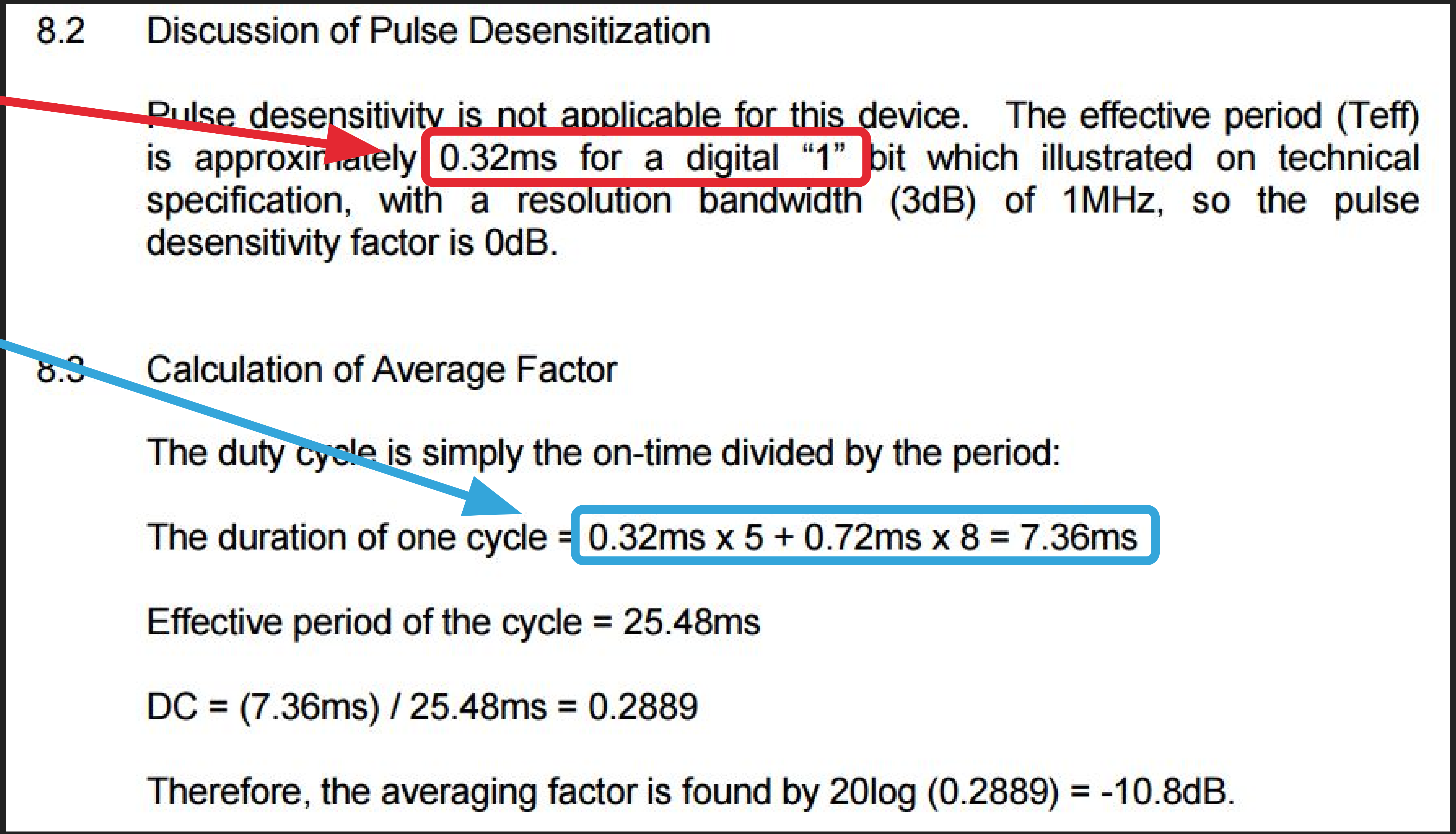

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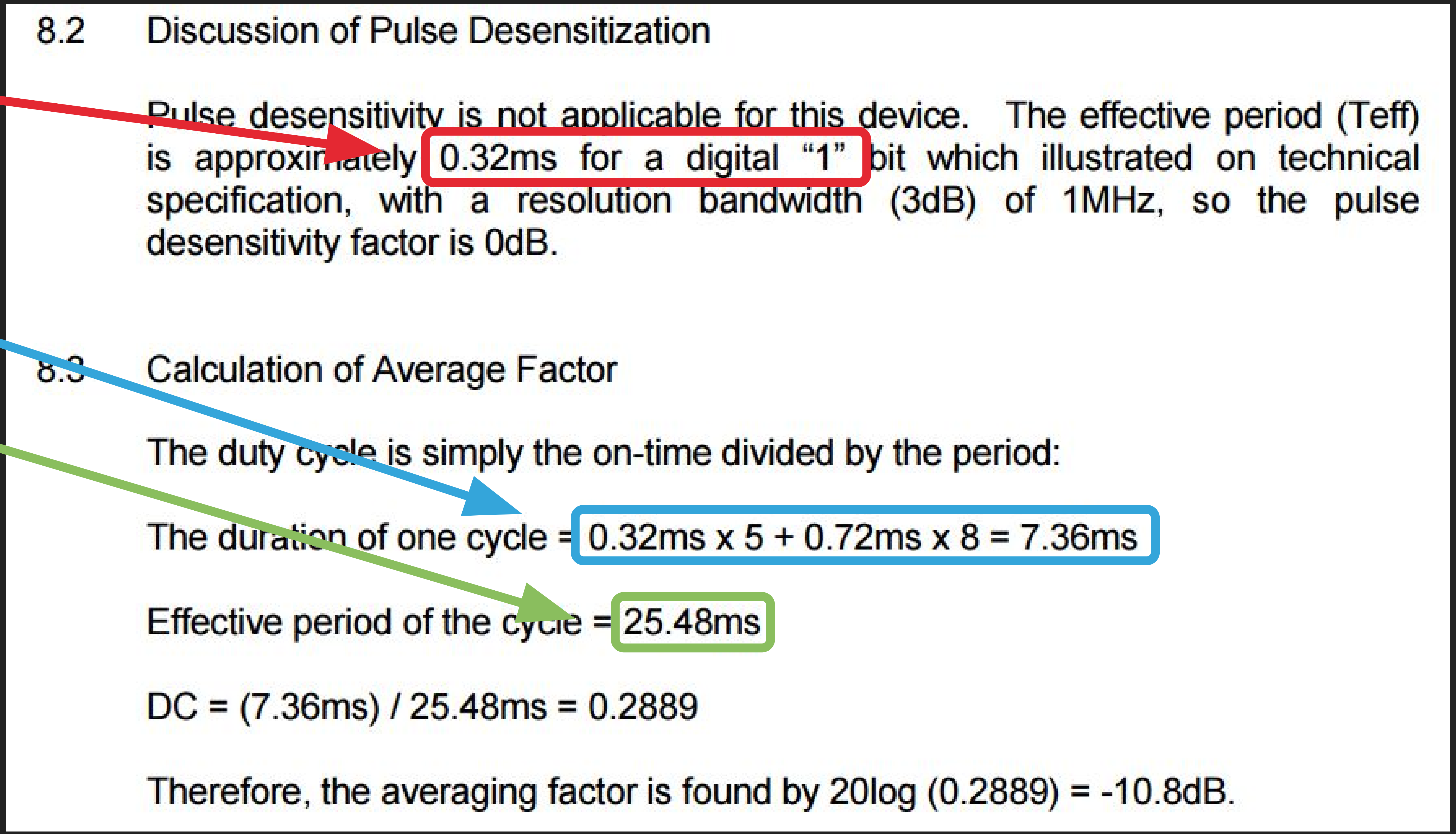

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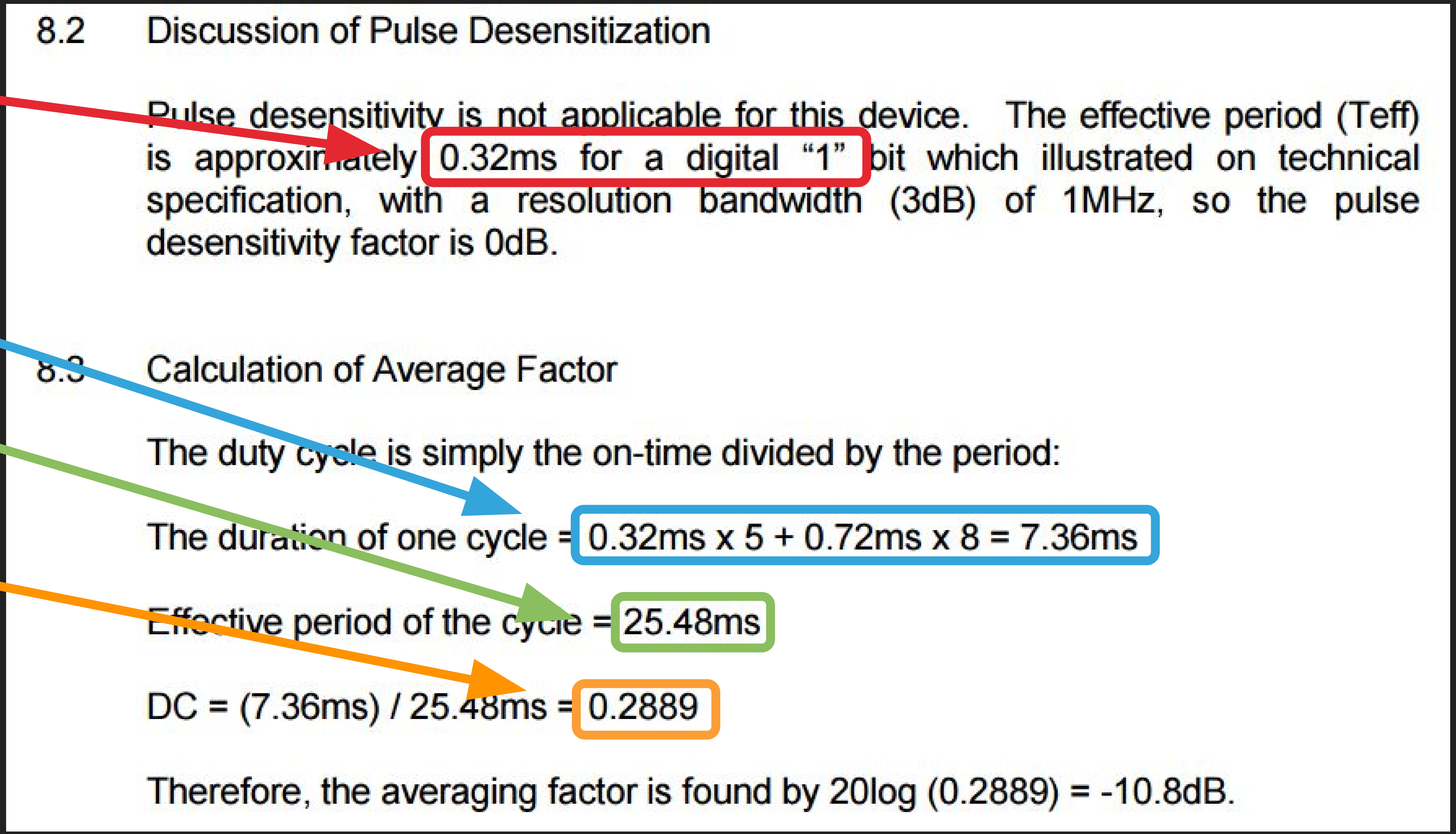

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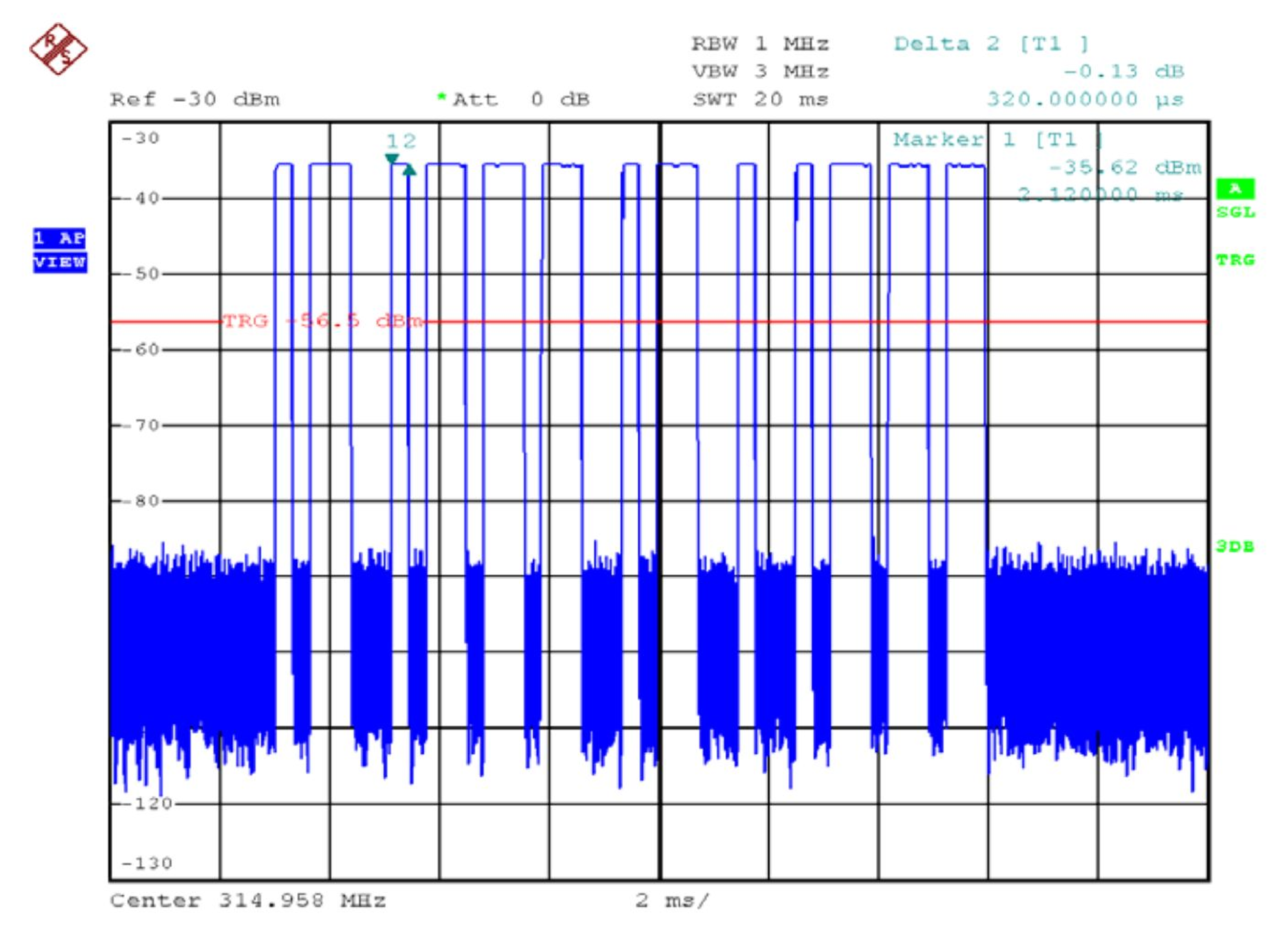
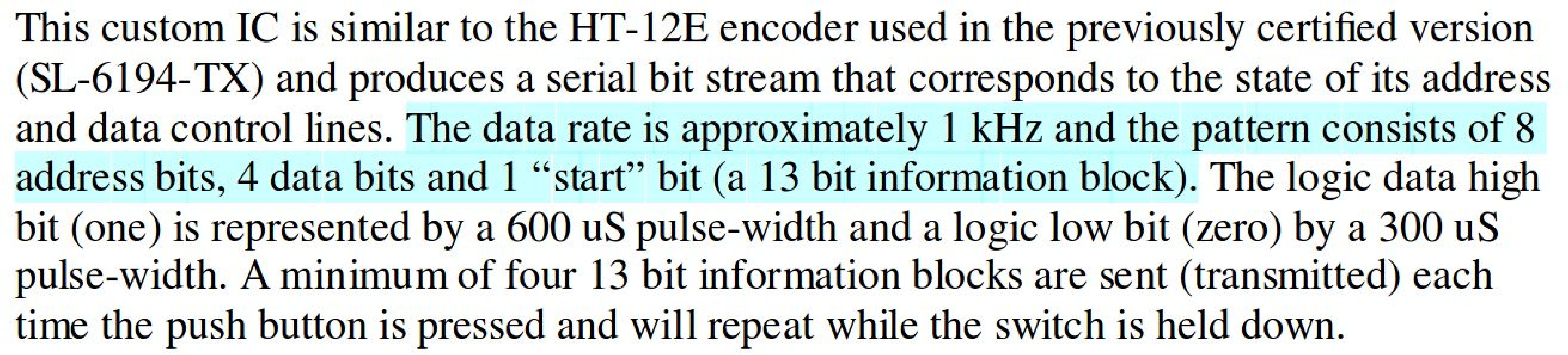
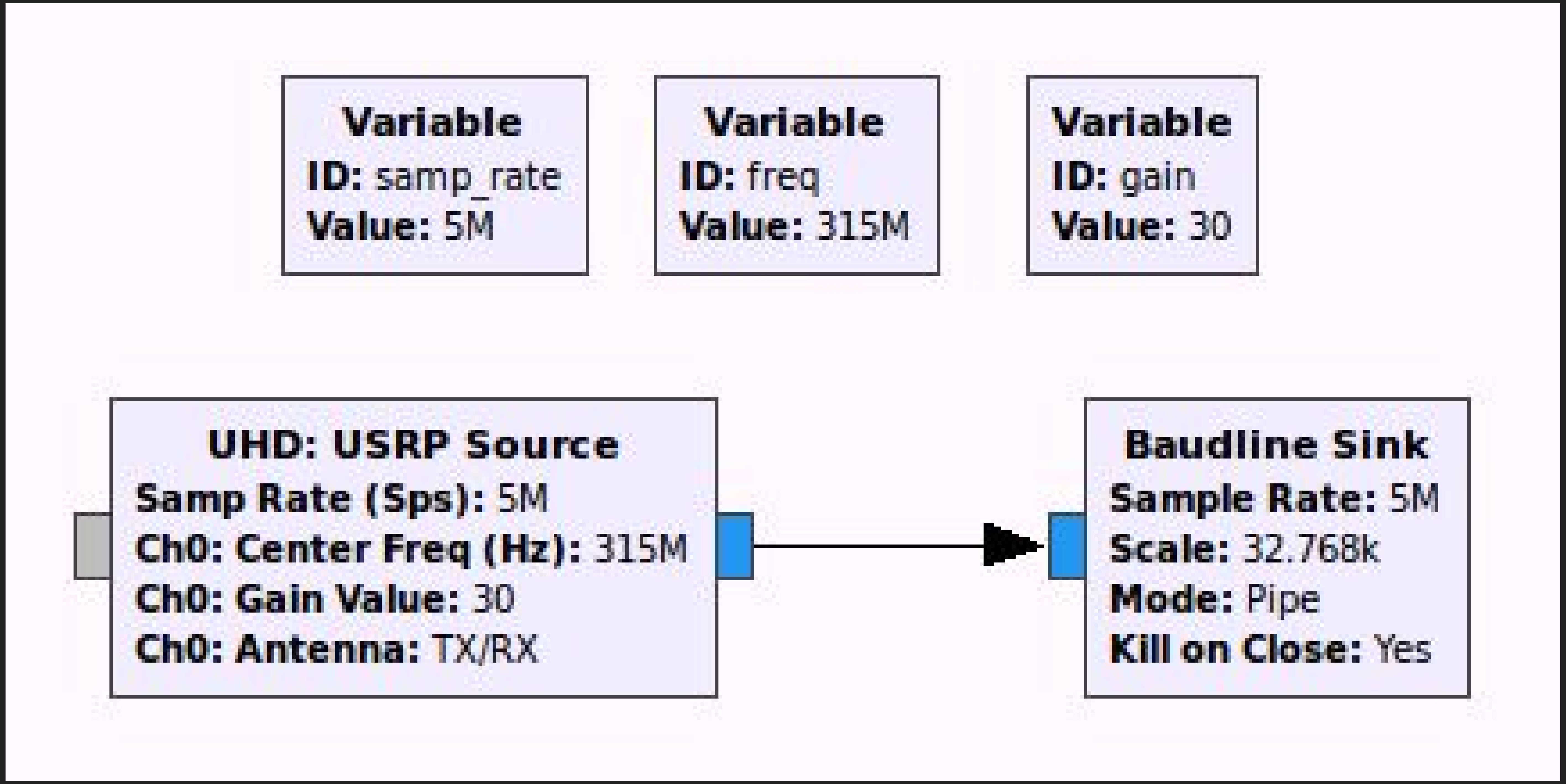

RBW 1 MHz
VBW 3 MHz
SWT 20 ms
Delta 2 [T1]
-0.13 dB
320.000000 µs
Ref -30 dBm
*Att 0 dB
Marker 1 [T1]
-35.62 dBm
2.120000 ms
1 AP
VIEW
A
SGL
TRG
3DB
12
TRG -56.5 dBm
-30
-40
-50
-60
-70
-80
-120
-130
Center 314.958 MHz
2 ms/

LOOK AT SIMILAR PRODUCTS



This custom IC is similar to the HT-12E encoder used in the previously certified version (SL-6194-TX) and produces a serial bit stream that corresponds to the state of its address and data control lines. The data rate is approximately 1 kHz and the pattern consists of 8 address bits, 4 data bits and 1 “start” bit (a 13 bit information block). The logic data high bit (one) is represented by a 600 uS pulse-width and a logic low bit (zero) by a 300 uS pulse-width. A minimum of four 13 bit information blocks are sent (transmitted) each time the push button is pressed and will repeat while the switch is held down.

OSINT SANITY CHECK



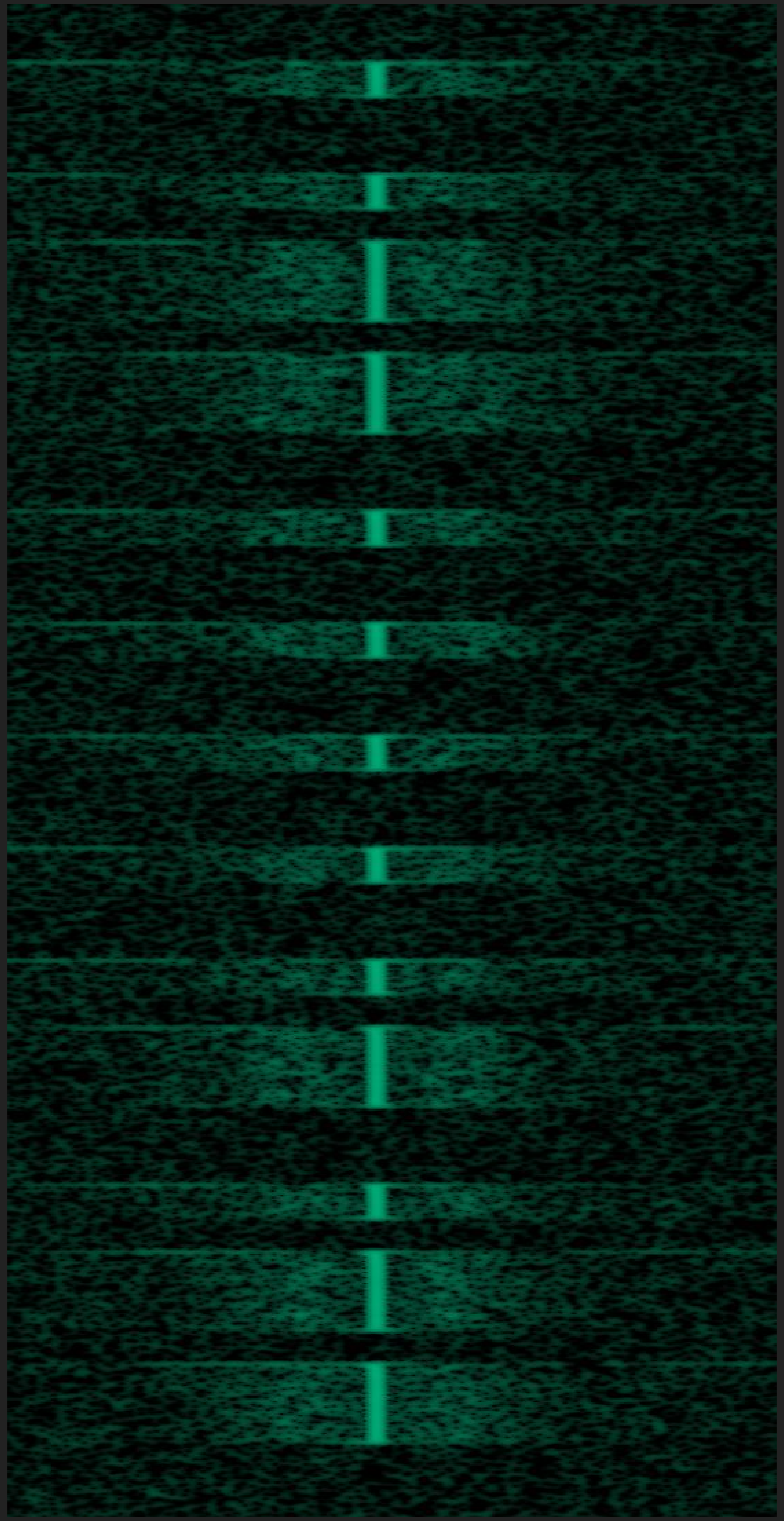
Variable
ID: samp_rate
Value: 5M

Variable
ID: freq
Value: 315M

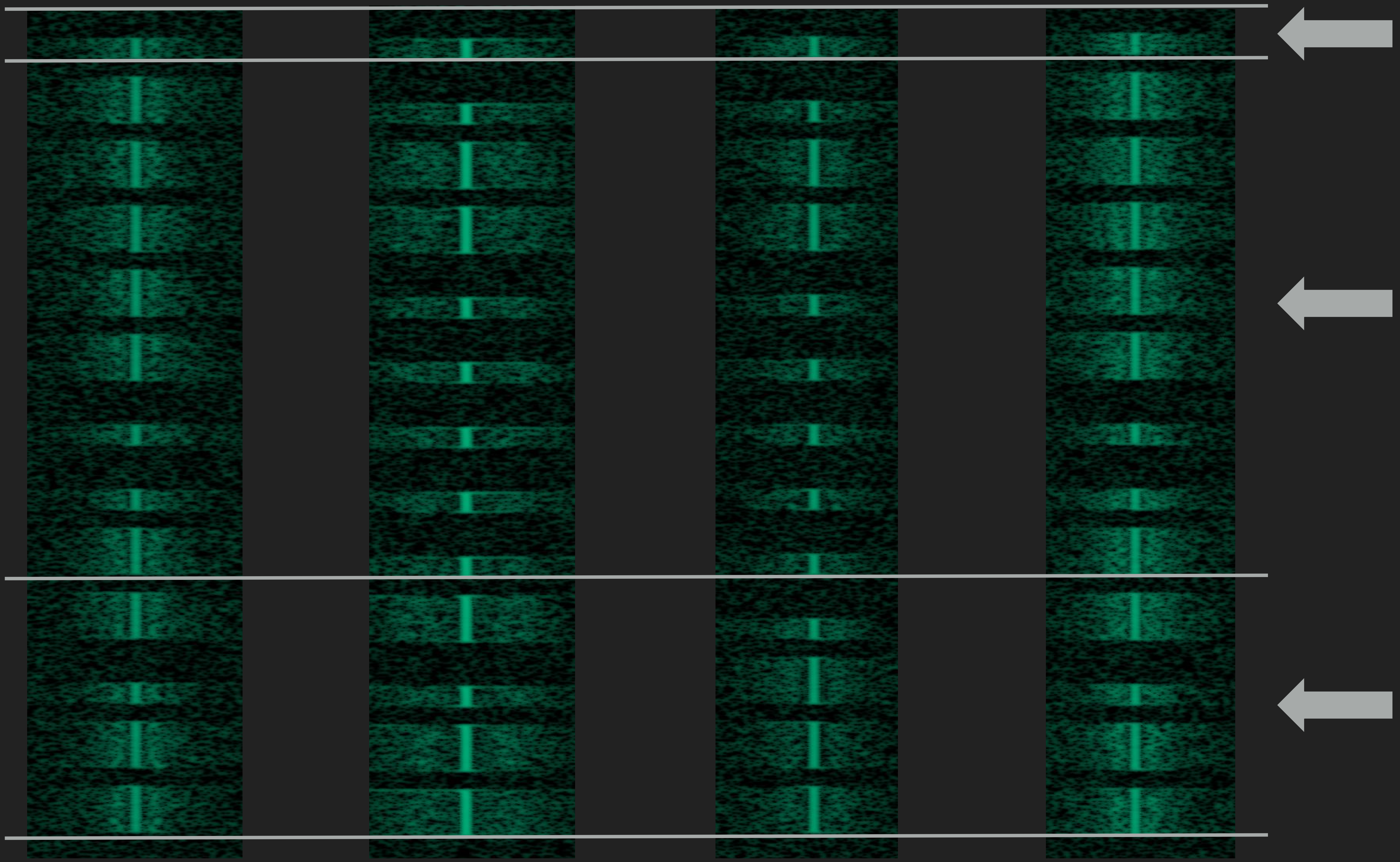
Variable
ID: gain
Value: 30

UHD: USRP Source
Samp Rate (Sps): 5M
Ch0: Center Freq (Hz): 315M
Ch0: Gain Value: 30
Ch0: Antenna: TX/RX

Baudline Sink
Sample Rate: 5M
Scale: 32.768k
Mode: Pipe
Kill on Close: Yes



BUTTON WAVEFORMS IN BAUDLINE



Start of Frame (1 bit)

Button ID (8 bits)

Tone ID (4 bits)

WHAT DID WE LEARN FROM OSINT?

- 315MHz center frequency [channel]
- Pulse width modulation [modulation]
  - 1KHz data rate [symbol timing]
  - Bit 1 is ~700us off and ~300us on
  - Bit 0 us ~300us off and ~700us on
- Packets are 13 bits long [synchronize]
  - 1 “start bit”
  - 8 button ID bits
  - 4 tone ID bits

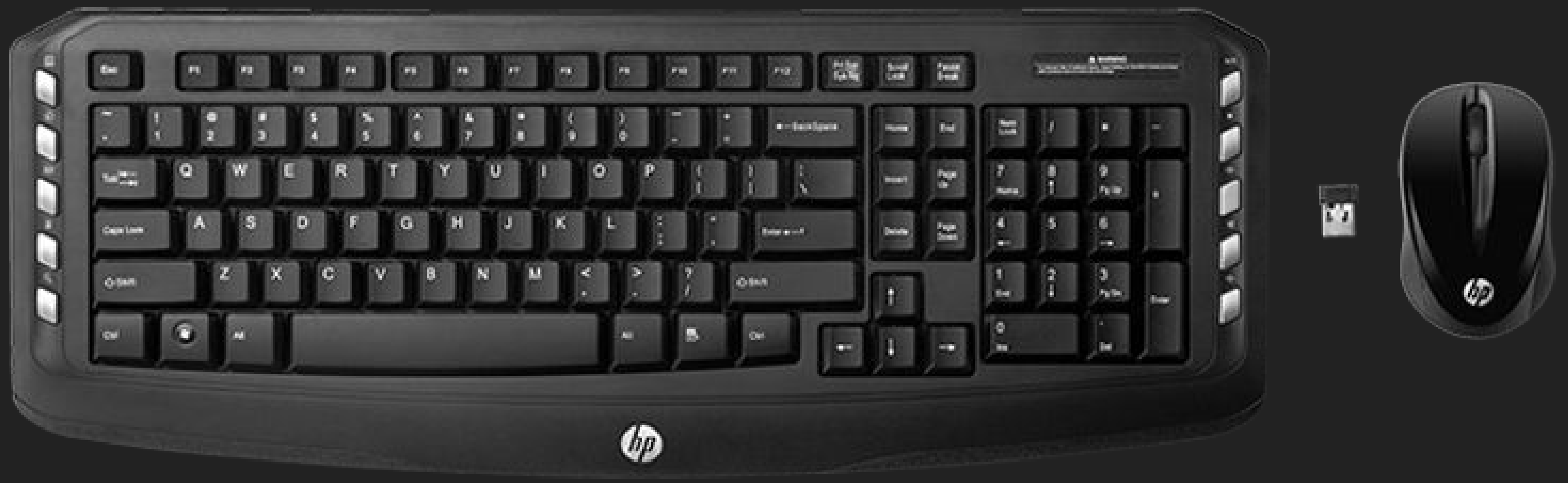
DOORBELL
DEMOS

TDMA Frequency Shift Keying

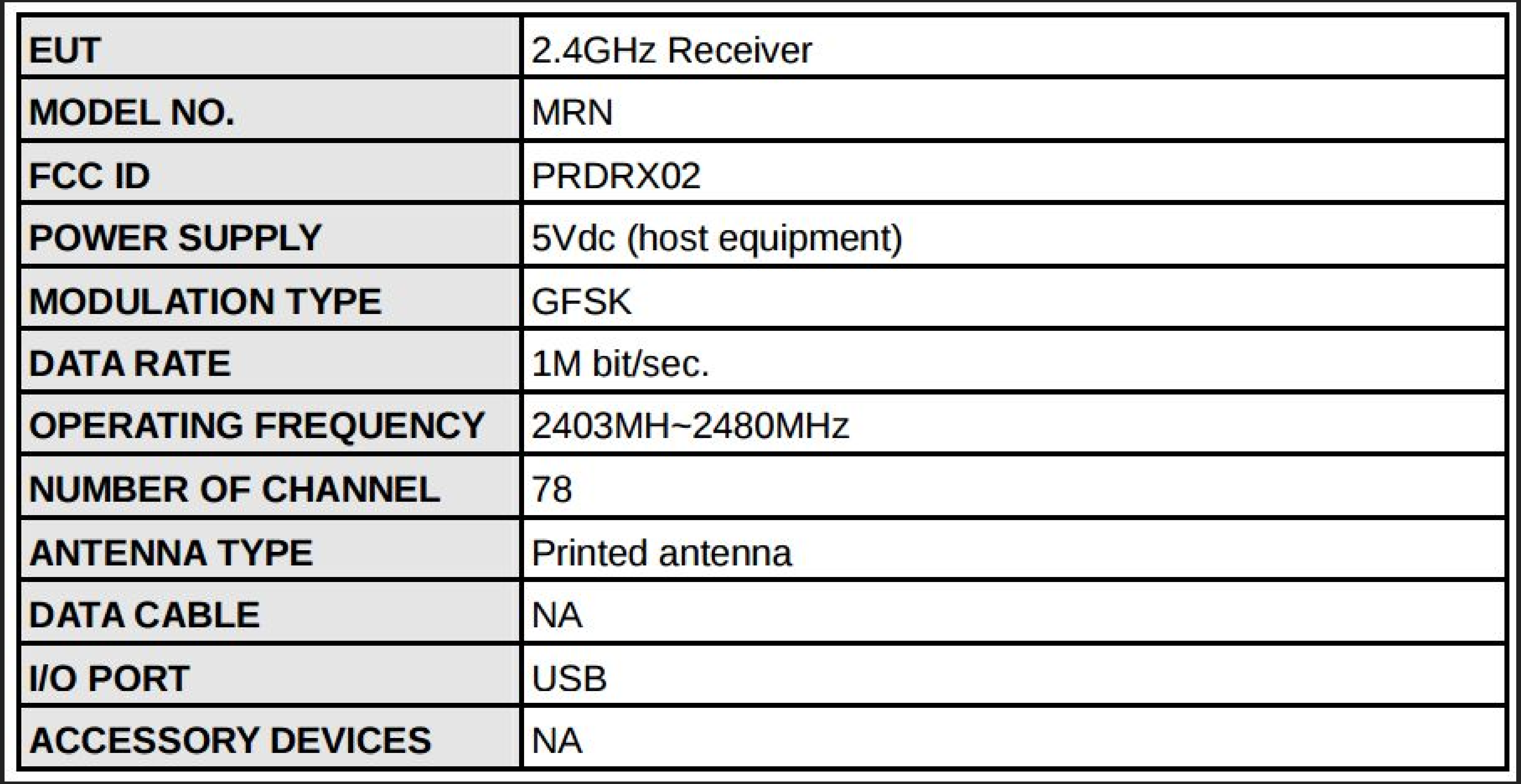
HP KEYBOARD

HP CLASSIC WIRELESS DESKTOP

- 2.4GHz Wireless Keyboard/Mouse
- OEM = ACROX
- Keyboard
  - FCC ID PRDKB14
- Mouse
  - FCC ID PRDMU26
- Dongle
  - FCC ID PRDRX02

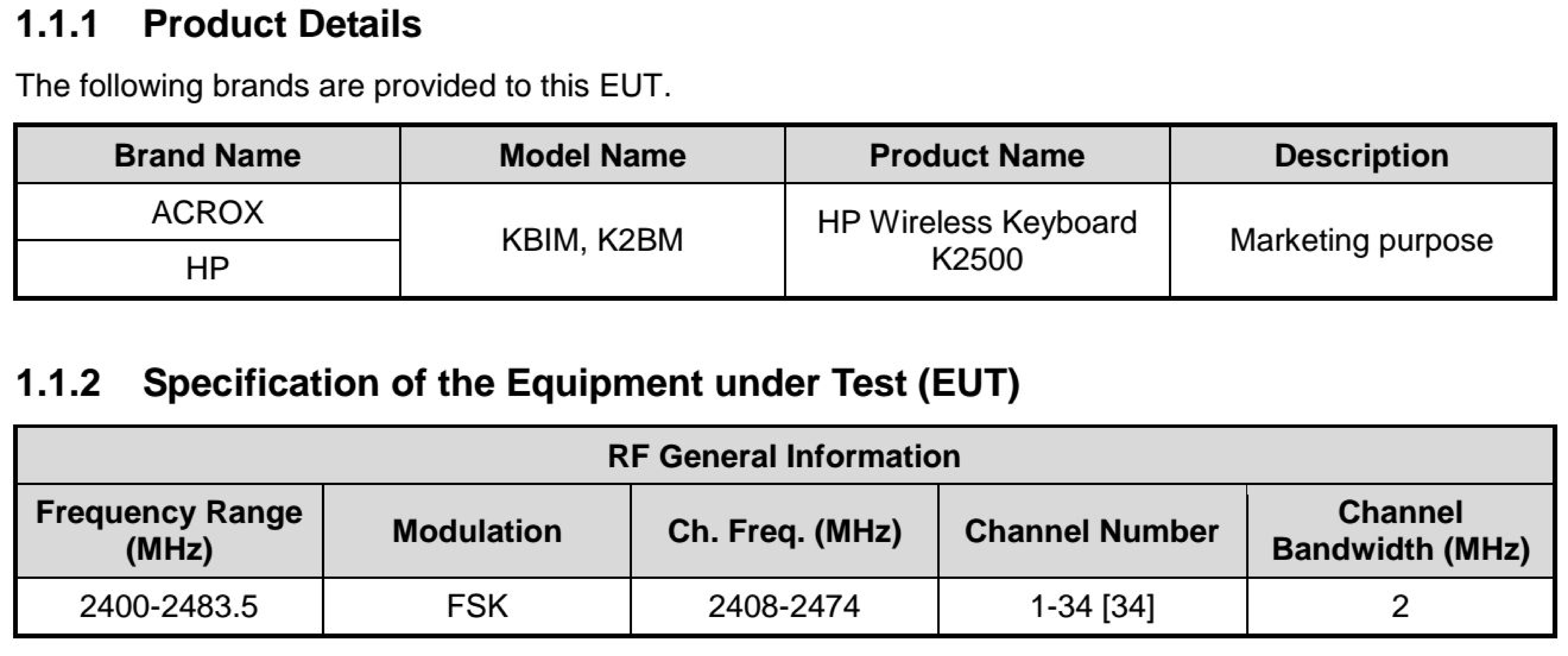


HP DONGLE TEST REPORT



EUT	2.4GHz Receiver
MODEL NO.	MRN
FCC ID	PRDRX02
POWER SUPPLY	5Vdc (host equipment)
MODULATION TYPE	GFSK
DATA RATE	1M bit/sec.
OPERATING FREQUENCY	2403MH~2480MHz
NUMBER OF CHANNEL	78
ANTENNA TYPE	Printed antenna
DATA CABLE	NA
I/O PORT	USB
ACCESSORY DEVICES	NA

HP KEYBOARD TEST REPORT



1.1.1 Product Details

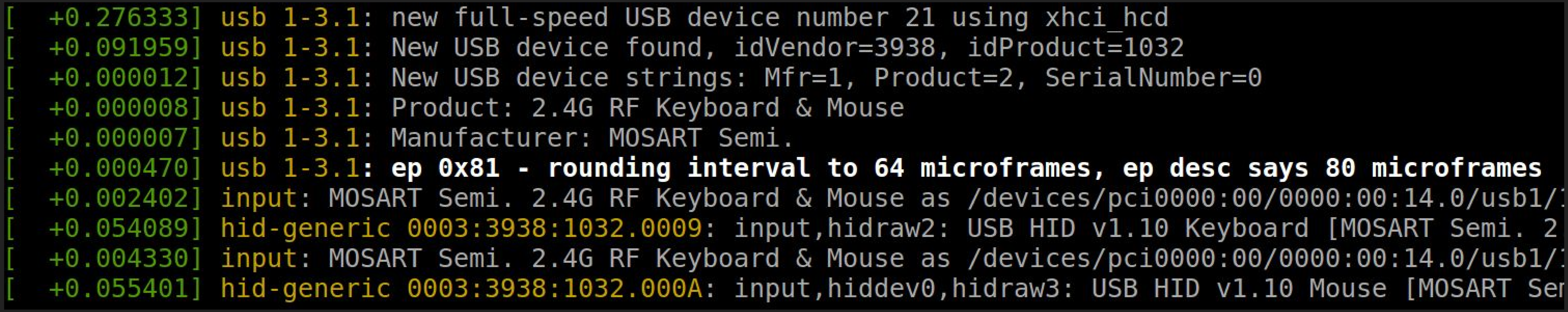
The following brands are provided to this EUT.

Brand Name	Model Name	Product Name	Description
ACROX	KBIM, K2BM	HP Wireless Keyboard K2500	Marketing purpose
HP			

1.1.2 Specification of the Equipment under Test (EUT)

RF General Information				
Frequency Range (MHz)	Modulation	Ch. Freq. (MHz)	Channel Number	Channel Bandwidth (MHz)
2400-2483.5	FSK	2408-2474	1-34 [34]	2

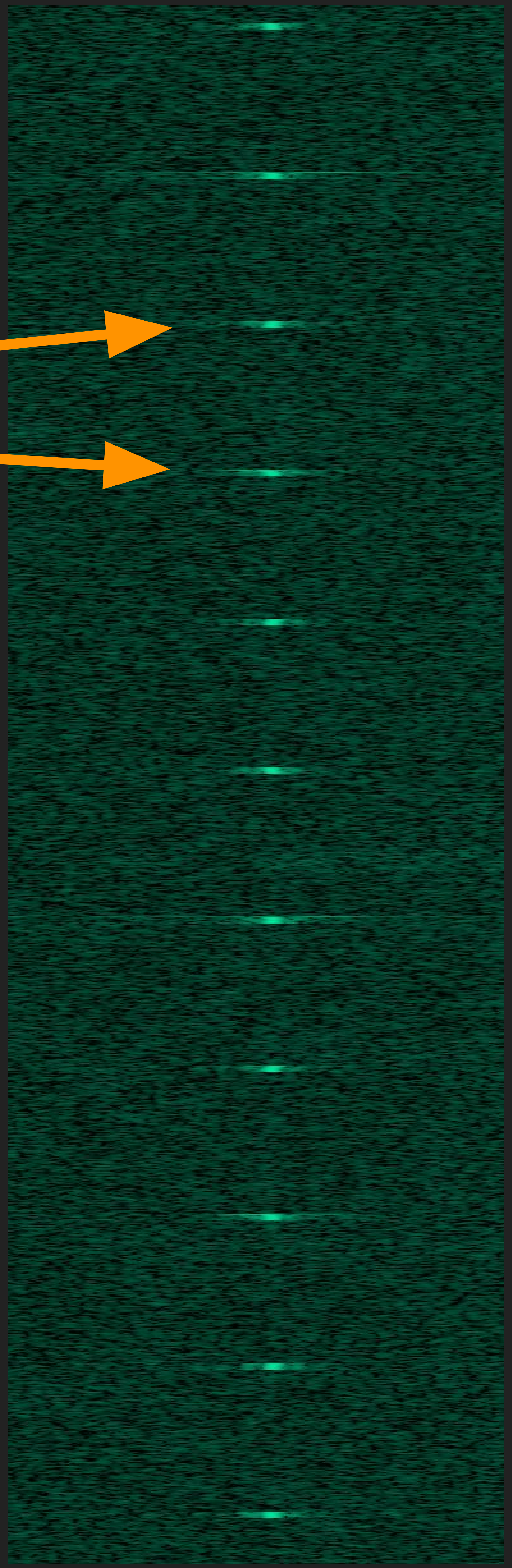
HP DONGLE DMESG OUTPUT



```
[  +0.276333] usb 1-3.1: new full-speed USB device number 21 using xhci_hcd
[  +0.091959] usb 1-3.1: New USB device found, idVendor=3938, idProduct=1032
[  +0.000012] usb 1-3.1: New USB device strings: Mfr=1, Product=2, SerialNumber=0
[  +0.000008] usb 1-3.1: Product: 2.4G RF Keyboard & Mouse
[  +0.000007] usb 1-3.1: Manufacturer: MOSART Semi.
[  +0.000470] usb 1-3.1: ep 0x81 - rounding interval to 64 microframes, ep desc says 80 microframes
[  +0.002402] input: MOSART Semi. 2.4G RF Keyboard & Mouse as /devices/pci0000:00/0000:00:14.0/usb1/
[  +0.054089] hid-generic 0003:3938:1032.0009: input,hidraw2: USB HID v1.10 Keyboard [MOSART Semi. 2
[  +0.004330] input: MOSART Semi. 2.4G RF Keyboard & Mouse as /devices/pci0000:00/0000:00:14.0/usb1/
[  +0.055401] hid-generic 0003:3938:1032.000A: input,hiddev0,hidraw3: USB HID v1.10 Mouse [MOSART Ser
```

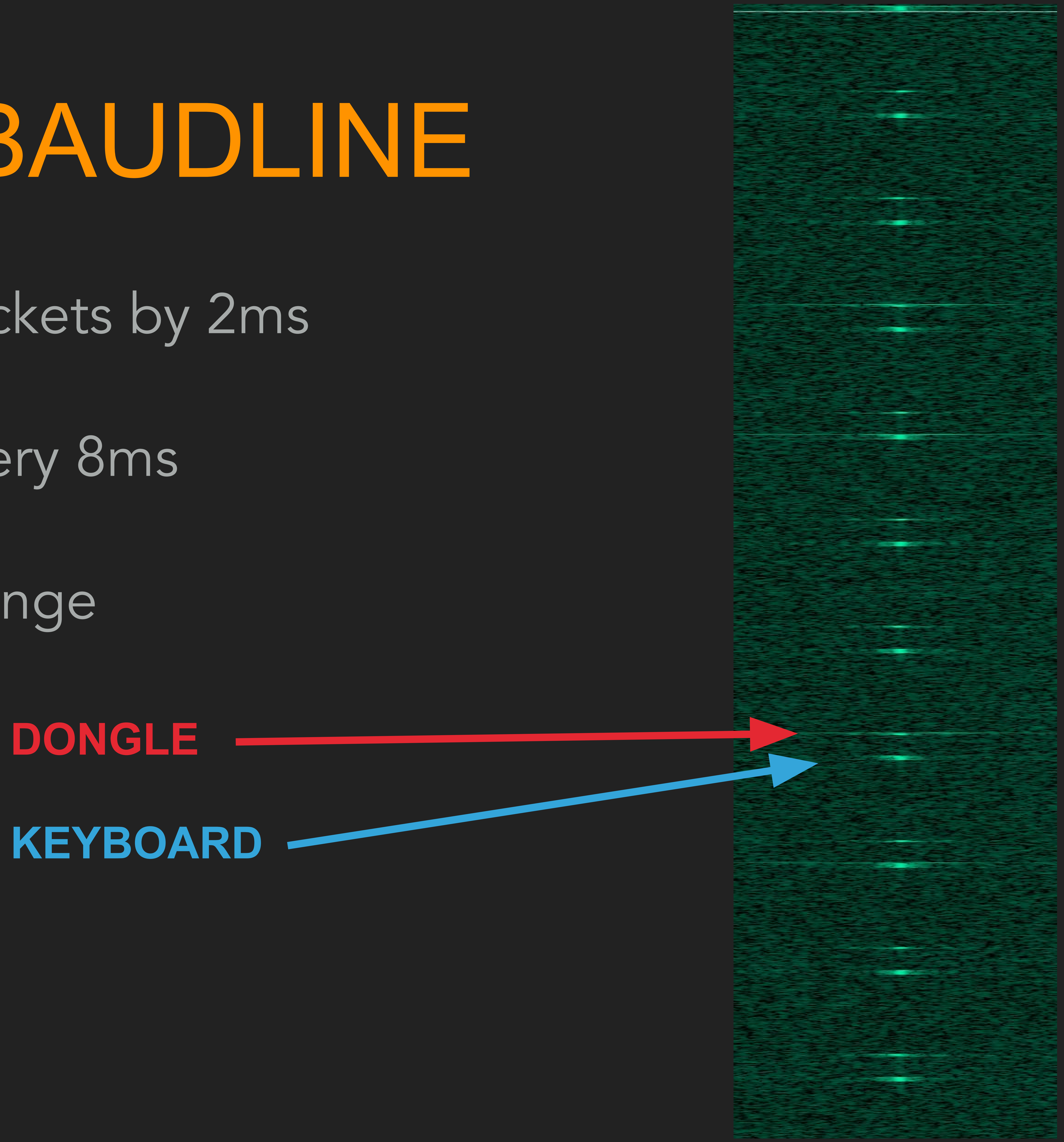
DONGLE IN BAUDLINE

- Always transmitting at 8ms intervals
- No channel hopping
- TDMA? (Time Division Multiple Access)

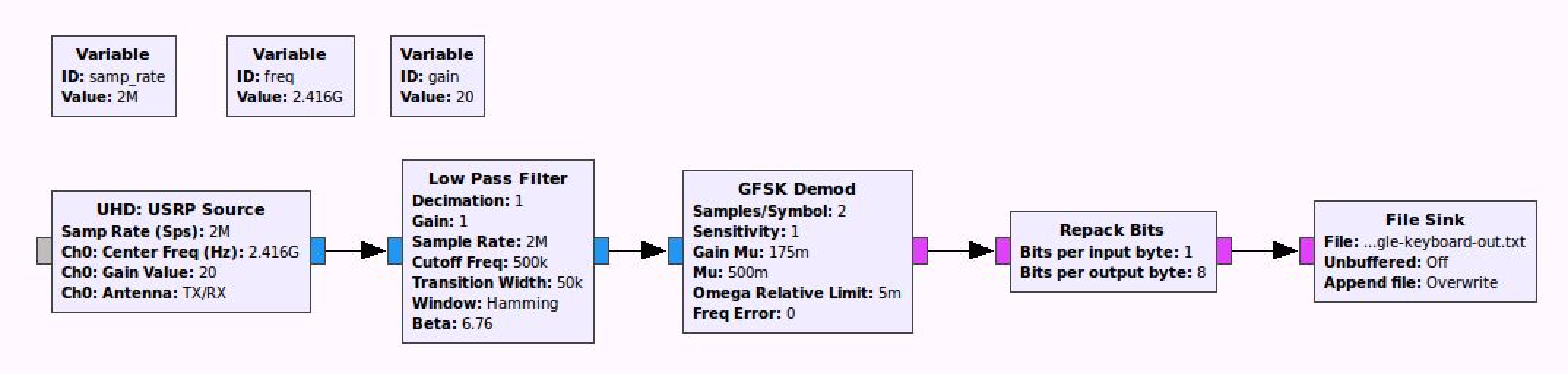


KEYBOARD IN BAUDLINE

- Keystrokes follow dongle packets by 2ms
- Keyboard transmits up to every 8ms
- Dongle behavior doesn't change



KEYBOARD DEMOD FLOWGRAPH



Variable
ID: samp_rate
Value: 2M

Variable
ID: freq
Value: 2.416G

Variable
ID: gain
Value: 20

UHD: USRP Source
Samp Rate (Sps): 2M
Ch0: Center Freq (Hz): 2.416G
Ch0: Gain Value: 20
Ch0: Antenna: TX/RX

Low Pass Filter
Decimation: 1
Gain: 1
Sample Rate: 2M
Cutoff Freq: 500k
Transition Width: 50k
Window: Hamming
Beta: 6.76

GFSK Demod
Samples/Symbol: 2
Sensitivity: 1
Gain Mu: 175m
Mu: 500m
Omega Relative Limit: 5m
Freq Error: 0

Repack Bits
Bits per input byte: 1
Bits per output byte: 8

File Sink
File: ...gle-keyboard-out.txt
Unbuffered: Off
Append file: Overwrite

GREP FOR PACKETS

```
xxd -p demod.out |

tr -d "\n" |

grep -Po "(00|ff|aa|55)+.{8}" |

sort |

uniq -c |

sort -nr |

Head -n 10
```

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Bytes to Hex

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Bytes to Hex

Grep for Packets

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tr -d "\n" |
grep -Po "(00|ff|aa|55)+.{8}" |
sort |
uniq -c |
sort -nr |
Head -n 10
```

Bytes to Hex

Grep for Packets

Sort by Count

DONGLE PACKET BYTES

```
ffffaaaaaaaaaaaaaaaaaeddd4e8
```

```
sed s/[dongle packets]//g
```

KEYBOARD PACKET BYTES

`aaaaaaddd4e8`

GREP, GREP, AND GREP SOME MORE!

```
aaaaaa ddd4e8 2e db 3f 384a
aaaaaa ddd4e8 2d db 37 6092
aaaaaa ddd4e8 28 db 3f 98f8
aaaaaa ddd4e8 25 db 3f c9ba
aaaaaa ddd4e8 25 db 21 3649
aaaaaa ddd4e8 21 db 27 30f5
aaaaaa ddd4e8 20 db 3f 3951
```

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aaaaaa ddd4e8 2d db 37 6092
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aaaaaa ddd4e8 25 db 3f c9ba
aaaaaa ddd4e8 25 db 21 3649
aaaaaa ddd4e8 21 db 27 30f5
aaaaaa ddd4e8 20 db 3f 3951
```

preamble

GREP, GREP, AND GREP SOME MORE!

```
aaaaaa ddd4e8 2e db 3f 384a
aaaaaa ddd4e8 2d db 37 6092
aaaaaa ddd4e8 28 db 3f 98f8
aaaaaa ddd4e8 25 db 3f c9ba
aaaaaa ddd4e8 25 db 21 3649
aaaaaa ddd4e8 21 db 27 30f5
aaaaaa ddd4e8 20 db 3f 3951
```

preamble address

GREP, GREP, AND GREP SOME MORE!

```
aaaaaa ddd4e8 2e db 3f 384a
aaaaaa ddd4e8 2d db 37 6092
aaaaaa ddd4e8 28 db 3f 98f8
aaaaaa ddd4e8 25 db 3f c9ba
aaaaaa ddd4e8 25 db 21 3649
aaaaaa ddd4e8 21 db 27 30f5
aaaaaa ddd4e8 20 db 3f 3951
```

preamble address sequence

GREP, GREP, AND GREP SOME MORE!

```
aaaaaa ddd4e8 2e db 3f 384a
aaaaaa ddd4e8 2d db 37 6092
aaaaaa ddd4e8 28 db 3f 98f8
aaaaaa ddd4e8 25 db 3f c9ba
aaaaaa ddd4e8 25 db 21 3649
aaaaaa ddd4e8 21 db 27 30f5
aaaaaa ddd4e8 20 db 3f 3951
```

preamble address sequence frame type

GREP, GREP, AND GREP SOME MORE!

```
aaaaaa ddd4e8 2e db 3f 384a
aaaaaa ddd4e8 2d db 37 6092
aaaaaa ddd4e8 28 db 3f 98f8
aaaaaa ddd4e8 25 db 3f c9ba
aaaaaa ddd4e8 25 db 21 3649
aaaaaa ddd4e8 21 db 27 30f5
aaaaaa ddd4e8 20 db 3f 3951
```

preamble address sequence frame type keystroke

GREP, GREP, AND GREP SOME MORE!

```
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aaaaaa ddd4e8 28 db 3f 98f8
aaaaaa ddd4e8 25 db 3f c9ba
aaaaaa ddd4e8 25 db 21 3649
aaaaaa ddd4e8 21 db 27 30f5
aaaaaa ddd4e8 20 db 3f 3951
```
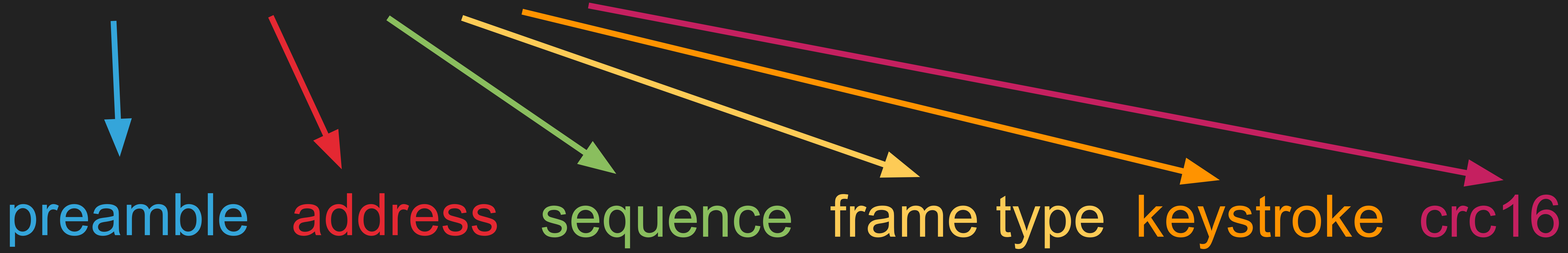



preamble address sequence frame type keystroke crc16 tl;dr

smarter people than me made that easy

Common Threads

Methodology Revisited

Reverse Engineering Methodology

0. Open-source intelligence research
1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate
4. Synchronize
5. Extract symbols

1. Channel Characterization

All 3 PHYs share a common notion of a channel

Z-Wave	Doorbell	Keyboard
+/- 20 kHz @ 908.42 (plus other channels)	315 MHz	2416 MHz

2. Identify Modulation

Modulation is the biggest variable

(but OSINT makes identifying it easy)

Z-Wave	**Doorbell**	**Keyboard**
Frequency Shift Keying	Pulse-Width Modulation / On-Off Keying	TDMA Frequency Shift Keying

3. Symbol Rate Recovery

All 3 PHYs share a common notion of discrete symbol timing

Z-Wave	**Doorbell**	**Keyboard**
19,200 symbols/s 40,000 symbols/s 100,000 symbols/s	1000 symbols/s	1,000,000 symbols/s

4. Synchronization

All 3 PHYs contain synchronization features

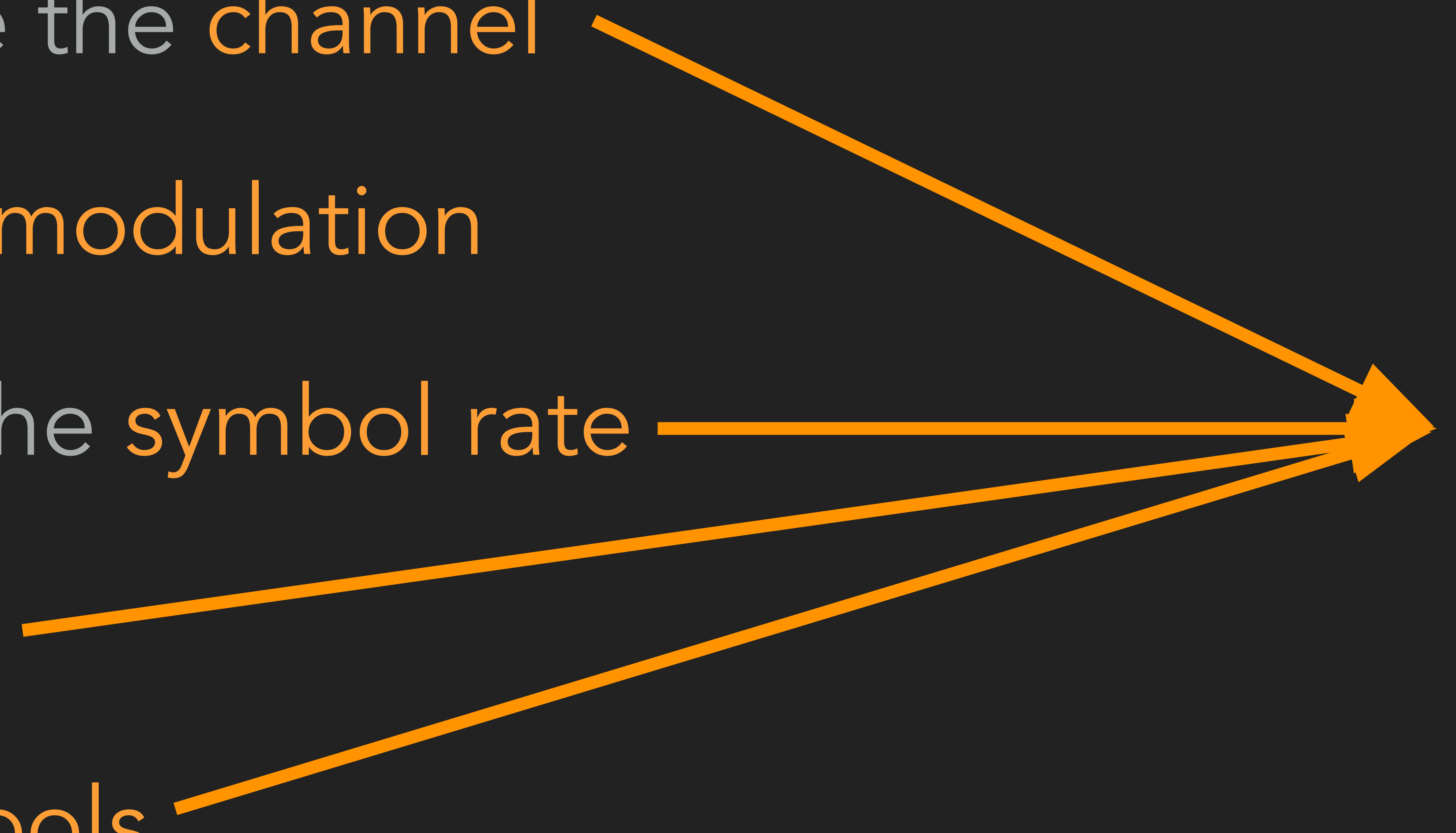
(preamble and/or Start of Frame delimiter)

Z-Wave	**Doorbell**	**Keyboard**
Manchester(0x55..55f0)	Start Bit	Preamble (0xaa..aa) SFD (3 byte address)

5. Symbol Extraction

Once you get here it’s just bits on a disk

Reverse Engineering Methodology



0. Open-source intelligence research
1. Characterize the channel
2. Identify the modulation
3. Determine the symbol rate
4. Synchronize
5. Extract symbols

Same process for 3 different PHYs!

Conclusions

Disparate wireless systems can be rationalized via process

OSINT will help you skip the complex/domain-specific radio parts

Once you demodulate, you have bits on a disk which you can handle any way you please

One last thought to leave you with…

The IoT is full of holes...

It’s up to you to find them!

Thanks!

marc@Bastille.net
@marcnewlin

matt@Bastille.net
@embeddedsec

Questions?

marc@Bastille.net
@marcnewlin

matt@Bastille.net
@embeddedsec