Frequency Configuration for LP-WANs in a Heartbeat

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Find out more about Chime at: https://www.witechlab.com/chime.html
Future City-Scale
Internet-of-Things
Low-Power Wide-Area Networks (LP-WANs)

LoRaWAN
Operates in 915 MHz ISM band

Bandwidth
125 KHz

Range
1-10 kms

Battery Life
10 years on AA battery
Battery Life of a LP-WAN client

Battery Life
10 years on AA battery

Fastest Data Rate Only

BATTERY USAGE

Wireless Communication
97% of battery usage

Urban Wireless Impairments ⇒ Significantly Lower Battery Life
Saving power in LP-WANs

Factors affecting the received signal power:

- Fading
- Interference
- Obstructions
- Frequency of Operation
- Datarate

Client cannot control:
- Interference
- Obstructions

Client Config:
- Frequency of Operation
- Datarate

Received Signal Power → Higher Datarate → Transmit Time → Battery Consumption
Frequency Configuration

902 MHz

915 MHz
ISM Band

916 MHz

928 MHz

26 MHz
x 8 freq configs per MHz

208 frequency configurations
Too many frequency configurations to choose from

Large variations in received signal power

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Rx SNR (in dB)</th>
</tr>
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<tbody>
<tr>
<td>902 MHz</td>
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</table>
Campus-Scale Motivation Study

- Top 3.6%
- Current state-of-the-art (pick a random freq)
- Median

CDF vs. Battery Life (% of optimum)
Brute force approach for frequency configuration

# 100s of packets

45 minutes

6.6% battery capacity
Wireless channel quality changes every few minutes

In fact, even interpolation-based methods are ineffective in estimating a good frequency.

All that brute force effort rendered futile.
Can low-power clients find a good frequency-of-operation, without sacrificing their battery life?
Chime – Frequency Configuration for LP-WANs in a Heartbeat

• First system which can estimate an optimal frequency using one packet

• Evaluated over a 0.329 sq. km. testbed at CMU campus in Pittsburgh.

• Achieved average 230% improvement in client battery life
What causes signal power to vary across frequencies?

RX signal power flat across frequencies

RX signal power varies across frequencies
Urban Multipath

Constructive (In phase)

Destructive (Out of phase)
Urban Multipath

Constructive (In phase)

Destructive (Out of phase)

Phase of each path = $2\pi f \tau$

Chime’s approach

Estimate the multipath

⇒ Estimate Rx SNR across frequencies

Rx SNR (in dB)
Chime – Frequency Configuration for LP-WANs in a Heartbeat

One Packet @ Freq $f_t$

Synchronized Phase Measurements

Reverse Engineer Multipath

More general distributed settings

Single antenna base stations

Typical approach to identify multipath (R2F2)
Synchronized Phase Measurements

Client phase offsets

Base station

Common across Base stations

\[ \phi_{B_2} - \phi_{B_1} \]

No client offsets
Synchronized Phase Measurements

Need to measure phases of both at the same time and frequency!

Each base station adds different offset

Master base station removes base station offsets
Need to measure phases of both at the same time and frequency!

1. Transmit at same time and frequency
   - COLLISION!
2. Transmit before/after the packet
   - LP-WAN packets long - Too much drift
3. Transmit in adjacent frequency band => Chime

![Diagram showing time vs frequency with overlapping packets leading to collision and drift issues.](image-url)
Need to measure both phases at the same time and frequency!

Still different frequencies?

\[ \phi_{BM} - \phi_C \]

Offset Free Channel

No base station offsets

\[ f_{\text{known}} \]
Chime – Frequency Configuration for LP-WANs in a Heartbeat

One Packet @ Freq $f_t$

Synchronized Phase Measurements

Reverse Engineer Multipath
Reverse Engineer Complex Web of Multipath

- Virtual Sources

Chime estimates the multipath by estimating these virtual sources

Behavior of reflectors

Where are the reflectors?

Base station 1

Base station 2

Not drawn to scale
Estimate the behavior of reflectors

Given the location of A and B, we can estimate $\alpha_{BA}$
Base station 1

$$BS_1 = h_{d_A} + \alpha_{BA} h_{d_B} + \alpha_{CA} h_{d_C} + \alpha_{DA} h_{d_D}$$

Base station 2

$$BS_2 = h_{d_A} + \alpha_{BA} h_{d_B} + \alpha_{CA} h_{d_C} + \alpha_{DA} h_{d_D}$$

Estimate the behavior of reflectors

Too many variables, too few equations
Feasibility of multipath model

Multipath model only works if $\# \text{reflectors} < \# \text{base stations}$

75% of locations only require us to estimate 2 – 3 dominant paths
Where are the reflectors?

Given the location of A and B, we can estimate $\alpha_{BA}$

For all virtual source locations A and B
- Calculate $\{h_{dA_1}, h_{dB_1}, h_{dA_2}, h_{dB_2}\}$
- Estimate $\alpha_{BA}$
- Check goodness-of-fit $G(A, B) = \frac{1}{\sum_{i=1}^{2}|BS_i - h_{dA_i} - \alpha_{BA}h_{dB_i}|^2}$

Choose $A, B, \alpha_{BA} = \arg\max_{A, B, \alpha_{BA}} G(A, B)$

(More details in the paper...)

Locally convex

Speed up using SGD
Chime – Frequency Configuration for LP-WANs in a Heartbeat

One Packet @ Freq $f_t$

Reverse Engineer Multipath

Recombine at all target frequencies

$f_1, f_2, \ldots, f_k$

Find best frequency
Chime – Estimating optimal frequency of operation

• For each path,
  \[ h_{f_1} \rightarrow h_{f_2} \]

• Channel of multiple paths
  \[ h_{f_2} = h_{f_2@p_1} + h_{f_2@p_2} + h_{f_2@p_3} + \ldots \]

• Channel quality across frequencies
  \[ |h_{f_2}|^2 = h_{f_2} h_{f_2}^* \]

• Choosing optimal frequency-of-operation
  \[ f_{opt} = \arg\max_f \frac{|h_f|^2}{\text{interference}_f + \text{noise}_f} \]

What about interference and noise?
Wideband base station can measure it to make an informed decision
Chime – Frequency Configuration for LP-WANs in a Heartbeat

One Packet @ Freq $f_t$

Reverse Engineer Multipath

Recombine at all target frequencies $f_1, f_2, \ldots, f_k$

Find best frequency

Advise optimum frequency of operation

$$f_{opt} = \arg\max_f \frac{|h_f|^2}{\text{interference}_f + \text{noise}_f}$$

1 packet few seconds 0.0024% of battery capacity
Implementation and Evaluation

**Base station**
- USRP
- GPSDO Clock

**Client device**
- Semtech SX1276
- LoRaWAN transceiver

**Key facts**
- SF 10 | 125 KHz BW
- Processing in the cloud

**Evaluation Testbed**
- 0.5 km
- 0.7 km

- Base stations
Variation in synchronized phase measurements

Synchronized Phase Measurements

Reverse Engineer Multipath

Mean deviation in phase (in radians)

Phase (in radians)

Low(-21dB) Medium(0dB) High(10dB)

Signal-to-noise ratio

Time (in μs)
3.4 dB of SINR improvement over median frequency of operation => 230% increase in battery life*

*Based on battery life model for transmit only clients from Charm
Coherent Combining

LoRaWAN client

Packet decoded collaboratively at the cloud

Baseline = Charm gain over random frequency of operation vs. median frequency of operation

Charm

Gain (in dB)

Number of base stations

4 5 6

Charm Charm + Chime
Other Results

• Comparison with interpolation using multiple frequencies

• CDF of accuracy of predicted SINR

• Ability to identify frequency nulls

More details in the paper ...
Related Work

Synchronizing Base Stations

- WiFi
  - MegaMIMO
    - ref
    - client

Estimating multipath

- Cellular
  - Argos
    - Uses a reference antenna for MU-MIMO systems

- LP-WAN
  - More drift over longer packets

Frequency Configuration

- Chronos
  - Frequency Hopping to estimate multipath

- R2F2
  - Measures uplink channel using downlink channel (Uses massive antenna array)

- Brute force approach

- Narrow bandwidth
  - Single antenna base stations

- 100s of choices
Limitations

• Mobility of clients

• Leverages sparsity of multipath in urban settings

• Does not model fleeting reflectors
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