Bringing Transmit Antenna Diversity to LPWANs: An Experimental Testbed Implementation

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Communications Engineering Lab

Agenda

1. LPWANs: Introduction and Use Cases
2. SpaRSe: From Idea to Implementation
3. Over-the-air Verification
4. Summary and Outlook

LPWANs: Introduction and Use Cases

Low Power Wide Area Networks (LPWANs) are for applications that

- need only (very) low data rates but great range/penetration.
- have relaxed requirements for latency and reliability.
- have strict power, size, and complexity constraints.
- expect devices to run on a single battery for up to 15 years without maintenance.

Popular use cases in **Smart Cities**:

- Smart Lighting
- Smart Mobility
- Smart Waste Management

LPWANs: Introduction and Use Cases

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- narrowband and wideband systems
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- sub-GHz *and 2.4 GHz ISM band frequencies*

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Why should you use the 2.4 GHz band?

- Worldwide availability
- No duty cycle restrictions
- More than 80 MHz of bandwidth
- *Lower wavelength enables diversity*

SpaRSe: From Idea to Implementation

The idea: Use available antennas at the sensor also for *transmission*!

- Provides increased resistance to multipath fading through transmit antenna diversity.
- Should not use additional resources (energy/space/money).

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The core: Full-Diversity Differential Spatial Modulation (FD-DSM)[1]

- 2×2 differential space-time block code
- Simple modulation and ML demodulation.
- Provides transmit diversity order of 2.
- Only requires an RF switch, *no second RF chain*.

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SpaRSe: **Spa**tial Modulation for long-**R**ange **Se**nsor Networks

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SpaRSe: From Idea to Implementation

System design: Builds on IEEE 802.15.4 LECIM DSSS PHY

- IEEE 802.15.4 LECIM DSSS PHY is compatible to Ingenu's RPMA.
- 16/24/32 byte payload size.
- Convolutional FEC with $R = 1/2$.
- DSSS with spreading factor of up to 32768.

$\rightarrow$ *Replace D-BPSK/-OQPSK modulation with FD-DSM.*

SpaRSe: From Idea to Implementation

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FD-DSM Modulation

$$\boldsymbol{X}(t) = \boldsymbol{X}(t-1) \cdot \boldsymbol{S}(t) = \boldsymbol{X}(t-1) \cdot \boldsymbol{A}_q \cdot \boldsymbol{V}_\ell \quad \in \mathbb{C}^{2\times 2},$$

$$\boldsymbol{A}_q \in \left\{ \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & \exp(\mathrm{j}\phi) \\ \exp(\mathrm{j}\phi) & 0 \end{bmatrix} \right\},$$

$$\boldsymbol{V}_\ell \in \mathrm{diag}\left(\exp\left(\mathrm{j}\frac{2\pi u_1 \ell}{L} \right), \exp\left(\mathrm{j}\frac{2\pi u_2 \ell}{L} \right) \right), \quad 0 \leq \ell < L$$

- L, u_1, u_2, and ϕ are design parameters
- $L = 2 \rightarrow u_1 = u_2 = 1$, $\phi = \pi/2 \rightarrow R = 1$ bit/s/Hz

SpaRSe: From Idea to Implementation

FD-DSM Demodulation

- Maximum-Likelihood:

$$(\hat{q}, \hat{\ell}) = \underset{(q,\ell)}{\arg\min} \, \|\boldsymbol{Y}(t) - \boldsymbol{Y}(t-1)\boldsymbol{A}_q \boldsymbol{V}_\ell\|^2$$

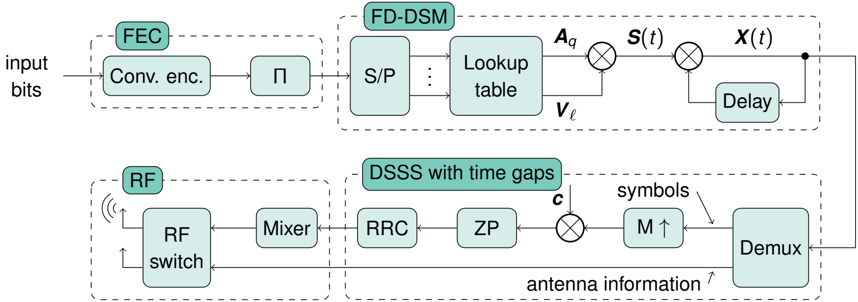
- Soft bits:

$$\mathrm{LLR}_i = \frac{\mathcal{M}_{i,1} - \mathcal{M}_{i,0}}{2\sigma_\mathrm{n}^2}$$

- Optimal symbol assignment depends on channel realization.
- Symbol assignment is done in a Gray-like fashion.

SpaRSe: From Idea to Implementation

Transmitter block diagram



- Zeropadding allows practical single-RF operation.
- Alleviates a crucial issue in Spatial Modulation systems.

SpaRSe: From Idea to Implementation

Receiver design considerations:

- Sensors use unslotted ALOHA.
- Received power is usually far below thermal noise.
- Frames may overlap at the receiver.

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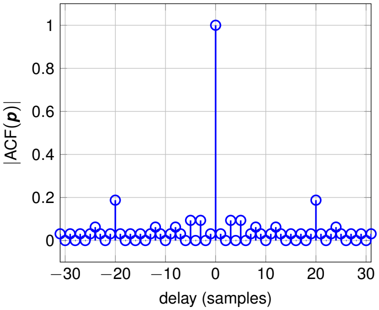
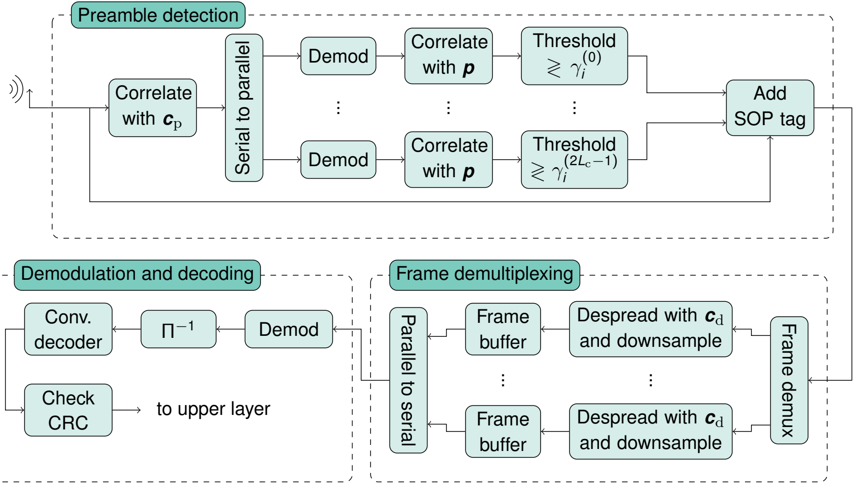
Synchronization:

- Detection using known preamble and adaptive thresholding.
- Filter bank approach to compensate unknown frequency offsets.
- Long frames cause clock drift problems.

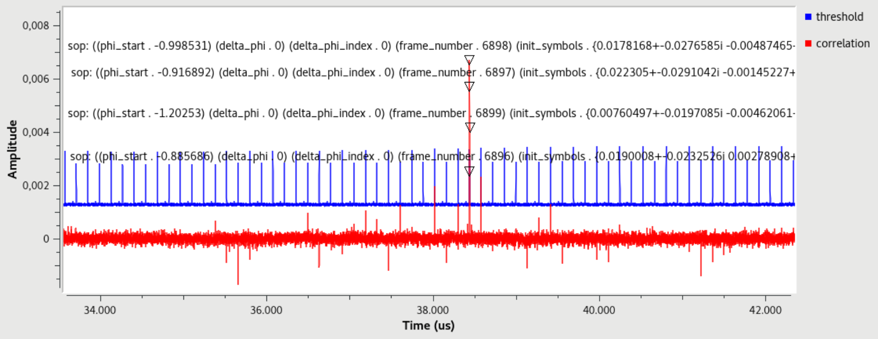


SpaRSe: From Idea to Implementation

Receiver block diagram (single frequency hypothesis)



Over-the-air Verification

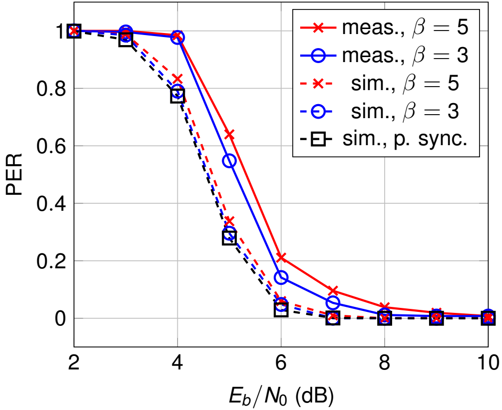


- Adaptive threshold $\gamma_i^{(n)}$ controls false alarm rate.
- Tag triggers demodulation and provides initial symbol and frequency offset estimates.

Over-the-air Verification

Transmission in LOS scenario with shared clock

parameter	value
center frequency	2.5 GHz
chip rate	1 Mchip/s
pulse shaping	RRC ($\alpha = 1$)
spreading factor	$\mathrm{SF} = 256$
payload length	16 byte
preamble length	4 byte
threshold	off, 3σ, 5σ
FD-DSM param.	$L = 2$
frame duration	76.6 ms
data rate	1.566 kbit/s
radio front end	USRP B210



Summary and Outlook

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Summary

- Testbed implementation of SpaRSe transceiver in GNU Radio
  - Polyphase synchronization algorithm
  - Adaptive thresholding
- Successful OTA verification using USRPs
- Get the code: `https://github.com/kit-cel/gr-lpwan`

Outlook:

- Further optimize code.
- Use FPGA for the synchronization part.
- Evaluate SpaRSe using channel measurements.

Thank you for your attention!