CSCE 438/838: Internet of Things

PROTOCOL STACK

Physical Layer

PHYSICAL LAYER

Source Coding (Data Compression)

- At the transmitter end, the information source is first encoded with a source encoder
  - Exploit the information statistics
  - Represent the source with a fewer number of bits,
  - → source codeword
- Performed at the application layer

Channel Coding (Error Control Coding)

- Source codeword is then encoded by the channel encoder
- → Channel codeword
  - Goal: address the wireless channel errors that affect the transmitted information

Source stream
Source Encoder
Source codeword
Channel Encoder
Channel codeword
Correlated bits
Control bits
Parity bits

Interleaving and Modulation

- The encoded channel codeword is then interleaved to combat the bursty errors
- Channel coding and the interleaving mechanism help the receiver either to
  - Identify bit errors to initiate retransmission
  - Correct a limited number of bits in case of errors.

Interleaving and Modulation

- Then, an analog signal (or a set thereof) is modulated by the digital information to create the waveform that will be sent over the channel
- Finally, the waveforms are transmitted through the antenna to the receiver

Wireless channel propagation

- The transmitted waveform travels through the channel
- Meanwhile, the waveform is attenuated and distorted by several wireless channel effects

Wireless Communication Basics

Overview

WIRELESS CHANNEL PROPAGATION

FROM WAVES TO BITS

CHANNEL MODELS

FREQUENCY BANDS

MODULATION

Overview

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Wireless Channel Propagation

- Attenuation: As the signal wave propagates through air, the signal strength is attenuated.

- a certain fraction of the wave propagates through the boundary, refraction.

Wireless Channel Propagation

- Diffraction: When signal wave propagates through sharp edges such as the tip of a mountain or a building, the sharp edge acts as a source,
  - New waves are generated
  - Signal strength is distributed to the new generated waves.
- Scattering: In reality, no perfect boundaries. When a signal wave is incident at a rough surface, it scatters in different directions

Wireless Channel Propagation

- Attenuation
- Multi-path effects

Wireless Channel

- Wireless transmission *distorts* any transmitted signal
  - *Wireless channel* describes these distortion effects
- Sources of distortion
  - Attenuation – Signal strength decreases with increasing distance
  - Reflection/refraction – Signal bounces of a surface; enter material
  - Diffraction – start "new wave" from a sharp edge
  - Scattering – multiple reflections at rough surfaces

Attenuation

- Results in path loss
- Received signal strength is a function of the distance *d* between sender and transmitter
- *Friis free-space model*
  - Signal strength at distance d relative to some reference distance $d_0 < d$ for which strength is known
  - d_0 is *far-field distance*, depends on antenna technology

FRIIS FREE-SPACE MODEL

$$P_{rx}(d) = \frac{P_{tx} G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

$$= \frac{P_{tx} G_t G_r \lambda^2}{(4\pi)^2 d_0^2} \left(\frac{d_0}{d}\right)^2 = P_{rx}(d_0) \left(\frac{d_0}{d}\right)^2$$

$$c = f \cdot \lambda$$

$$\lambda = \frac{c}{f}$$

$$P_r = \frac{P_t \cdot G_t \cdot A_r}{4\pi d^2}$$

$$A_r = \frac{\lambda^2}{4\pi} G_r$$

$$P_{rx} = \frac{P_{tx} G_t G_r \lambda^2}{(4\pi d)^2}$$

$$\frac{P_{tx}}{dB} = \frac{P_{rx}}{dB} + \frac{PL}{dB}$$

$$\frac{P_{rx}}{P_{tx}} = \frac{G_t G_r \lambda^2}{(4\pi d)^2}$$ Path loss

$$10 \log_{10}\left(\frac{P_{rx}}{P_{tx}}\right) = P_{rx}[dBm] - P_{tx}[dBm]$$

$$\hookrightarrow P_{tx} - P_{rx}$$

Non-line-of-sight

- Because of reflection, scattering, …, radio communication is not limited to direct line of sight communication
- Effects depend strongly on frequency, thus different behavior at higher frequencies

Non-line-of-sight

- Different paths have different lengths = propagation time
  - Results in *delay spread* of the wireless channel

Multi-path

- Brighter color = stronger signal
- Simple (quadratic) free space attenuation formula is not sufficient to capture these effects

Generalizing the Attenuation Formula

- To take into account stronger attenuation than only caused by distance (e.g., walls, …), use a larger exponent $\gamma > 2$
  - γ is the *path-loss exponent*

$$P_{\text{recv}}(d) = P_{\text{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^{\gamma}$$

  - Rewrite in logarithmic form (in dB):

$$\text{PL}(d)[\text{dB}] = \text{PL}(d_0)[\text{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

Generalizing the Attenuation Formula

- Obstacles, multi-path, etc?
- Experiments show can be represented by a random variable
- Equivalent to multiplying with a lognormal distributed r.v. in metric units ! *lognormal shadow fading*

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0)[\mathrm{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[\mathrm{dB}]$$

Log-normal Fading Channel Model

$$P_r(d) = P_t - PL(d_0) - 10\eta \log\left(\frac{d}{d0}\right) + X_\sigma$$

Received Power

Transmit Power

Path loss

Path loss exponent

Log-normal Shadow fading

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Noise and interference

- So far: only a single transmitter assumed
  - Only disturbance: self-interference of a signal with multi-path "copies" of itself
- In reality, two further disturbances
- Noise – due to effects in receiver electronics, depends on temperature
- Interference – from third parties
  - Co-channel interference: Another sender uses the same spectrum
  - Adjacent-channel interference: Another sender uses some other part of the radio spectrum, but receiver filters are not good enough to fully suppress it

Symbols and bit errors

- Extracting symbols out of a distorted/corrupted wave form is fraught with errors
  - Depends essentially on strength of the received signal compared to the corruption
  - Captured by *signal to noise and interference ratio (SINR)*

$$\text{SINR} = 10\log_{10}\left(\frac{P_{\text{recv}}}{N_0 + \sum_{i=1}^{k} I_i}\right)$$

Symbols and Bit Errors

- For IoT
  - Interference is usually low → MAC protocols
  - SINR ~ SNR
  - SNR = $P_r - P_n$ (in dB)
- P_n – Noise power (noise floor)

Noise Floor

- Changes with time
- Varies according to location (indoor vs. outdoor)
- Even if received power is the same, SNR varies with time!

Noise Floor

Empirical Noise Floor
indoor environment
outdoor environment
Analytical Noise Floor (−115 dBm)
Noise Floor (dBm)
sample number
−90
−95
−100
−105
−110
−115
−120
0
1000
2000
3000
4000
5000
6000
7000
8000

Bit Error Rate

- p_b – Probability that a received bit will be in error
  - 1 sent → 0 received
- p_b is proportional to SNR (channel quality)
  - Exact relation depends on modulation scheme

Which concept was the most intriguing? (one word)

Total Results: 0

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MODULATION

Connected Region
Transitional Region
Disconnected Region

Channel Models

- Main goal: Stochastically capture the behavior of a wireless channel
  - Main options: model the SNR or directly the bit errors
- Simplest model
  - Transmission power and attenuation constant
  - Noise – an uncorrelated Gaussian variable

Channel Models

- Non-line-of-sight path
  - Amplitude of resulting signal has a *Rayleigh* distribution (*Rayleigh fading)*
- One dominant line-of-sight plus many indirect paths
  - Signal has a *Rice* distribution (*Rice fading*)

Channel Model for IoT

- Typical IoT properties
  - Low power communication
  - Small transmission range
  - Implies small delay spread (nanoseconds, compared to micro/milliseconds for symbol duration)
  - Frequency-non-selective fading, low to negligible inter-symbol interference
    - Coherence bandwidth often > 50 MHz

Channel Model for IoT

- Empirical evaluations for Mica2

Marco Zuniga, Bhaskar Krishnamachari, "An Analysis of Unreliability and Asymmetry in Low-Power Wireless Links", ACM Transactions on Sensor Networks, Vol 3, No. 2, June 2007. (Conference version: "Analyzing the Transitional Region in Low Power Wireless Links", IEEE SECON 2004)

$$P_r(d) = P_t - PL(d_0) - 10\eta \log\left(\frac{d}{d_0}\right) + X_\sigma$$

Channel Model for IoT

- Log-normal fading channel best characterizes WSN channels
- η path loss exponent
- Shadow variance σ^2

environment	η (95% conf. bounds)	σ (95% conf. bounds)
outdoor	4.7 (4.30 - 5.10)	4.6 (2.80 - 6.40)
indoor	3.0 (2.67 - 3.23)	3.8 (2.60 - 5.00)

Channel Model for IoT

- PRR – Packet reception rate
  $(1-p_b)^k$
- Transitional region for packet reception
  - Not too good, not too bad

Channel Model for IoT

- PRR – Packet reception rate $(1\text{-}pb)^k$

- Transitional region for packet reception
  - Not too good, not too bad

Channel Model for IoT

- PRR significantly varies in the transitional region
- d = 20m
  - PRR = [0,1]
- We cannot operate solely in the connected region
  - Communication distance too short

Outdoor, PRR vs. Distance, P_{out} = 5dBm
PRR (%)
distance (m)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20

Outdoor, PRR vs. Distance, P_{out} = −7dBm
PRR (%)
distance (m)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20

Indoor, PRR vs. Distance, P_{out} = 5dBm
PRR (%)
distance (m)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20

Indoor, PRR vs. Distance, P_{out} = −7dBm
PRR (%)
distance (m)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20

Channel Models – Digital

- Directly model the resulting bit error behavior (p_b)
- Each bit is erroneous with constant probability, independent of the other bits
  - *Binary symmetric channel (BSC)*
- Capture fading models' property that channel is in different states! Markov models – states with different BERs
  - Example: Gilbert-Elliot model with "bad" and "good" channel states and high/low bit error rates

Channel Models – Digital

- Fractal channel models describe number of (in-)correct bits in a row by a heavy-tailed distribution
- Burst errors (bit errors are NOT independent)

Source symbols
Channel symbols
Channel symbols
Digital waveform
Information source
Channel encoder (FEC)
Inter-leaver
Modula-tor
Tx antenna
Channel
Rx antenna
Information sink
Channel decoder
Deinter-leaver
Demo-dulator
Source symbols
Channel symbols
Channel symbols
Digital waveform

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Radio Spectrum for Communication

- Which part of the electromagnetic spectrum is used for communication
- Not all frequencies are equally suitable for all tasks – e.g., wall penetration, different atmospheric attenuation, processor/radio capability, etc.

Frequency allocation

- Some frequencies are allocated to specific uses
  - Cellular phones, analog television/radio broadcasting, DVB-T, radar, emergency services, radio astronomy, …
- Particularly interesting: ISM bands ("Industrial, scientific, medicine") – license-free operation

Some typical ISM bands	
Frequency	Comment
13,553-13,567 MHz	
26,957 – 27,283 MHz	
40,66 – 40,70 MHz	
433 – 464 MHz	Europe
900 – 928 MHz	Americas
2,4 – 2,5 GHz	WLAN/WPAN
5,725 – 5,875 GHz	WLAN
24 – 24,25 GHz	

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

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Transmitting Data Using Radio Waves

- Basics: Wireless communication is performed through radio waves
  - Transmitter can send a radio wave
  - Receiver can detect the wave and its parameters
- Typical radio wave = sine wave:

$$s(t) = A(t)cos(2\pi f(t)t + \phi(t))$$

  - Parameters: amplitude A(t), frequency f(t), phase ϕ(t)
- Modulation: Manipulate these parameters

Modulation

- Data to be transmitted is used to select transmission parameters as a function of time
- These parameters modify a basic sine wave, which serves as a starting point for *modulating* the signal onto it
- This basic sine wave has a *center frequency* f_c
- The resulting *signal* requires a certain *bandwidth* to be transmitted (centered around center frequency)
- For each bit (or a group of bits), a corresponding *waveform* with specific parameters is used

Receiver: Demodulation

- Receiver tries to match the received waveform with the tx'ed data bit
  - Necessary: One-to-one mapping between data and waveform
- Problems (Wireless Channel Errors)
  - Carrier synchronization: Frequency can vary between sender and receiver (drift, temperature changes, aging, …)
  - Bit synchronization: When does symbol representing a certain bit start/end?
  - Frame synchronization: When does a packet start/end?
- Biggest problem: Received signal is *not* the transmitted signal!

Which concept was the most intriguing? (one word)

Total Results: 0

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Last Class

- Wireless communication
- Modulation

Questions?

Modulation (Keying) examples

$$s(t) = A(t)cos(2\pi f(t)t + \phi(t))$$

- **Use data to modify**
  - Amplitude - *Amplitude Shift Keying (ASK) – A(t)*
  - Frequency - *Frequency Shift Keying (FSK) – f(t)*
  - *Phase* - *Phase Shift Keying (PSK) - $\theta(t)$*

Modulation Schemes

- GSM
  - GMSK - Gaussian-filtered minimum shift keying
- CDMA
  - QPSK - Quadrature phase shift keying
  - 8-PSK - 8-ary phase shift keying
  - 16-QAM - 16-ary quadrature amplitude modulation
- LTE (4G) – 5G
  - QPSK, 16-QAM, 64-QAM
- WiFi
  - BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM

Binary Phase Shift Keying (BPSK)

Binary Phase Shift Keying (BPSK)

Binary Phase Shift Keying (BPSK)

$$S_{BPSK}(t) = \sqrt{\frac{2E_b}{T_b}} cos(2\pi f_c t + \theta_c)$$

$$0 \leq t \leq T_b$$

$$S_{BPSK}(t) = \sqrt{\frac{2E_b}{T_b}} cos(2\pi f_c t + \pi + \theta_c)$$

$$= -\sqrt{\frac{2E_b}{T_b}} cos(2\pi f_c t + \theta_c)$$

Signals as Complex Numbers

- Complex numbers
  - z = a + jb, where $j^2 = -1$
- A signal can be represented as the real part of a complex number

$$
\begin{aligned}
s(t) &= Re\left\{\tilde{s}(t)e^{j2\pi f_c t}\right\} \\
&= Re\left\{A(t)e^{j\phi(t)}e^{j2\pi f_c t}\right\} \\
&= Re\left\{A(t)e^{j(2\pi f_c t+\phi(t))}\right\} \\
&= A(t)cos\left(2\pi f_c t + \phi(t)\right)
\end{aligned}
$$

$$s(t) = Re\left\{\tilde{s}(t)e^{j2\pi f_c t}\right\}$$
$$= Re\left\{A(t)e^{j\phi(t)}e^{j2\pi f_c t}\right\}$$
$$= Re\left\{A(t)e^{j(2\pi f_c t+\phi(t))}\right\}$$
$$= A(t)cos\left(2\pi f_c t + \phi(t)\right)$$

$$\tilde{s}(t) = A(t)e^{j\phi(t)} = s_I(t) + js_Q(t)$$

I-Q Plane

Signals as Complex Numbers

- Each signal can be represented as a vector on the complex I-Q plane
- Magnitude of the vector - amplitude of the signal - A(t)
- Angle of the vector - phase of the signal - Φ(t)

$$\tilde{s}(t) = A(t)e^{j\phi(t)} = s_I(t) + js_Q(t)$$

I-Q Plane

Why IQ?

- Practical reasons: It is hard to identify the phase of a single cosine function (phase ambiguity)
- A few trigonometric identities
  - $\cos(\alpha+\beta) = \cos(\alpha)\cos(\beta) - \sin(\alpha)\sin(\beta)$
  - $cos\left(\theta + \frac{\pi}{2}\right) = -\sin(\theta)$
- $cos(2\pi f_c t + \theta_c) = \cos(\theta_c)\cos(2\pi f_c t) + \sin(\theta_c)\cos\left(2\pi f_c t + \frac{\pi}{2}\right)$

Binary Phase Shift Keying (BPSK)

$$S_{BPSK}(t) = \sqrt{\frac{2E_b}{T_b}} cos(2\pi f_c t + \theta_c)$$

$$S_{BPSK}(t) = \sqrt{\frac{2E_b}{T_b}} cos(2\pi f_c t + \pi + \theta_c)$$

$$= -\sqrt{\frac{2E_b}{T_b}} cos(2\pi f_c t + \theta_c)$$

E_s - energy per symbol
E_b - energy per bit

Decoding BPSK

$$P_s(\epsilon|s_i) \leq \sum_{j=1, j\neq i} Q\left(\frac{d_{ij}}{\sqrt{2N_0}}\right)$$

$$P_{\mu,\sigma^2}(x) = \frac{1}{\sqrt{2\sigma^2\pi}}\, e^{\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)}$$

$$Q(x) \triangleq \int_x^{\infty} \frac{1}{\sqrt{2\pi}}\, e^{-y^2/2}\, dy$$

$\mu = 0$

$\sigma = 1$

$$P(x \leq 0) = \int_{-\infty}^{0} \frac{1}{\sqrt{2\sigma^2\pi}}\, e^{\left(-\frac{(x-\sqrt{E_b})^2}{2\sigma^2}\right)}\, dx \qquad \sigma^2 = \frac{N_0}{2}$$

$$P(x' \geq \sqrt{E_b}) = \int_{\sqrt{E_b}}^{\infty} \frac{1}{\sqrt{2\sigma^2\pi}}\, e^{\left(-\frac{x'^2}{2\sigma^2}\right)}\, dx'$$

$$y^2 = \frac{2x'^2}{N_0}$$

$$y = \frac{\sqrt{2}\cdot x'}{\sqrt{N_0}}$$

$$dy = \frac{\sqrt{2}\cdot dx'}{\sqrt{N_0}}$$

$$= \int_{\sqrt{E_b}}^{\infty} \frac{1}{\sqrt{\pi N_0}} \cdot e^{-\frac{x'^2}{2\cdot\frac{N_0}{2}}} \cdot dx'$$

y^2

$$dx' = \frac{\sqrt{N_0}\, dy}{\sqrt{2}} \qquad y = \frac{\sqrt{2}\, x}{\sqrt{N_0}}$$

$$x = \sqrt{E_b}$$

$$P_b(1) = \int_{\sqrt{\frac{2E_b}{N_0}}}^{\infty} \frac{1}{\sqrt{2\pi}} \cdot e^{-y^2/2}\, dy \qquad y = \frac{\sqrt{2E_b}}{\sqrt{N_0}}$$

$$\left.\begin{aligned} P_b(\varepsilon|1) &= Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \\ P_b(\varepsilon|0) &= Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \end{aligned}\right\}$$

$$P_b(\varepsilon) = \overset{1/2}{p(1)} \cdot P_b(\varepsilon|1) + \overset{1/2}{p(0)} \cdot P_b(\varepsilon|0)$$

$$P_b(\varepsilon) = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

Decoding BPSK

$$P_s(\epsilon|s_i) \leq \sum_{j=1, j\neq i} Q\left(\frac{d_{ij}}{\sqrt{2N_0}}\right)$$

$$P_{s,BPSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

Decoding BPSK

Can we do better?

QPSK

$$E_s = 2E_b$$

$$0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$$

$$\frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \frac{7\pi}{4}$$

$$P_{b,QPSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

Bit Rate and BER

EXAMPLES:	2PAM	4QAM	8PSK	16QAM
Bits/symbol	1	2	3	4
Symbol energy	E_b	$2E_b$	$3E_b$	$4E_b$
BER	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	$\approx \frac{2}{3}Q\left(\sqrt{0.87\frac{E_b}{N_0}}\right)$	$\approx \frac{3}{2}Q\left(\sqrt{\frac{E_{b,\max}}{2.25N_0}}\right)$

BER vs Eb/No

2PAM/4QAM
8PSK
16QAM
Bit-error rate (BER)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2
4
6
8
10
12
14
16
18
20
E_b / N_0 [dB]

LoRa Revisited

Chirp Spread Spectrum (CSS)

- LoRa uses CSS as the modulation scheme
- Operates on scalable bandwidth (125kHz, 250kHz, 500kHz)
- Spreads the signal to make it robust to interference
- Bit rate: 300bps – 37.5kbps
- CSS symbol

$$s(t) = e^{-j2\pi f(t)\,t}$$

- Spreading factor (S)
- Minimum frequency (f_{min})
- Maximum frequency (f_{max})
- Bandwidth ($B = f_{max} - f_{min}$)
- Input bit (f_0)

Chirp Spread Spectrum (CSS)

- CSS symbol

$$s(t) = e^{-j2\pi f(t)\,t}$$

  - Spreading factor (S)
  - Minimum frequency (f_{min})
  - Maximum frequency (f_{max})
  - Bandwidth ($B = f_{max} - f_{min}$)
  - Input bit (f_0)

LoRa Waveform: Spreading Factor

Source: http://www.sghoslya.com

Spreading Factor

SF	BW (kHz)	Rate (bits/s)	Sensitivity
10	125	980	-132dBm
9	125	1,760	-129dBm
8	125	3,125	-126dBm
7	125	5,470	-123dBm
12	500	980	-129dBm
11	500	1,760	-128dBm
10	500	3,900	-125dBm
9	500	7,000	-122dBm
8	500	12,500	-119dBm
7	500	21,900	-116dBm

US 902-928 MHz LoRaWAN Spec

CSS Modulation

- Bits are modulated onto symbols based on the spreading factor
- Spreading factor (SF) determines
  - Modulation order, i.e., how many bits are mapped to a symbol (SF)
  - Symbol duration t_s

$$t_s = \frac{2^{SF}}{B} = \frac{2^{SF}}{f_{max} - f_{min}}$$

- Data rate R_b

$$R_b = \frac{SF}{t_s}$$

$$R_b = \frac{SF(f_{max} - f_{min})}{2^{SF}}$$

CSS Modulation

- Input bits determine the initial frequency f_0
- Depending on SF, there are 2^{SF} different initial frequencies (2^{SF} inputs)
- For a given input m, the signal chirps over all frequencies [f_{min}, f_{max}]
  - Starts from f_0 for m
  - Chirps up to f_{max}
  - Cycles back to f_{min}
  - Chirps up to f_0
- e.g., for m=0, start from f_{min}, chirp up to f_{max}

LoRa Packet

Source: LoRa Alliance

Example

- LoRa message with SF=8 at 125kHz
- 8 bits per symbol
- 2^8=256 levels (symbols)
- 125kHz/256 = 488.3Hz step size
- Message
  - Preamble – 4 symbols (fixed, zeros)
  - Sync – 2 down chirp symbols
  - Payload – 4 symbols (10, 80, 185, 55)

Example

Source: http://www.sghoslya.com

CSS Demodulation

- Goal: Find the initial frequency f_0 and map to the input bits
- Nice trick: Dechirping
  - Multiply each received symbol with an upchirp
  - Results in a flat signal at the initial frequency
- + FFT
  - Results in a peak at the input symbol location

Example

Source: http://www.sghoslya.com

Dechirping Example

Source: http://www.sghoslya.com

Dechirping+FFT Example

Source: http://www.sghoslya.com

Dechirping a Large Packet

Source: http://www.sghoslya.com

LoRa

- Why do we need a preamble?

Receiving a LoRa Packet: Preamble Detection

Dechirp + FFT

Receiving a LoRa Packet: Preamble Detection

Dechirp + FFT

Receiving a LoRa Packet: Preamble Detection

Dechirp + FFT

Receiving a LoRa Packet: Preamble Detection

4 Identical Symbols Premable Detected!

Dechirp + FFT

Receiving a LoRa Packet: Preamble Detection

Receiving a LoRa Packet: Preamble Detection

Receiving a LoRa Packet: Preamble Detection

Receiving a LoRa Packet: Preamble Detection

Receiving a LoRa Packet: Preamble Detection

Receiving a LoRa Packet: SYNC Word

Receiving a LoRa Packet: SYNC Word

SYNC Word Found

Premable End Identifid!

Questions?