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IoT technologies: LoRa and NB-IoT

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Outline

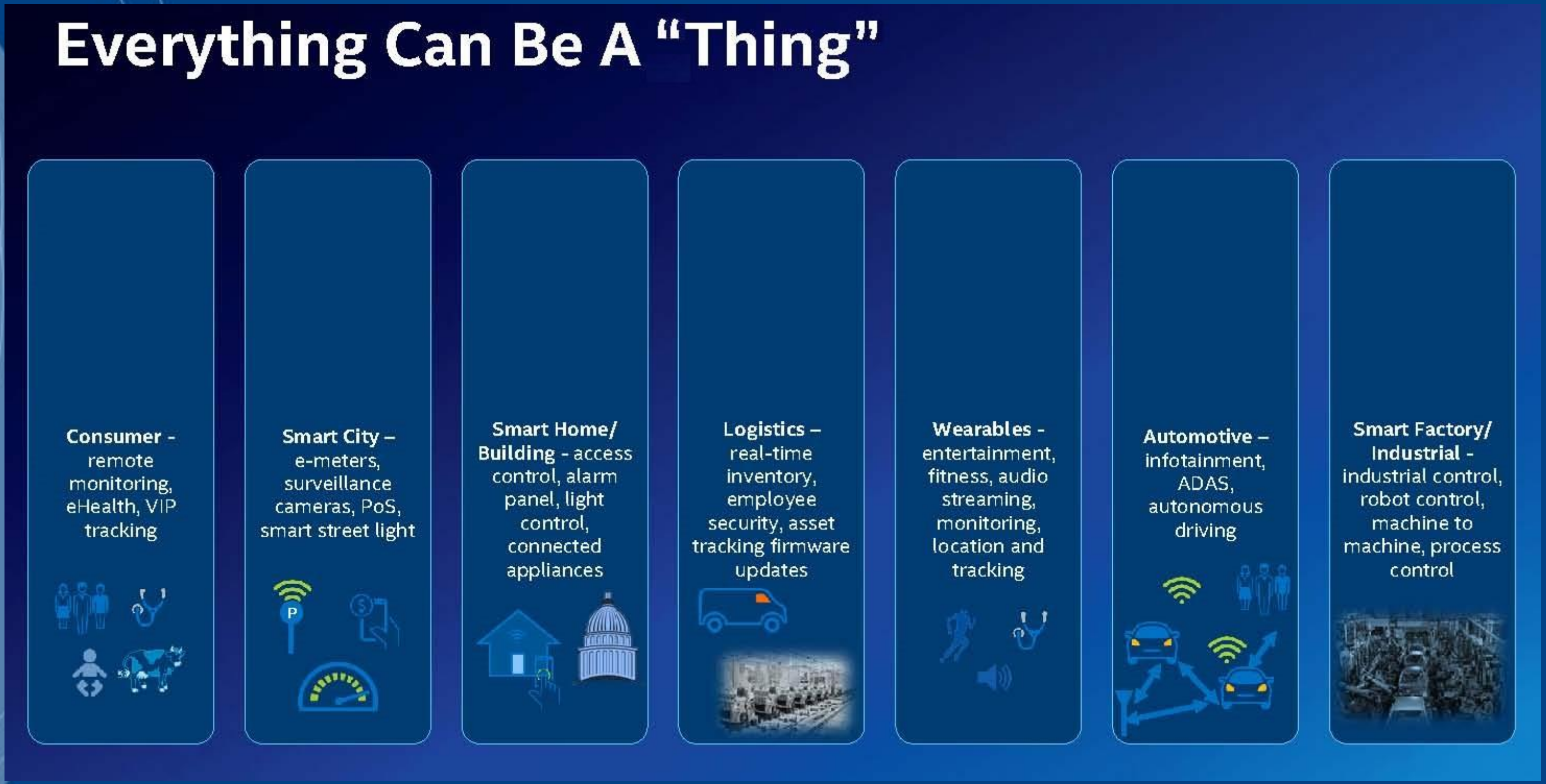
Introduction – motivation

Chirp spread spectrum (CSS) and LoRa characteristics
- Modulation – demodulation
- Complete transceiver chain
- Multiple access
- Interference – scalability
- Synchronization aspects

OFDM and the cellular service perspective
- OFDM concept and synchronization sensitivity
- From LTE to NB-IoT Network architecture
- NB-IoT basics - Design principles
- Radio resource control (idle and connected modes)
- Physical layer
- NB-IoT DL – UL transceivers diagrams

Comparisons and discussion

Introduction – IoT applications…



Introduction – Challenges…

General characteristics

Extended coverage: IoT can be located where the coverage is very low (subsoil, underground parking, interior of buildings, etc.). Due to spectral mask restrictions, IoT device cannot increase its power. This results in a very low SNR regime, i.e., mechanisms are required to reach areas of low coverage.

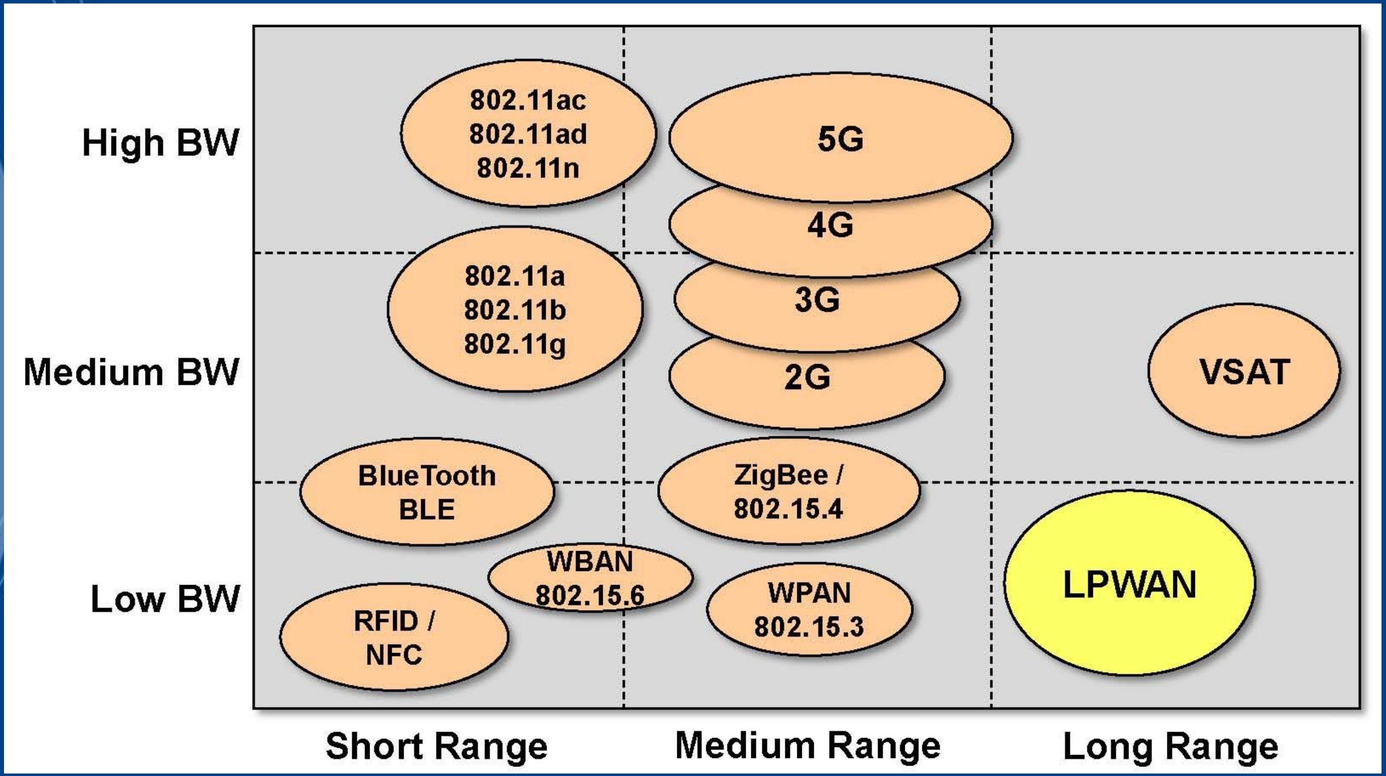
Massive number of devices: In case of IoT cellular technologies, growth in the number of devices will be huge. Managing a massive number of accesses to the network, while minimizing outage and providing adequate quality of service for different types of devices is a key requirement.

Low power consumption: Since IoT do not require continuous data transmission and the amount of data per transmission is small, they do not need to be constantly connected or active. Also, IoT devices are generally low cost and low data rate with long-lasting batteries (10 years or more).

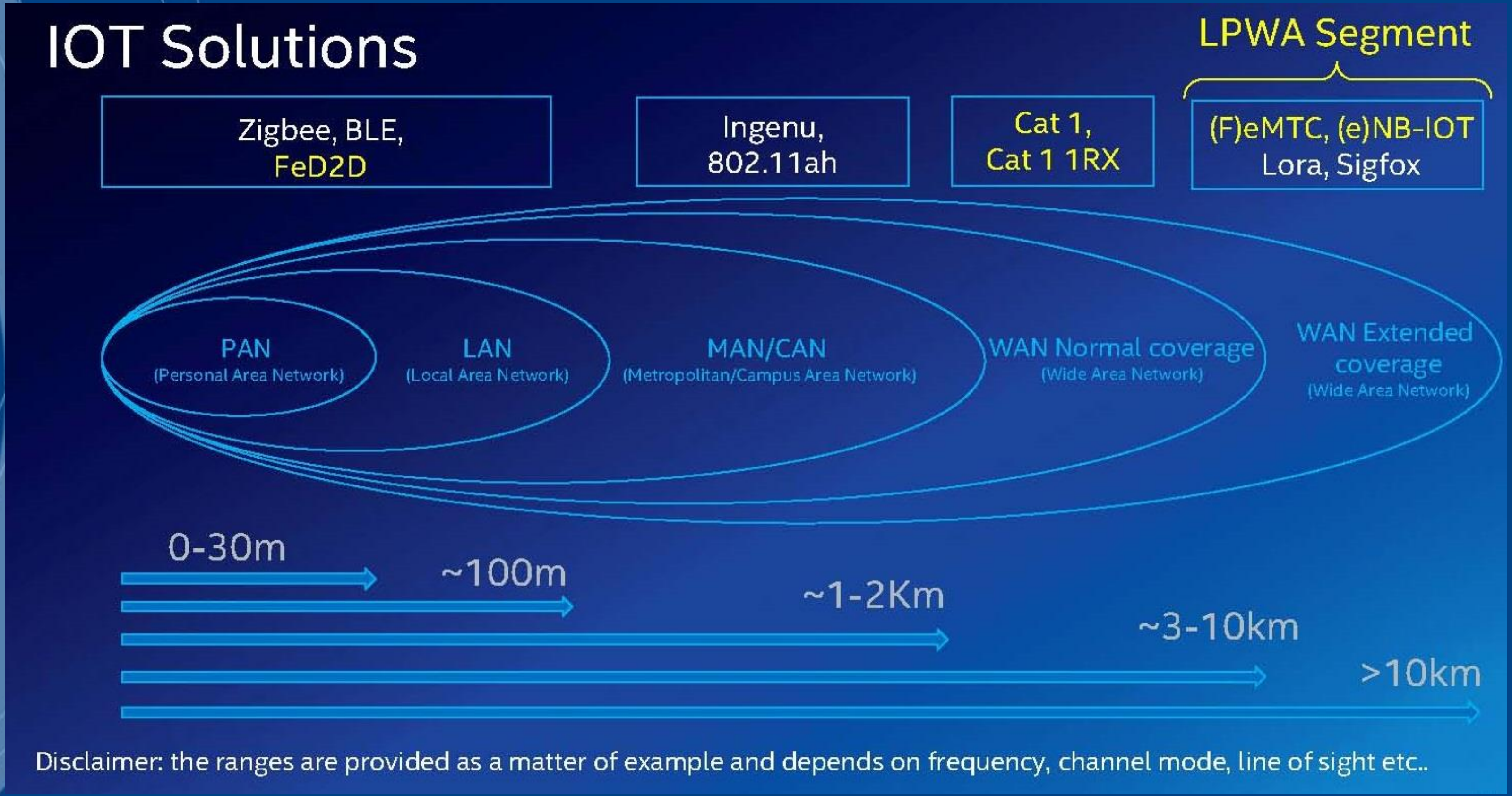
High data rate – low latency vs low data rate – delay-tolerant devices: The current performance of communications networks (LTE) is oriented to H2H devices. That is not the case to allow an efficient service of a massive number of low-data rate delay-tolerant IoT devices associated to smart meter data.

Introduction – Coverage…

Bandwidth required versus coverage



Introduction – Coverage…



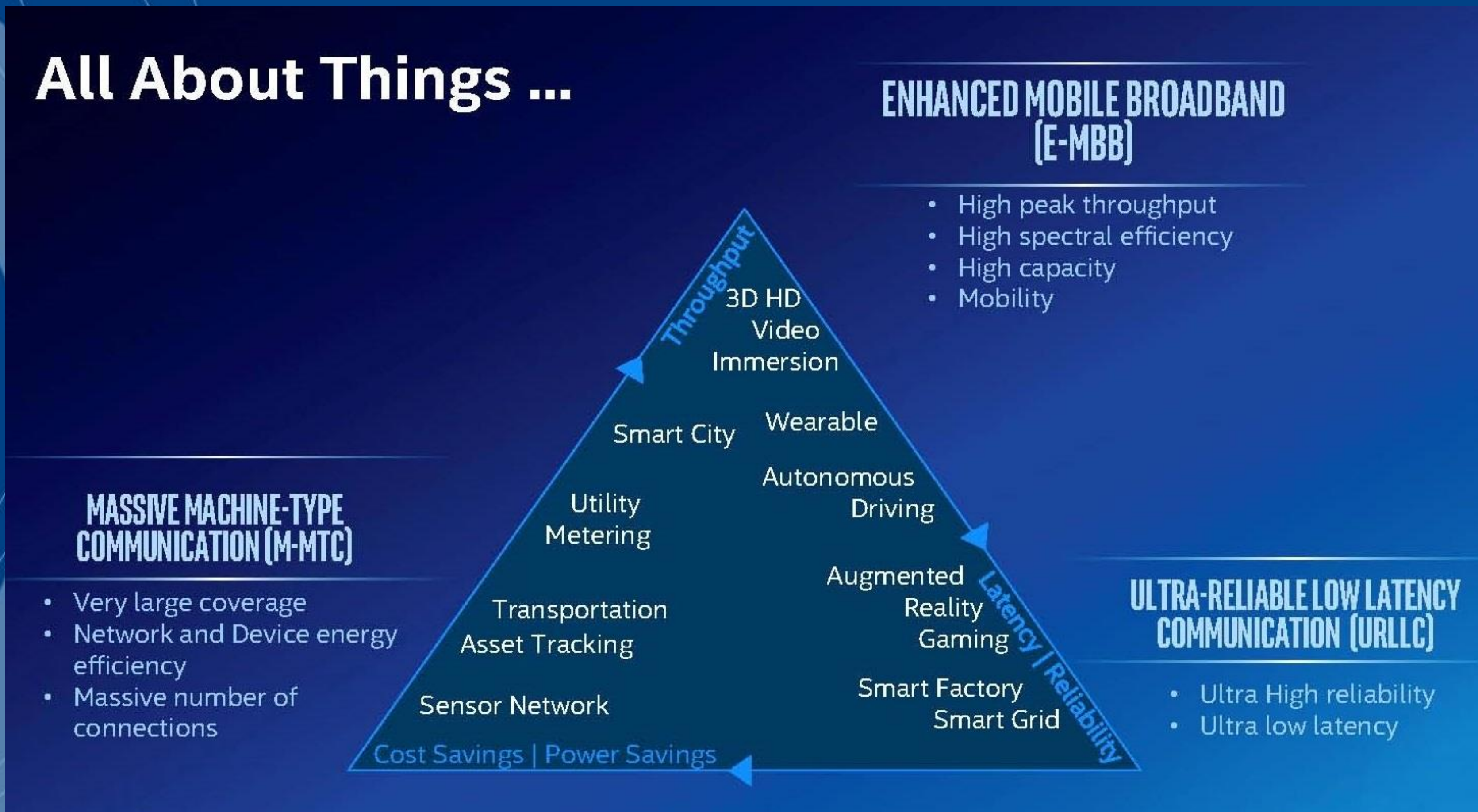
Introduction – Proprietary LPWAN…

General characteristics of proprietary LPWAN

Table 9.1 Characteristics of typical unlicensed bandwidth, low energy - long range technologies.

	LoRa	**SigFox**	**Ingenu**
Modulation:	Chirp spread spectrum	Ultra narrow band DBPSK (UL), GFSK (DL)	Random phase multiple access DSSS (UL), CDMA (DL)
Bandwidth:	125 kHz	160 Hz	1 MHz
Frequency bands:	Sub-GHz ISM	Sub-GHz ISM	ISM 2.4 GHz
Data rate:	0.3 - 27 kps (50 kps with FSK)	100 bps (UL), 600 bps (DL)	156 kbps (UL), 624 kbps (DL)
Coverage:	5 km (urban), 15 km (rural)	10 km (urban), 50 km (rural)	5 - 6 km (urban)
Ner. of channels:	10 in EU 64+8 (UL) and 8 (DL) in US	360 channels	40 x 1 MHz channels up to 1200 signals/channel
Link symmetry:	Yes	No	No
FEC:	Yes	No	Yes
MAC:	unslotted ALOHA	unslotted ALOHA	CDMA similar
Adaptive data rate:	Yes	No	Yes
Payload length:	up to 250 B	12 B (UL), 8 B (DL)	10 kB
Multicast updates:	Yes	No	Yes
Localization:	Yes	No	No

3GPP applications…



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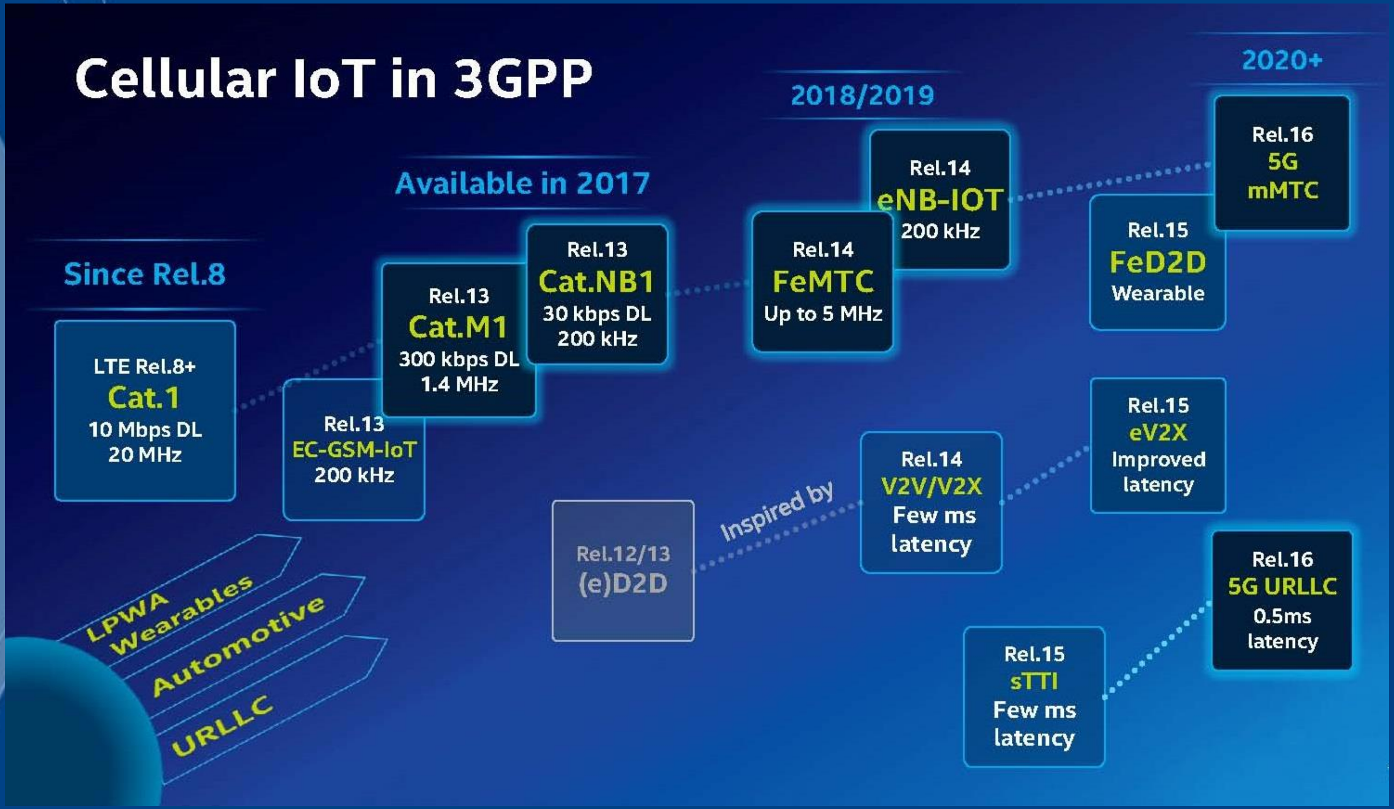
Introduction – Licensed (3GPP) LPWAN…



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Chirp spread spectrum (CSS) and LoRa characteristics

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LoRa: Introduction

LoRaWAN is a very popular LPWAN communications protocol for the Internet of things (IoT).

Its physical layer (PHY), which is called LoRa, is based on a proprietary spread spectrum modulation (in fact, a Frequency Shift Chirp Spread Spectrum) scheme that uses chirp modulation (a particular Zadoff – Chu sequence) as its basis.

LoRa is able to work in a wide range of operational signal-to-noise ratios (SNRs), due to the support of multiple spreading factors (SF) and code rates.

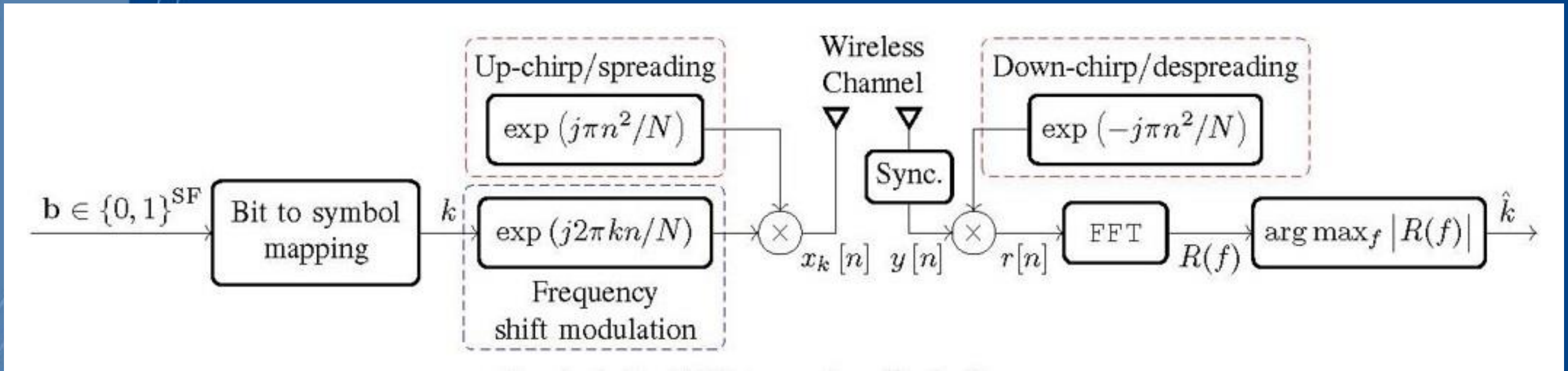
The physical layer of LoRa is the only part of LoRaWAN which is not open-source.

The LoRa modulation

LoRa uses a spread-spectrum modulation with a bandwidth *B* and $N = 2^{SF}$, chips per symbol, where *SF* is called the *spreading factor* with $SF \in \{7, \cdots, 12\}$.

The general *discrete-time baseband equivalent equation* of a LoRa symbol *k* (when *fs =B*) is:

$$x_k[n] = e^{j2\pi\left(\frac{n^2}{2N} + \frac{kn}{N}\right)}$$



The LoRa modulation

A *special defined* LoRa symbol *s* (when *fs* =*B*) is:

$$x_s[n] = e^{j2\pi\left(\frac{n^2}{2N}+(\frac{s}{N}-\chi_s[n])n\right)}$$

where now

$$s = N(k + \chi_s[n]) \qquad \chi_s[n] = \begin{cases} 1/2, & n < N - s \\ 3/2, & n \geq N - s \end{cases}$$

This mapping defines a continuous phase (identical instantaneous phase at the beginning and end of each symbol) that is useful for time and frequency synchronization.

The processing gain is

$$G = 10\log_{10}\left(\frac{N}{SF}\right)$$

The LoRa modulation…

When considering the discrete-time baseband-equivalent signal, the bandwidth *B* is split into *N* frequency steps.

The symbol duration is: $T_s = \frac{N}{B}$

A symbol $s \in \mathcal{S}$, where $\mathcal{S} = \{0, \cdots, N-1\}$, begins at frequency $\left(s\frac{B}{N} - \frac{B}{2}\right)$.

Frequency increases by $\frac{B}{N}$ at each chip until it reaches the Nyquist frequency $\frac{B}{2}$.

When Nyquist frequency is reached, there is a frequency fold to $-\frac{B}{2}$ at chip $n_{fold} = N - s$.

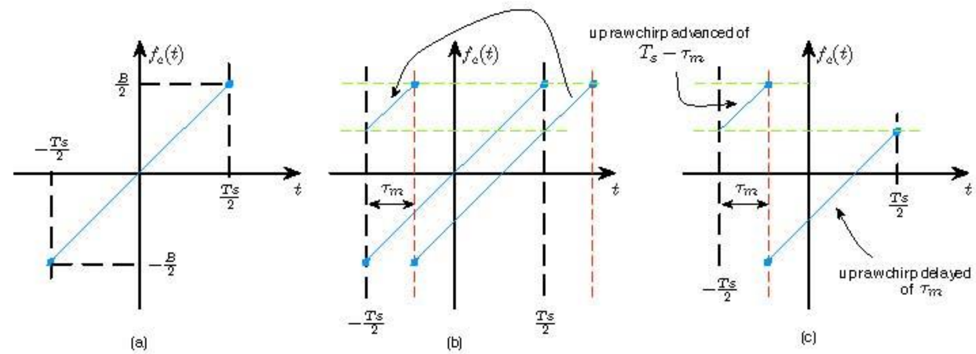


Figure 1. Symbol $\rightarrow$ chirp association process - (a) up raw chirp - (b) process illustration - (c) chirp associated to the mth symbol

The LoRa Demodulation

After transmission over a time-invariant and frequency-flat wireless channel and AWGN *z[n]*, the received LoRa symbol is *y[n]*.

To demodulate the symbols, the inner product of the received signal with all the possible symbols (Maximum Likelihood) is computed as

$$X_k = \sum_{n=0}^{N-1} y[n]x_k^*[n] = \sum_{n=0}^{N-1} e^{j2\pi(\frac{s-k}{N})n+\phi} + \overline{z}[n]$$

where $\overline{z}[n] \sim \mathcal{CN}(0, N\sigma^2)$. In a typical non-coherent LoRa receiver a symbol estimate is obtained as

$$\hat{s} = \arg\max_{k \in \mathcal{S}}(|X_k|)$$

The complexity is $O(N^2)$

The LoRa demodulation…

An alternative low-complexity method: First, the received signal is multiplied by the complex conjugate of the reference signal *xref[n]* (a pure *upchirp,* symbol for *s* = 0):

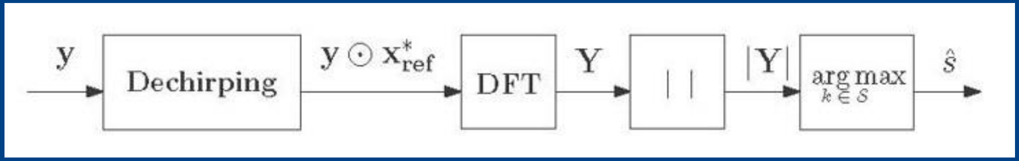
$$x_{ref}[n] = e^{j2\pi\left(\frac{n^2}{2N} - \chi_s[n]n\right)}$$

Then, the non-normalized discrete Fourier transform (DFT) is applied to obtain

$$\boldsymbol{Y} = \mathrm{DFT}(\boldsymbol{y} \odot \boldsymbol{x}^*_{ref})$$

Non-coherent demodulation can be performed by selecting the frequency bin index with the maximum magnitude

$$\hat{s} = \arg\max_{k \in \mathcal{S}}(|Y_k|)$$



Using FFT the complexity is

$$O(N \log N)$$

Complete transceiver chain…

Whitening
The payload data to be transmitted may contain long sequences of either ones or zeros, introducing a DC-bias which results in the signal to have non-uniform power distribution.

Error-Correction Coding
LoRa uses simple schemes for error detection and error correction.

Interleaving
LoRa uses a diagonal interleaver to distribute the (up to SF) bit errors resulting from a symbol error over multiple (SF) code words.

Gray mapping
LoRa uses a reverse Gray code for the mapping from bits to symbols.

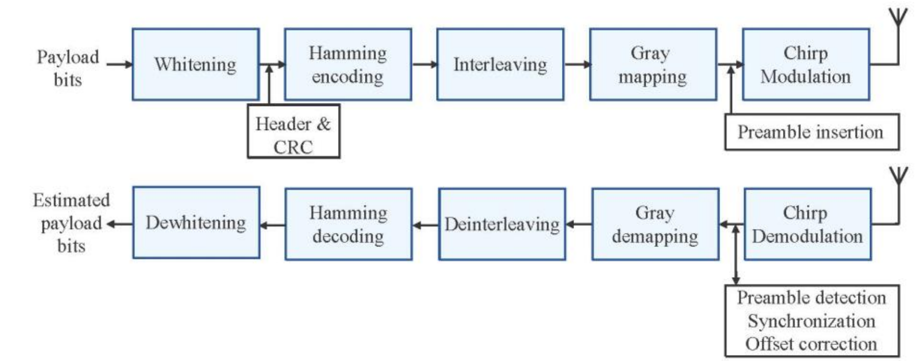


Figure 2.2 – The LoRa PHY Tx and Rx chains.

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LoRa packet structure

The structure of a LoRa packet consists of a preamble, an optional PHY Header, the PHY payload, and an optional CRC of the payload.

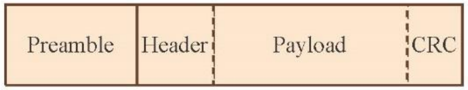


Figure 2.3 – The structure of a LoRa packet.

Preamble
Upchirps: programmable number of upchirps, i.e., symbols **x**0, used to detect the existence of a LoRa packet.

Network Identifiers: 2 symbols used for frame synchronization and to distinguish between devices from different networks.

Downchirps: two and a quarter frequency synchronization symbols, downchirps, used to distinguish between CFO and STO.

Header (Optional): length of the packet, code rate, presence of CRC.

Payload and CRC: data packets or MAC layer control packets.

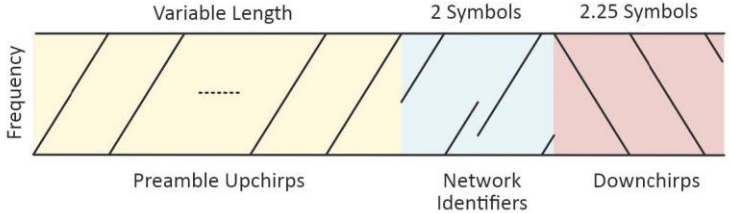


Figure 2.4 – The structure of the LoRa preamble.

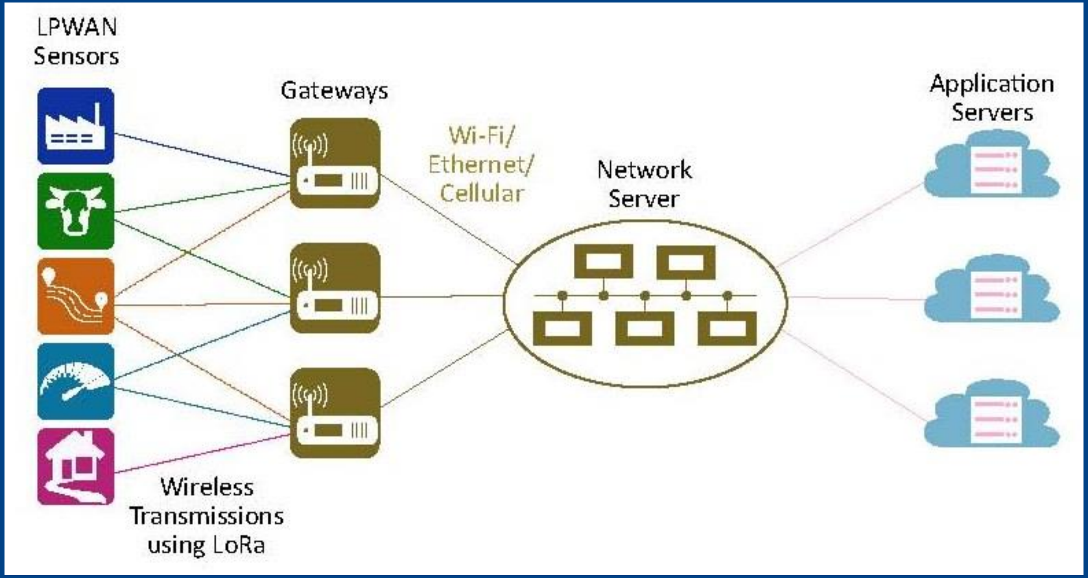
LoRaWAN Multiple Access

The MAC scheme of LoRaWAN is relatively simple, based on an open-source protocol of the LoRa Alliance that is stacked on top of the LoRa PHY layer. LoRaWAN uses a star topology.

Gateways: reception and demodulation of LoRa packets and forward data to the network server.

Network server: collects receptions from multiple gateways (same packet can arrive from multiple paths) using associated diversity. Schedules downlink packets (ACKs) to the end nodes, as well as MAC commands.

Application servers: owned by third parties allowing multiple applications connected to the same network server.



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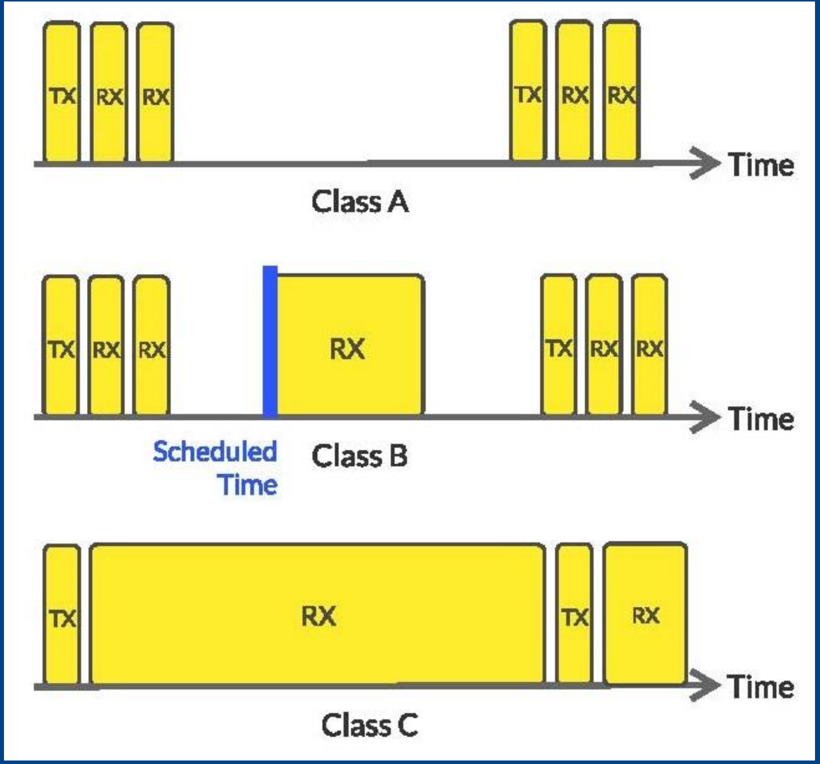
LoRaWAN Multiple Access…

LoRaWAN Classes of Devices

Class A: nodes with the lowest power consumption since transmissions can only be initiated by themselves, using ALOHA protocol. As a result, the end-node radio is turned off most of the time.

Class B: adds that the end nodes periodically open reception windows for scheduled DL messages. Requires a precise timer (to be synchronized to the network server).

Class C: continuously listen for DL messages, with Parameters set to the 2nd window parameters of Class A devices, except when they are transmitting an UL message or during the 1st window that follows an UL message. Leads to the highest power consumption.



LoRaWAN Multiple Access…

Adaptive Data Rate Mechanism

The ADR mechanism dynamically changes SF, coding rate and the transmission power of an end node to maximize both the battery life and to optimize the total network throughput.

The ADR mechanism runs in both the end node (specified by the LoRa Alliance) and the network server (defined by the operator), and each end node can choose if it will allow the network server to govern the ADR or if the end node will govern it itself.

The ADR algorithm on the network server can modify the SF and the transmission power, while the ADR algorithm on the end node can only increase the SF, after some failed attempts to deliver a packet.

Interference in LoRa

LoRa networks operate in the ISM band, together with many other wireless technologies. Moreover, due to the pure ALOHA MAC scheme of LoRaWAN, the number of LoRa packet collisions in a network increases rapidly with the number of connected end nodes.

Cross-Technology Interference

Research results show that LoRa is relatively resilient to interference from IEEE 802.15.4g, and more susceptible to interference from UNB (Sigfox) than the other way around.

Due to the spread spectrum nature of LoRa, cross-technology interference essentially shows up – and can be modeled – as AWGN. Hence, the effect of cross-technology interference can be included as a reduced SNR.

Interference in LoRa…

Same-Technology Interference

Same-technology interference can be divided in two main categories: the first is interference from other LoRa nodes which use different spreading factors, which is called *inter-SF interference*. The second, and most severe type, comes from LoRa nodes transmitting with the same spreading factor, and is called *same-SF interference*.

In general, inter-SF interference (due to the approximated orthogonality between different SF) can be treated as white noise. That is not the case of same-SF interference.

Interference in LoRa…

Same SF interference

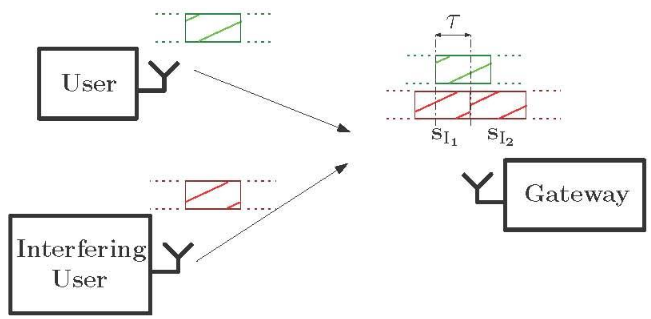


Figure 3.2 – Illustration of LoRa uplink transmission with one interfering user having an arbitrary offset τ.

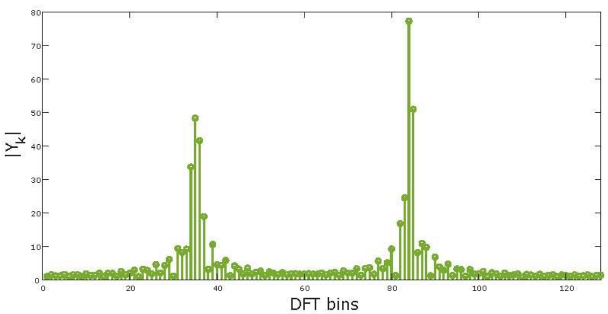


Figure 3.3 – The magnitude of an example transmitted interference pattern for SF = 7, $s_{I_1} = 83$, $s_{I_2} = 4$, and $\tau = 48.8$.

Interference in LoRa…

Same SF interference

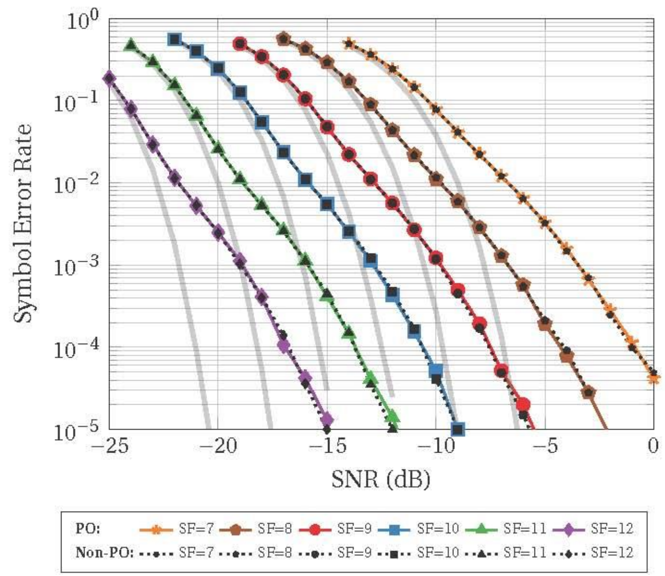


Figure 3.6 – Symbol error rate of the LoRa modulation under AWGN and same-SF interference for SF ∈ {7, . . . , 12} and SIR = 3 dB. Black dotted lines show the SER when ignoring the phase offset ω and thick transparent lines show the SER when there is only AWGN for comparison

LoRaWAN scalability

Deployments of LoRa links between an end-node and a gateway, or in peer-to-peer links, can provide important experimental measurements regarding the RSSI, the coverage for different SF, the packet delivery ratio of a single device placed in different positions, etc.

LoRaWAN *scalability* is difficult to be assessed directly through deployments, since scalability with large deployments is difficult, costly, and results cannot easily be generalized to any network configuration.

For this reason, either mathematical LoRaWAN models have been developed or system-level simulations have been carried out to assess the scalability of LoRa networks.

Remark: as the main drawback of LoRa techniques, load scalability (increasing traffic) cannot be predefined and/or well established.

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LoRa synchronization

Frame Synchronization

The main synchronization parameters to be considered with the simplified demodulation technique are:

The sample time offset (STO), τ_{STO} that can be separated into an integer part $L_{STO} = \lfloor \tau_{STO} \rfloor$ and a fractional part $\lambda_{STO} = \tau_{STO} - \lfloor \tau_{STO} \rfloor$.

The carrier frequency offset (CFO), Δf_c expressed as an equivalent time $\tau_{CFO} = (\Delta f_c N)/f_s$, can also be split into an integer part $L_{CFO} = \lfloor \tau_{CFO} \rfloor$ and a fractional part $\lambda_{CFO} = \tau_{CFO} - \lfloor \tau_{CFO} \rfloor$.

The sampling frequency offset (SFO), related to a fractional correction of the clock used.

The time offset start time ambiguity related to header or payload.

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LoRa synchronization

Effects of sample time offset (STO) and carrier frequency offset (CFO)

Both (time and frequency) offsets are related and must be compensated at the same time.

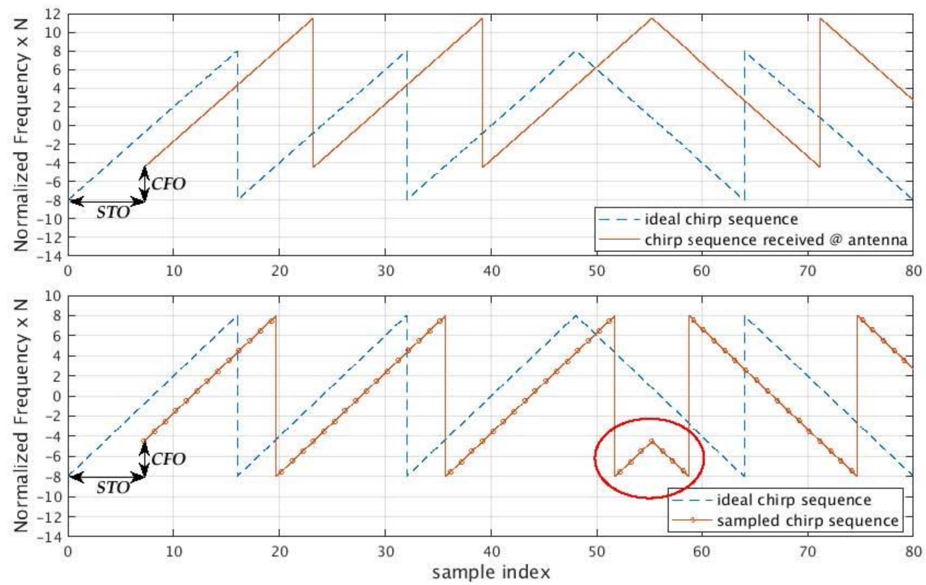

Fig. 3. Plot of $N*$ normalized frequency component of $S_{N_0}(n)$ assuming $N = 16$ and $N_0 = 0$ and for a signal composed of three *up-chirps* and two *down-chirps*. Top: signal received at the antenna suffering from an STO of 7.2 samples and a CFO of 3.5 frequency bins. Bottom: same signal after sampling at a normalized rate of $1/N$ (assuming $SFO = 0$).

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LoRa synchronization

Preamble estimation of the integer part of STO and CFO

Ignoring λ_{STO}, λ_{CFO} an SFO and considering the firsts symbols in the preamble (upchirps), the received signal is

$$y[n] = e^{j2\pi\left(\frac{n^2}{2N}+(\frac{N-L_{STO}}{N}-\chi[n])\right)} \times e^{j2\pi n\frac{L_{CFO}}{B}+\phi}$$

Then, using the product by $x^*_{ref}[n]$ we obtain

$$x[n] \times x^*_{ref}[n] = e^{j2\pi n\left(\frac{L_{CFO}}{B}+(\frac{N-L_{STO}}{N})\right)} \times e^{j\phi}$$

Now using the lasts symbols in the preamble (downchirps), and the product by $x_{ref}[n]$ we obtain

$$x[n] \times x_{ref}[n] = e^{j2\pi n\left(\frac{L_{CFO}}{B}-(\frac{N-L_{STO}}{N})\right)} \times e^{j\phi}$$

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LoRa synchronization

Preamble estimation of the integer part of STO and CFO

Then, after the DFT and the maximum bin we obtain

$$\begin{aligned} f_{up} &= \frac{L_{CFO}}{B} + \left(\frac{N - L_{STO}}{N}\right) \\ f_{down} &= \frac{L_{CFO}}{B} - \left(\frac{N - L_{STO}}{N}\right) \end{aligned}$$

Finally

$$\frac{L_{CFO}}{B} = \frac{f_{up} + f_{down}}{2}$$

LoRa synchronization

Preamble estimation of the fractional part of CFO

Considering now the maximum bin at the DFT output of one upchirp symbol with the corrected L_{STO},

$$e^{j\phi_1} = e^{j2\pi k f_{up} + j2\pi k \frac{\lambda_{CFO}}{B}}$$

Then, for two consecutive symbols

$$\phi_2 - \phi_1 = (k+N)\frac{\lambda_{CFO}}{B} - (k)\frac{\lambda_{CFO}}{B}$$

From where

$$\lambda_{CFO} = \frac{B}{N}(\phi_2 - \phi_1)$$

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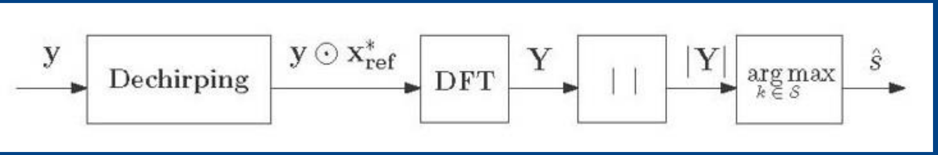
LoRa synchronization

Full receiver demodulation and synchronization



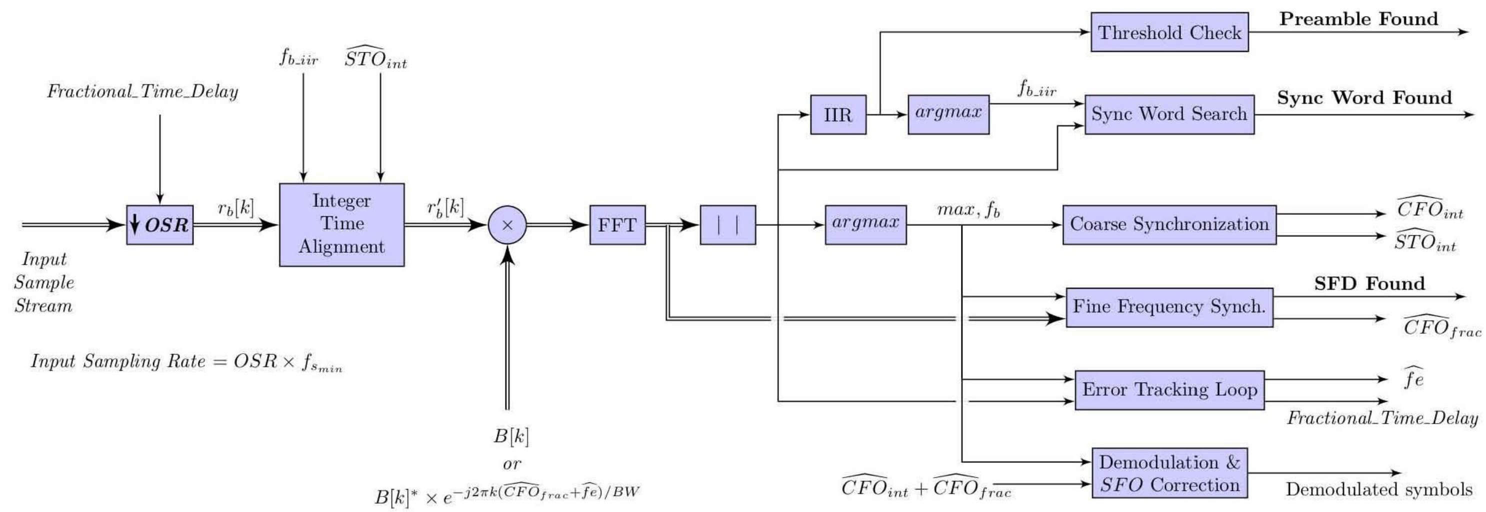


Fig. 5. Conceptual view of LoRa start-of-frame synchronization algorithm. Double arrows indicate complex signals.