EE-432
Systeme de Telecommunication

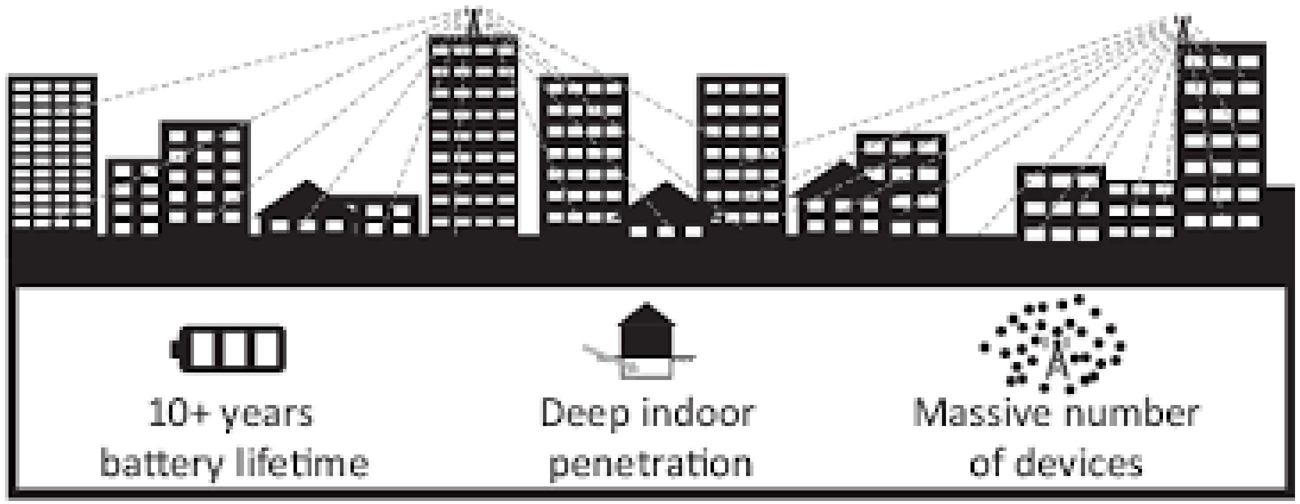
Prof. Andreas Burg
Joachim Tapparel, Yuqing Ren, Jonathan Magnin

Spread Spectrum Modulation for IoT

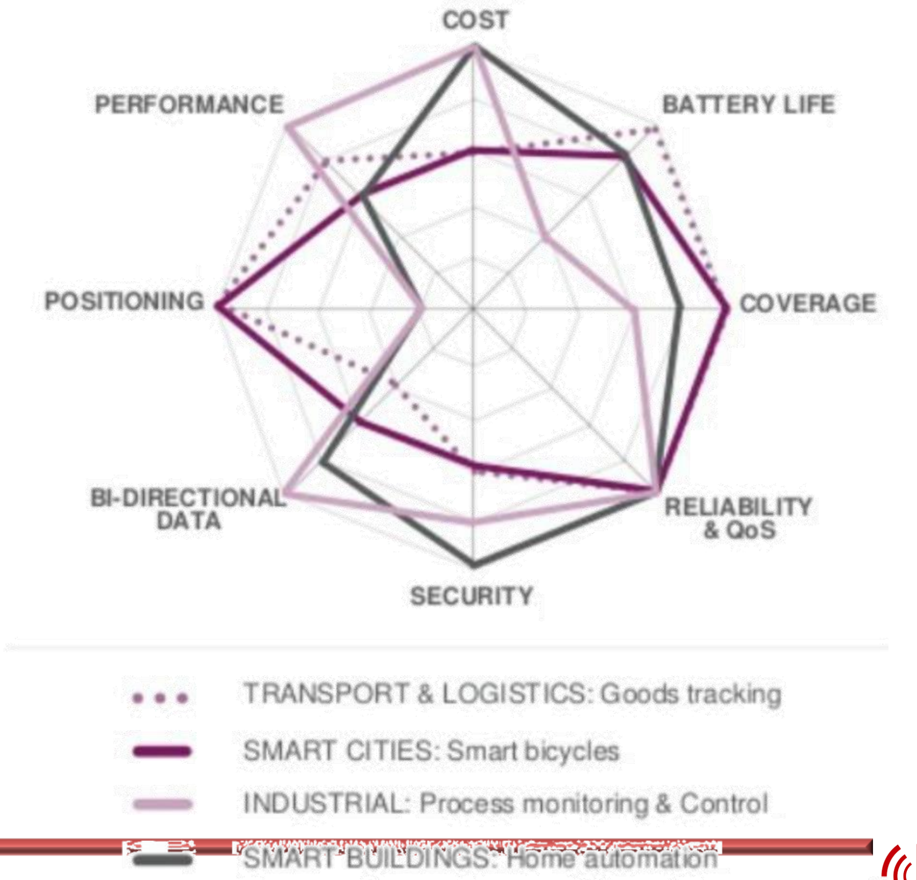
Machine type communication (MtC)

- **MTC provides connectivity for the Internet of Things (IoT)**

- **Requirements are tailored for a huge number of low-cost devices**
  - Low cost and long battery life with low data rates



MTC for IoT objectives



Machine type communication (MtC) KPIs

- **Evolution of wireless standards for IoT needs to address four major challenges**

Ultra-long battery lifetime

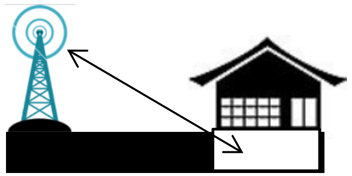
Battery lifetime of 10+ years through ultra-short duty cycle with energy efficient wakeup and low-complexity synchronization, efficient sleep modes (eDRX)

System device density

High device density and large number of devices for ultra-low data rates by low-overhead channel access procedures

Device cost

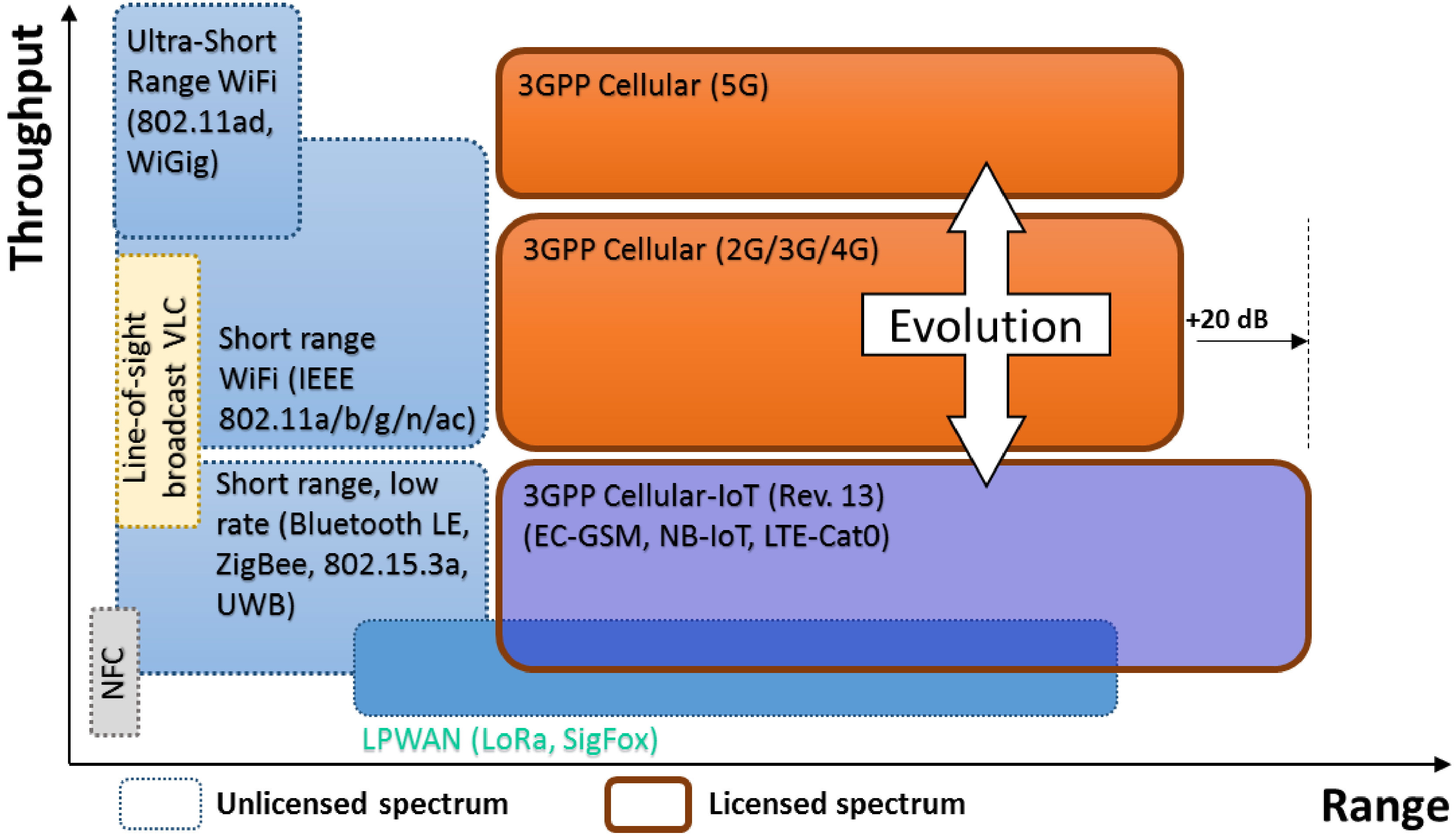
Ultra-low cost devices through simple physical layer modulation and MAC layer protocols



Long-range & Coverage

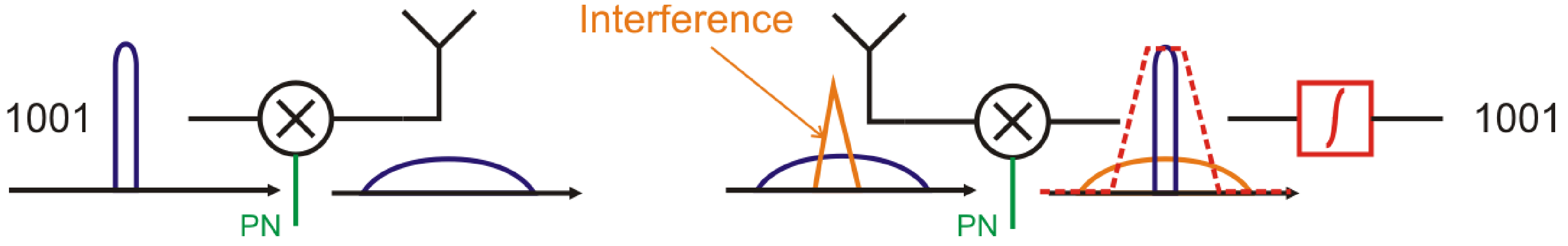
Long range and coverage of indoor / basement areas with 15 – 20 dB additional link budget, achievable with redundancy at the cost of data rate

IoT Standards Landscape



Spread Spectrum Modulation

- **Spread spectrum:** Distribute signal across a larger bandwidth than required
  - Time domain view: transmit power and symbol duration remain unchanged
  - Frequency domain view: power spectral density is reduced (same signal power is distributed over wider bandwidth)
- **A simple example of Spread-Spectrum Modulation:**
- **Direct sequence spread spectrum illustrates the idea and advantages**



- Distribute the signal over a large bandwidth (more dimensions that required)
- Transmit signal (and expose it to noise and interference)
- Collect back only the signal from the places where it was actually located

Flavors of Spread Spectrum Modulation

- **Direct Sequence (DS):** A carrier is modulated by a digital code sequence in which bit rate is much higher than the information signal bandwidth
- **Frequency Hopping (FH):** A carrier frequency is shifted in discrete increments in a pattern dictated by a code sequence
- **Time Hopping (TH):** Bursts of the carrier signal are initiated at times dictated by a code sequence
- **Hybrid Systems:** Use of combination of the above

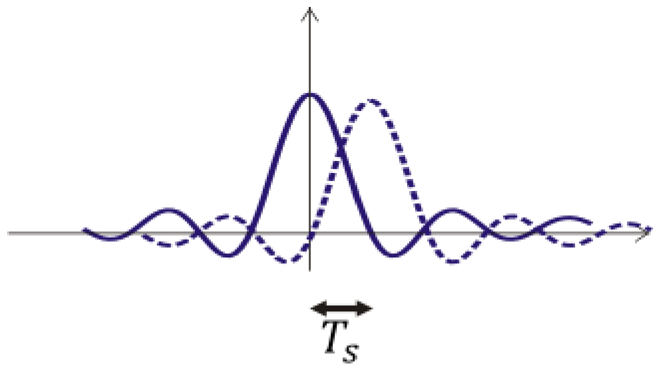
We consider only Direct Sequence Spread Spectrum (DSSS) modulation

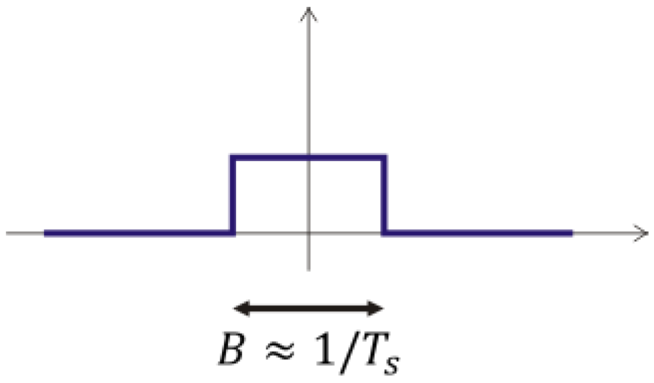
Signal Representation

- **Remember:** Narrow-band modulation with symbol duration T_s

$$x(t) = \sum_{j=-\infty}^{+\infty} b_j g(t - jT_s)$$

  - Each symbol is represented by the waveform of a (narrow band) pulse shaping filter
  - Bandwidth of the pulse shape: $B \approx 1/T_s$



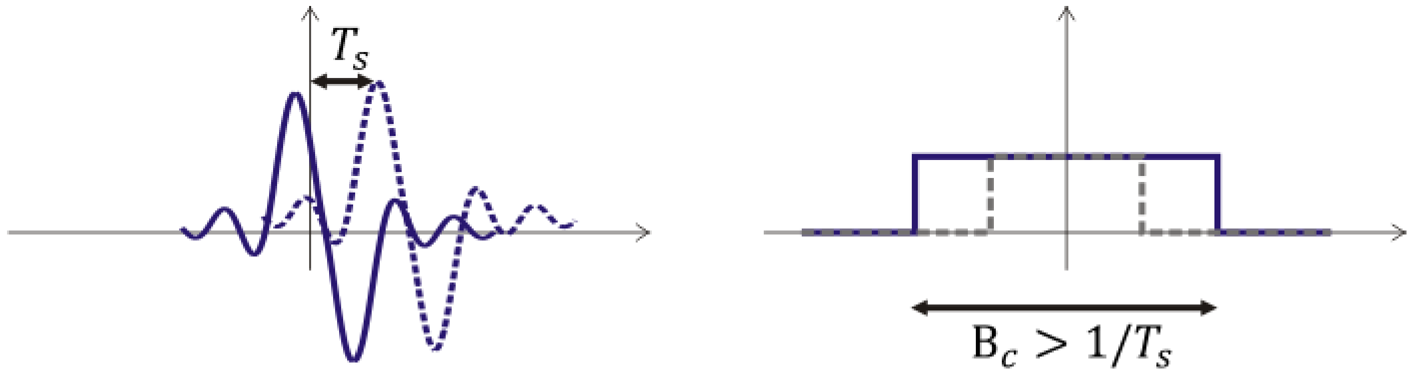


Signal Representation

- **Spread spectrum modulation**
  - Replace the narrow band pulse shaping filter $g(t)$ with a signal waveform $c(t)$ with bandwidth B_c

$$x(t) = \sum_{j=-\infty}^{+\infty} b_j c(t - jT_s)$$

  - For $\mathrm{B}_c > 1/T_s$ we get a bandwidth expansion
  - Bandwidth expansion factor (spreading factor): $G = \mathrm{B}_c/B$



Implications of Increasing Bandwidth

- **What is the difference between the "narrow band" pulse shape and the "wideband" symbol waveform?**

- **Consider the signal-space representation of $g(t)$ and $c(t)$**
  - Write as sum of orthogonal basis functions $\varphi_j(t)$

$$\mathrm{g}(t) = \sum_{j=1}^{N} g_j \varphi_j(t) \qquad c(t) = \sum_{j=1}^{N_c} c_j \varphi_j(t)$$

  - **Signal space dimension**: number of orthogonal basis functions required to represent a signal
  - Bandwidth and symbol duration define the signal space dimension

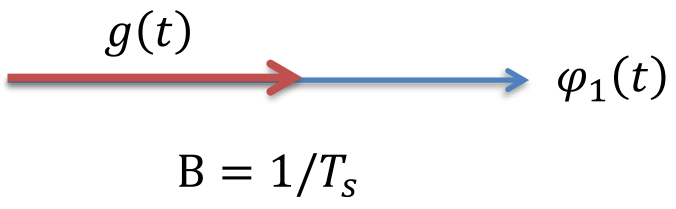
$$N \approx T_s B \qquad N_c \approx T_s B_c = GN$$

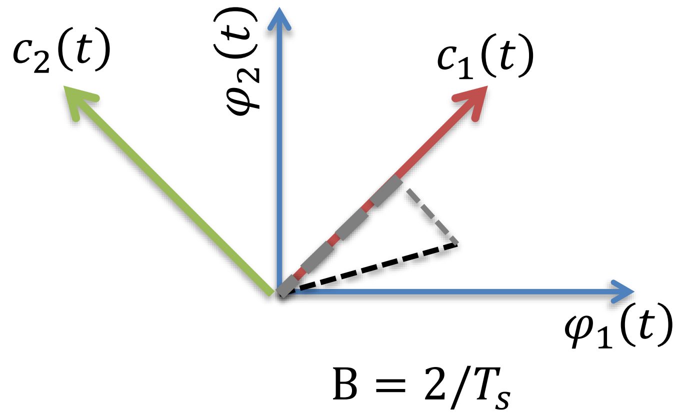
  - Narrowband signal (pulse shape): $B \approx 1/T_s$ => $N = 1$
  - Wideband signal (spreading waveform): $B_c \approx G/T_s$ => $N_c = G$

Spread spectrum modulation increases the dimension of the signal space

Signal Space Representation

- **Geometric interpretation**





- Signal space dimensions can be for example: subsequent pulses, orthogonal carriers, …
- Wideband signals
  - Symbols can span more than one independent dimensions
  - Multiple spreading sequences are possible
  - **Up to N_c spreading sequences are completely orthogonal**

Direct Sequence Spread Spectrum (DSSS)

- **Basis functions for wideband signal waveform (spreading sequence)**
  - Time-orthogonal Nyquist pulses with bandwidth $B_c = \mathrm{G}/T_s$

$$\varphi_i(t) = g_c(t - iT_c)$$

  - Individual pulses are called **chips**
  - Chip duration $T_c = \frac{T_s}{G} = 1/B_c$

- **Signal waveform is fully described by its G dimensional signal space representation at sampling rate G/T_s**

$$\mathbf{c} = [c_1 \quad \cdots \quad c_G]$$

$$c_j(t) = \sum_{j=1}^{G} c_j g_c(t - jT_c)$$

Direct Sequence Spread Spectrum

- **Power normalization for constant Energy per Symbol**
  - Before spreading, signal power was located in *one* signal dimension $g(t)$ and

$$\int_{-\infty}^{+\infty} g(t)\, g^*(t) dt = 1$$

  - After spreading power is distributed over G orthogonal signal space dimensions

$$E_s = \int_{-\infty}^{+\infty} c(t)\, c^*(t) dt = \sum_{j=1}^{G} \left|c_j\right|^2 = 1$$

  - To keep the symbol energy E_s unaltered, we set

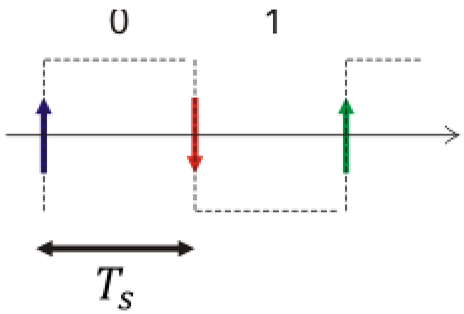
$$\left|c_j\right|^2 = \frac{1}{G}$$

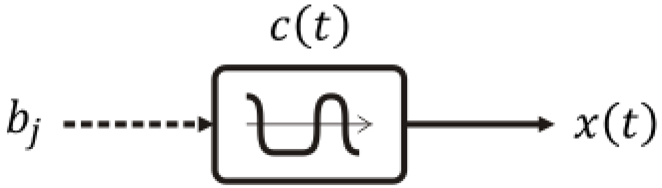
- **Often we choose $c_1 \in \left\{\pm \frac{1}{\sqrt{G}}\right\}$**

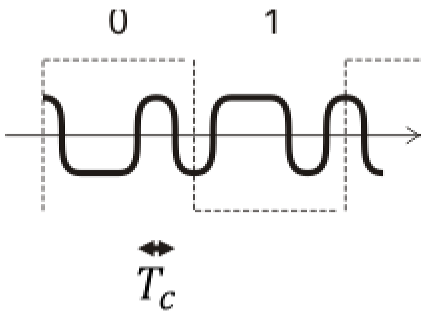
(no preferred direction in signal space,
to distribute power equally across dimensions)

DSSS Modulation

- **Discrete-time signal b_j at symbol rate T_s used to excite a *modulation filter* with the impulse response of the chosen (cont. time) wideband signal waveform**

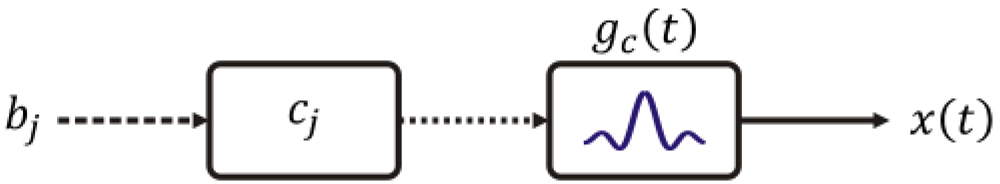


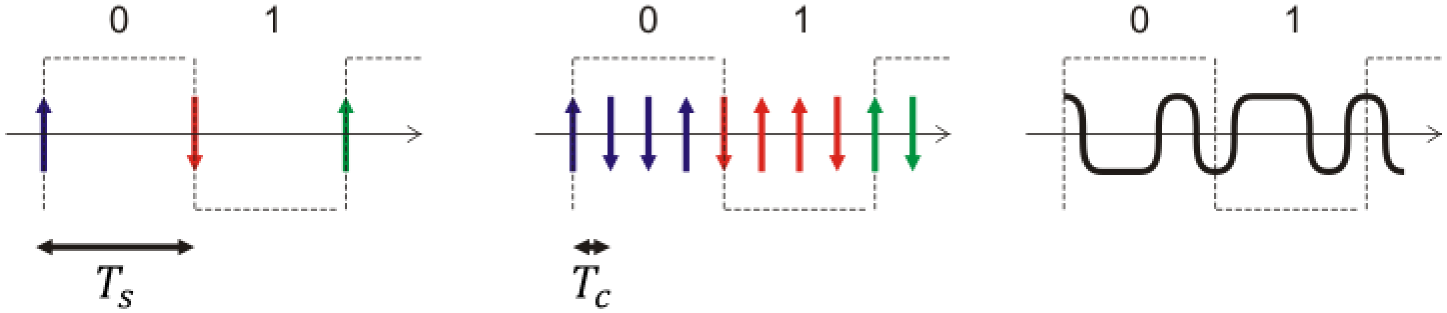




$$x(t) = \sum_{j=-\infty}^{+\infty} b_j c(t - jT_s)$$

- **Modulation in two steps**
  - Signal space representation at the chip rate
  - Chip-rate pulse shaping filter



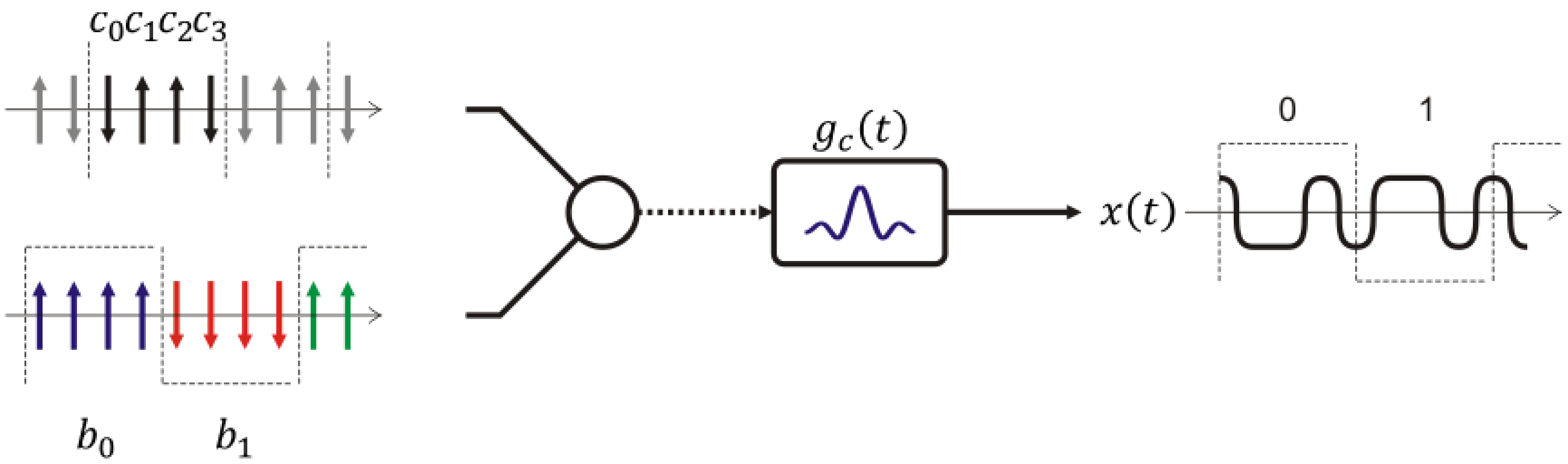


DSSS Modulation with Spreading

- Spreading = multiplication of a narrow band signal with another signal with a wider bandwidth

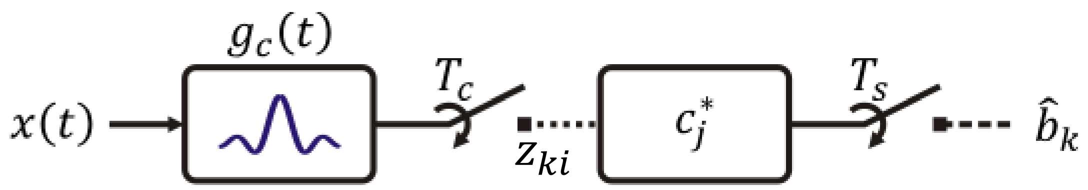
$$x(t) = \sum_{i=-\infty}^{+\infty} b_i \sum_{j=1}^{G} c_j g_c(t - jT_c - iT_s)$$

- Discrete time data signal is upsampled (repeated) to the chip-rate
- Multiplication with the discrete time chip sequence
- Pulse shaping with $g_c(t)$: controls the shape of the wideband spectrum



DSSS Receiver

- **DSSS receivers are fundamentally built in two steps**
  - Filtering (based on spread bandwidth) and sampling at the chip rate T_c
  - Signal-space matched filter with the discrete-time chip sequence

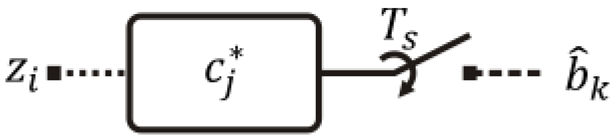


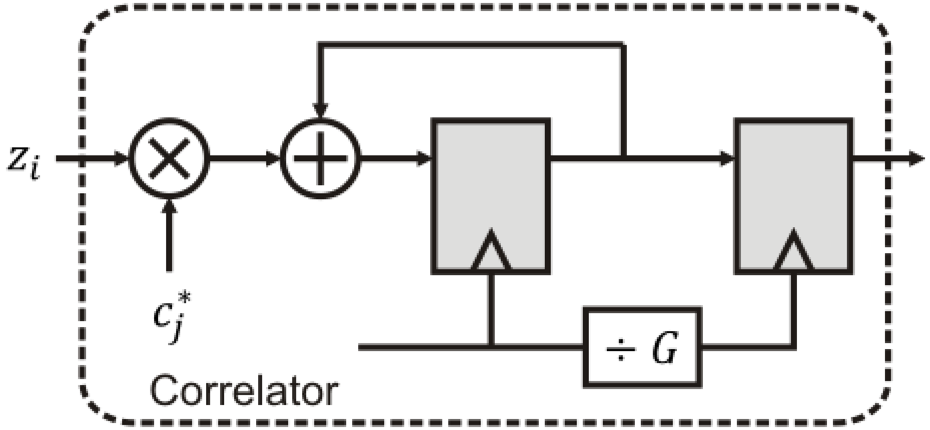
$$z_{ki} = \int_{-\infty}^{+\infty} y(t - kT_s)\, g_c^*(t - iT_c) dt \qquad \hat{b}_k = \sum_{i=1}^{G} c_i^* z_{ki}$$

- **Matched filtering (with the signal space representation) followed by down-sampling by a factor of G (T_c to T_s)**
  - Entails many unnecessary computations
  - Corresponds to computing the correlation

DSSS Receiver with Correlator

- **Filtering with the chip sequence followed by down-sampling can be realized more efficiently with a correlator**
  - Correlation can be implemented with low complexity using a multiply-accumulate operation (1 Multiplier, 1 adder, a register)





$$\hat{b}_k = \sum_{i=1}^{G} c_i^* z_{ki}$$

DSSS Performance with Constant E_s and $BW \sim G$

- **We use the discrete time signal model (chip spaced sampling)**
  - Consider only the transmission of a single symbol b

$$y_i = bc_i + n_i + I_i$$

  - c_i : Signal space representation of the spreading waveform $E_s = \sum_{i=1}^{G} |c_i|^2$
  - n_i : Additive white Gaussian noise $\mathcal{CN}(0, N_0)$ with PSD N_0
  - I_i : Interferer with constant power (fixed BW) $E_I = \sum_{i=1}^{G} |I_i|^2$
- Despreading (Signal-space matched filter)

$$\hat{b} = \sum_{i=1}^{G} c_i^* y_i = b \sum_{i=1}^{G} c_i^* c_i + \sum_{i=1}^{G} c_i^* n_i + \sum_{i=1}^{G} c_i^* I_i$$

n_i: $\mathcal{CN}(0, N_0)$

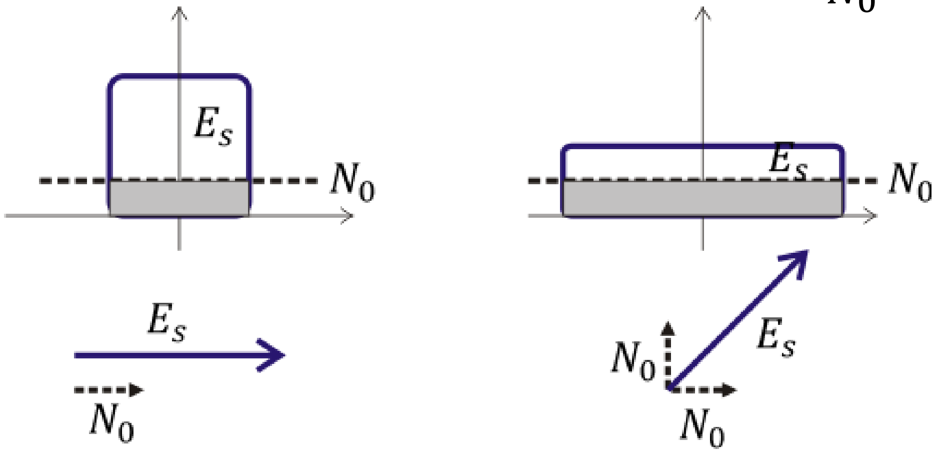
  - Signal, noise and interference power after despreading:

$$\overline{E_s} = E_s \qquad \overline{E_N} = N_0 \qquad \overline{E_I} = E_I / G$$

DSSS Performance with Constant E_s and $BW \sim G$

- **Impact of spreading on SNR (ratio of signal energy to noise PSD)**
  - AWGN has constant power across all frequencies and signal dimensions
  - AWGN can not be avoided by escaping into other dimensions of the signal space

  - The total noise power increases with increasing bandwidth (dimensions)
  - However, at least the amount of noise in direction of the signal remains the same
- $SNR = E_s/N_0$ => $\overline{SNR} = \frac{\overline{E_s}}{N_0} = E_s/N_0$



Spreading factor does not influence SNR (Es/N0)
when symbol Energy is normalized

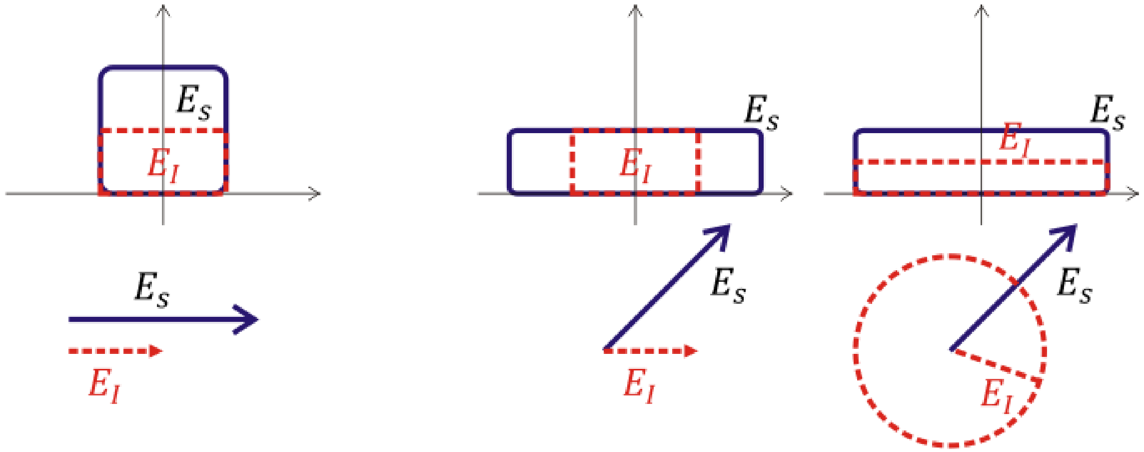
EPFL

DSSS Performance with Constant E_s and $BW \sim G$

- **Impact of spreading on SIR (ratio of signal energy to interferer energy)**
  - Interferer has given bandwidth and energy E_I
  - When increasing bandwidth (adding dimension) of the signal, interference lies only in a particular direction (subspace) of the signal space

  - Spreading the signal across all dimensions (frequencies) reduces the component of the interference in the direction of the signal (better SIR)
    - $SIR = E_s/E_I$ => $\overline{SIR} = \frac{\overline{E_s}}{\overline{E_I}} = E_s \cdot \frac{G}{E_I}$

Processing gain



SIR improves with the increasing spreading factor

DSSS Performance with Fixed BW and Power

- **Consider the case where the spreading factor G increases, but the energy per chip is not scaled accordingly (i.e., the chip waveform remains the same, just more chips are used for one symbol)**
  - How does the SNR change?
  - How does the SIR change?

DSSS Performance with Fixed BW and Power

- **We use the discrete time signal model (chip spaced sampling)**
  - Consider only the transmission of a single symbol b

$$y_i = bc_i + n_i + I_i$$

  - c_i : Spreading waveform signal space representation $E_s = \sum_{i=1}^{G} |c_i|^2 = G,\ |c_i|^2 = 1$
  - n_i : Additive white Gaussian noise with PSD N_0, Hence, $n_i \sim \mathcal{CN}(0, N_0)$
  - I_i : Interferer with constant power (fixed BW) $E_I = \sum_{i=1}^{G} |I_i|^2 = G,\ |I_i|^2 = 1$
- Despreading (Signal-space matched filter)

$$\hat{b} = \sum_{i=1}^{G} c_i^* y_i = b \sum_{i=1}^{G} c_i^* c_i + \sum_{i=1}^{G} c_i^* n_i + \sum_{i=1}^{G} c_i^* I_i$$

  - Signal, noise and interference power after despreading:

$$\overline{E_s} = G^2 E_s \qquad \mathcal{CN}(0, GN_0) \qquad \overline{E_I} = GE_I$$

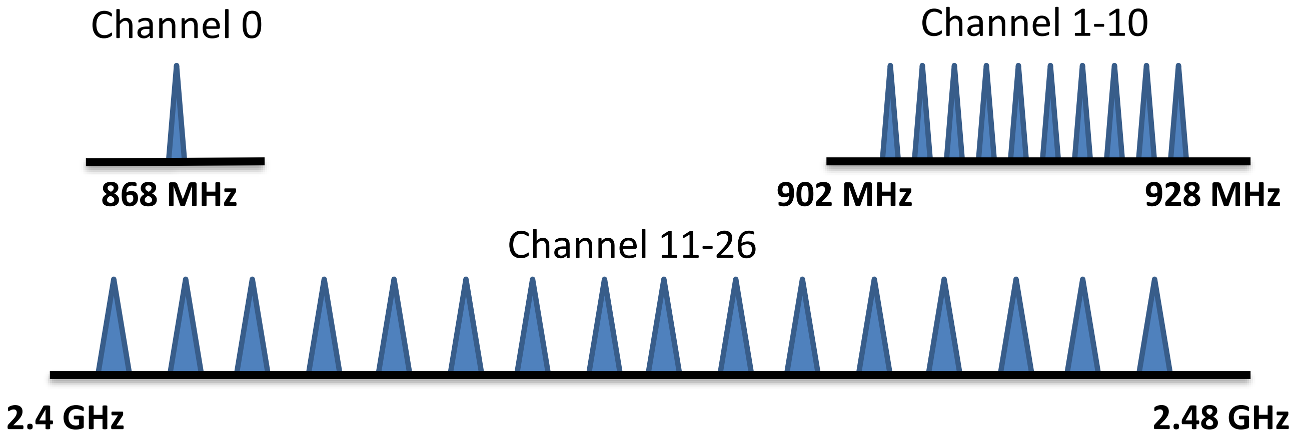
$$\overline{SNR} = \frac{\overline{E_s}}{N_0} = G\frac{E_s}{N_0} \qquad \overline{SIR} = \frac{\overline{E_s}}{\overline{E_I}} = G\frac{E_s}{E_I}$$

IEEE 802.15.4 PHY/MAC

- **Physical layer (PHY) and media access control (MAC) for low-rate wireless personal area network** (**LR-WPAN**)
- **1998:** Start development by IEEE 802.15 working group as IEEE 802.15.4
- **Objectives of the standardization**
  - Low cost and low-power connectivity for sensors
  - Optimized for low duty cycle devices (efficient sleep modes)
  - Simpler and less expensive than Bluetooth (*reduced-complexity protocol stack*)
  - Support larger networks (hundreds to thousands of sensor nodes)
    for example star and point-to-point topologies
  - Large coverage area with short-medium range (10-100m) links
  - Facilitate implementation of security on higher layers
  - **2003**: Completion of the IEEE 802.15.4 standard (ratified Dec. 2004)
- **IEEE 802.15.4 is the basis for Zigbee, ISA100.11a, WirelessHART, MiWi, 6LoWPAN, Thread, and SNAP**

The 802.15.4 Physical Layer

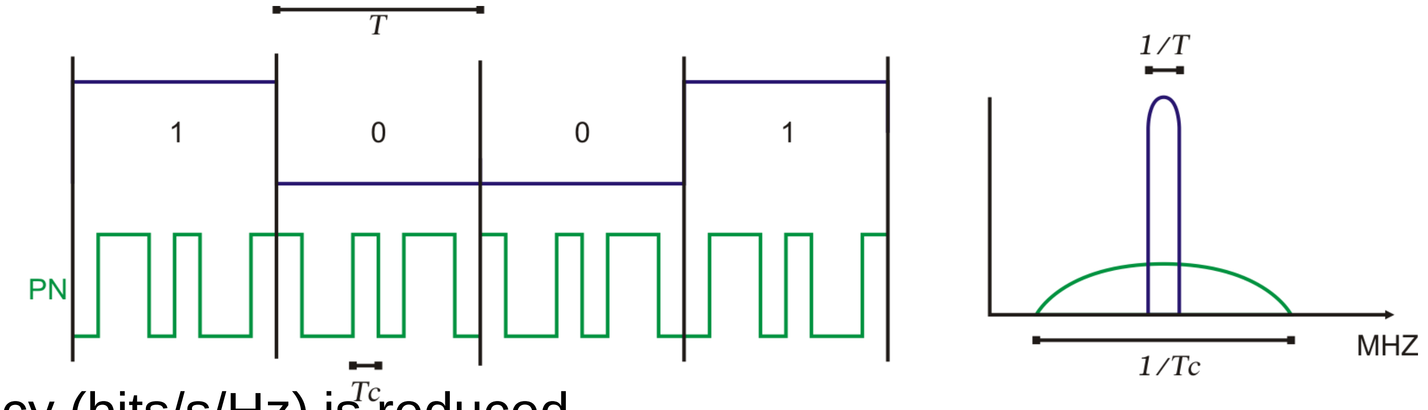
- **IEEE 802.15.4 PHY parameters**
  - Support for 3 unlicensed ISM frequency bands: 868 MHz, 915 MHz, 2.4 GHz
  - *Multiple channels in support parallel networks and avoid interference*
  - Supported data rate depend on the frequency band



Frequency	Channels	Spacing	Datarate	Region
868-870 MHz	1		20 kbit/s	Europe
902-928 MHz	10	2 MHz	40 kbit/s	America
2.4 GHz	16	5 MHz	250 kbit/s	World

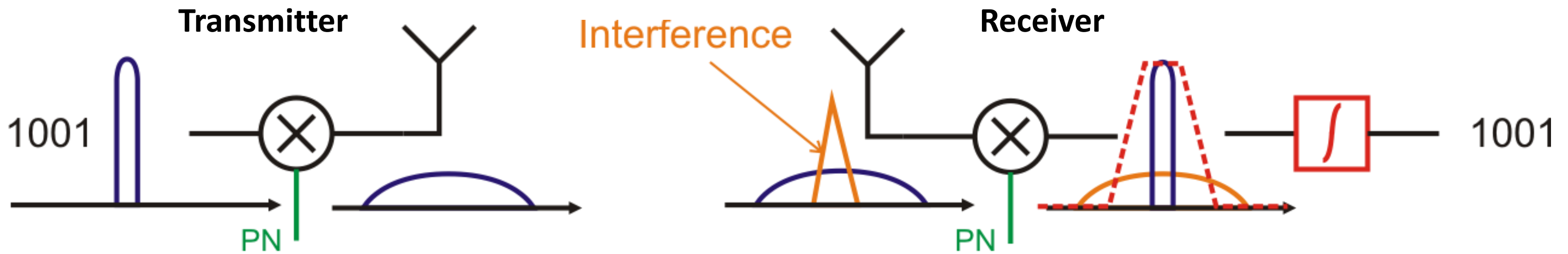
The 802.15.4 Physical Layer

- **Direct Sequence Spread Spectrum (DSSS) Modulation**
  - Each symbol is represented by a (modulated) pseudo-noise (PN) sequence (chips)
  - Chip-rate is higher than the symbol rate => signal is spread in the frequency domain



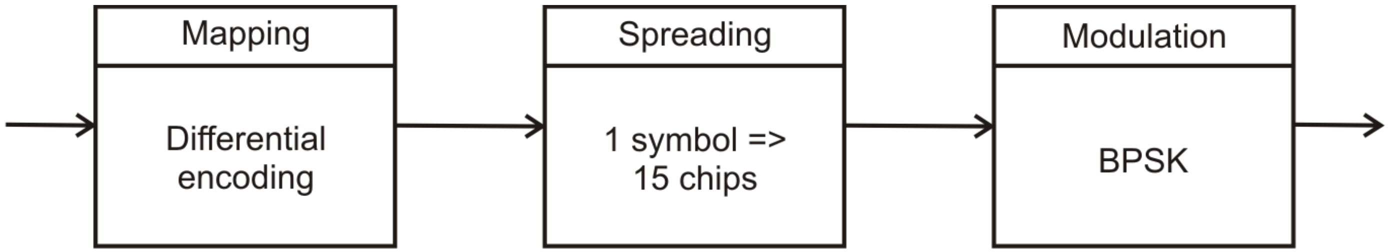
  - Spectral efficiency (bits/s/Hz) is reduced

- **Reduces interference to and from other users in the same frequency band**

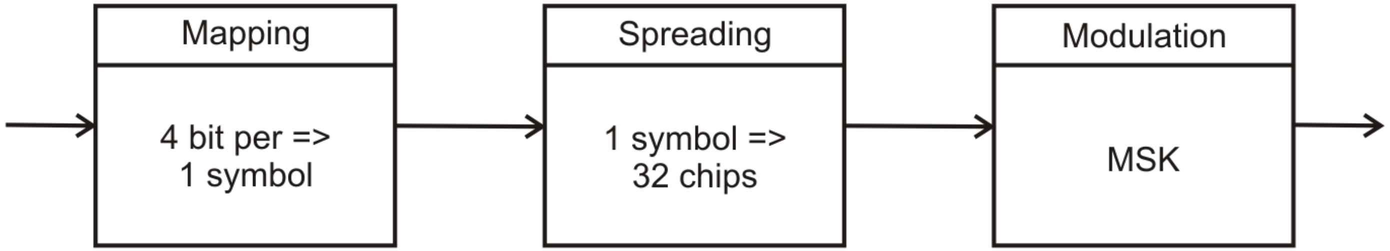


The 802.15.4 Physical Layer

- **DSSS modulation with different spreading factors**
  - The details of the modulation scheme and the spreading depend on the frequency bands



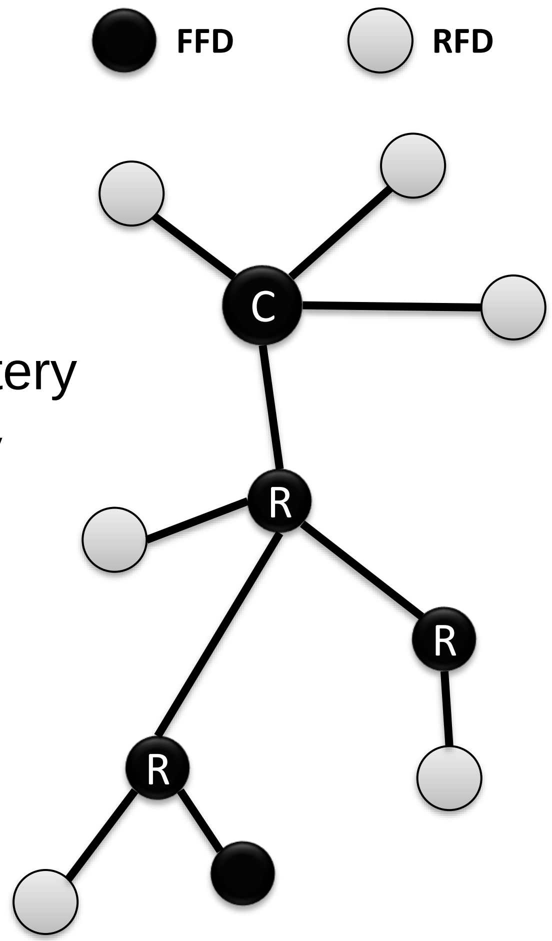
868 MHz	20 kbps	20 kHz	300 kchips/s	300 kHz
915 MHz	40 kbps	40 kHz	600 kchip/s	600 kHz



2.4 GHz	250 kbps	62.5 KHz	2 Mchips/s	2 MHz

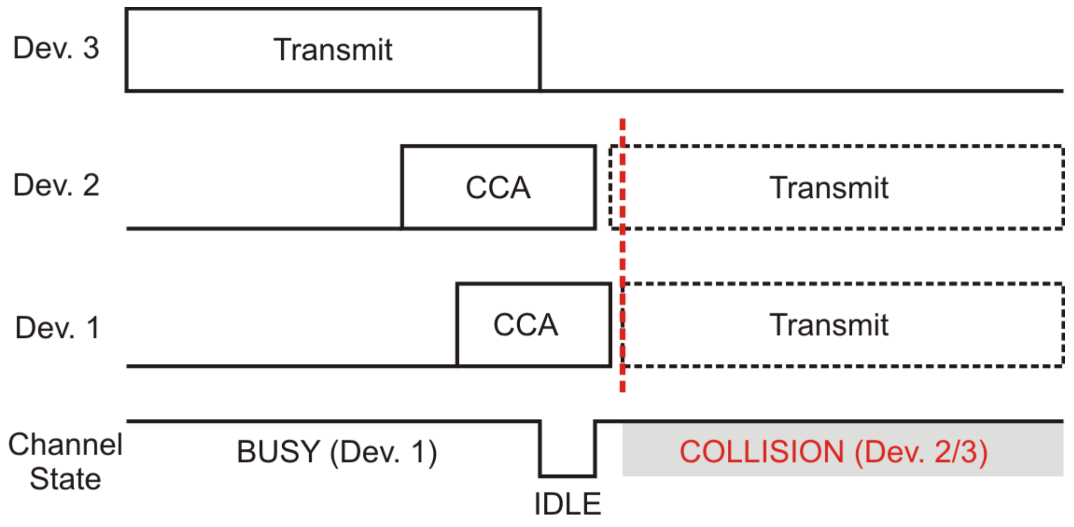
802.15.4

- **IEEE 801.15.4 knows 2 types of devices**
  - Different in cost and power consumption
- **The full function device (FFD)**
  - Can act as router and as coordinator in a network
  - Can also act as an end device
  - Typically equipped with a power connection or a stronger battery
  - Relatively complex protocol stack and need for more memory
  - Code: 15-30k; RAM: 2.5k – 4k
- **Reduced function devices (RFD)**
  - Reduced protocol stack and less memory required
  - Can only be leaves in the tree and can only talk to a router or to the coordinator
  - Code: 6k; RAM: <2k



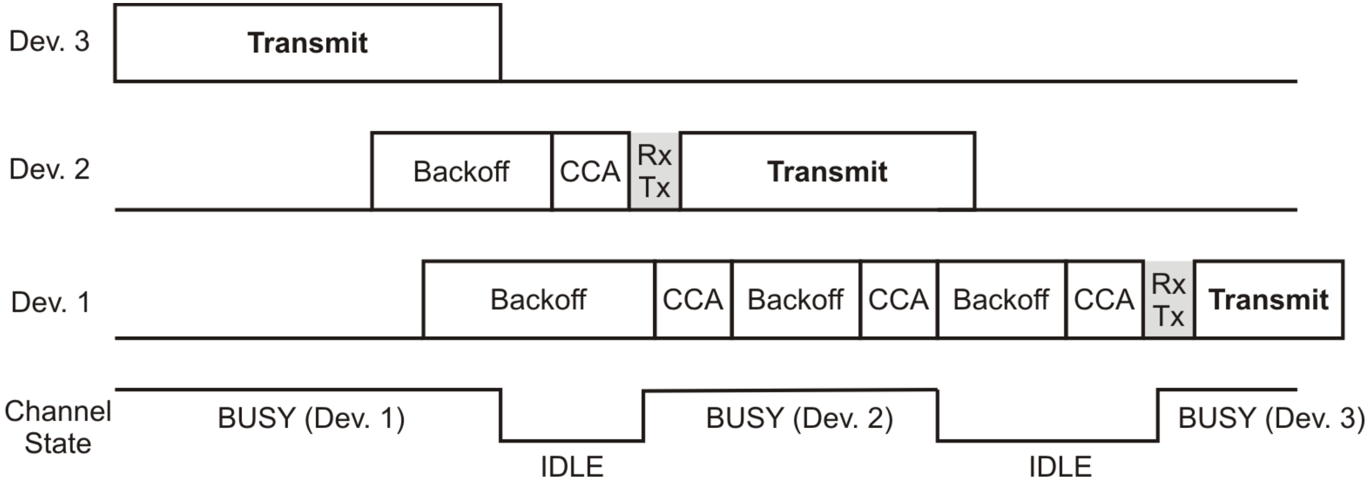
IEEE 802.15.4 Channel Access

- **Channel access**
  - Devices are not synchronized and have no assigned time slots
  - Need other means to avoid collisions between devices
- **Carrier sense multiple access (CSMA)**
  - Devices listen before sending : clear channel assessment (CCA)
  - Send only if channel has been idle for a specified period
  - Collisions still occur frequently with multiple nodes due to delays



IEEE 802.15.4 Channel Access

- **Carrier sense multiple access (CSMA)** with collision avoidance (CA): CSMA/CA
  - Wait for a randomly chosen backoff interval before CCA

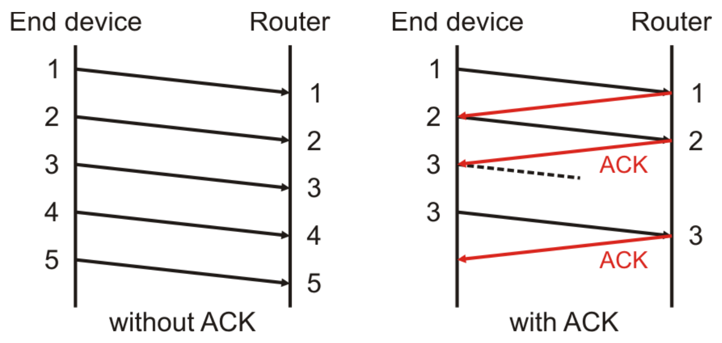


  - If CCA fails, choose a new backoff time and try again
  - For each attempt, the maximum length of the backoff interval increases exponentially

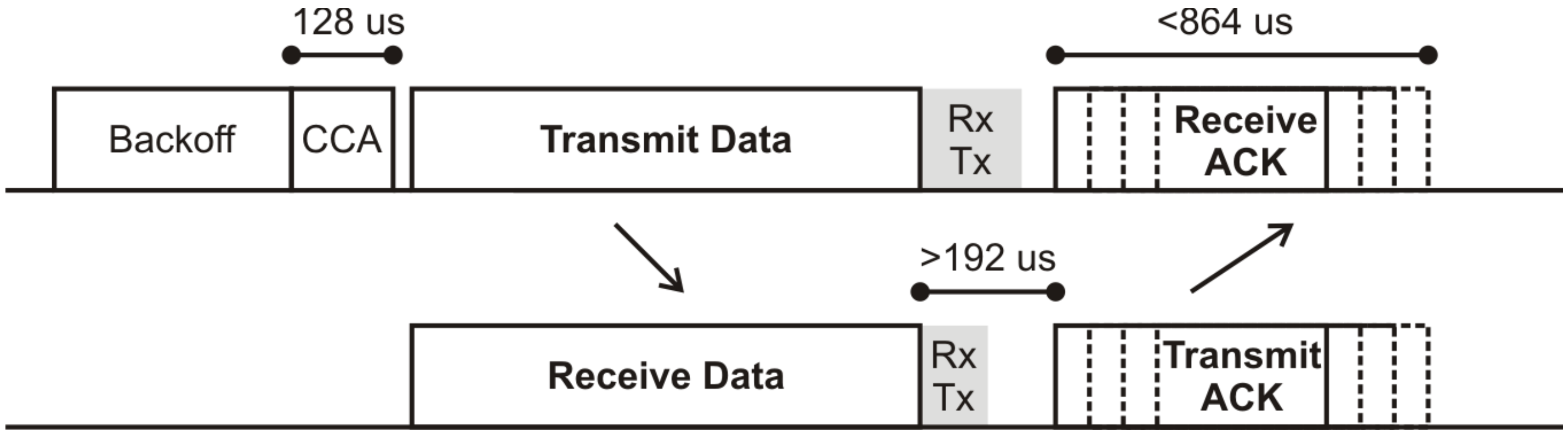
  - **Devices can sleep during backoff**

IEEE 802.15.4 Channel Access

- **Data transfer between two nodes can be *with* or *without* acknowledge**
  - Competing for channel access to send a short ACK is inefficient
  - A packet and its ACK should be a single, unbreakable entity to simplify packet management



- **ACK is sent without new CCA**
  - Receiver waits at least T_{ack} = 192us before sending the ACK (Rx/Tx and Tx/Rx turnaround)
  - T_{ack} is short enough to prevent other devices from capturing the channel (in most cases!)



IEEE 802.15.4 / ZigBee

Low-power low-data-rate wireless ad-hoc network with medium range for

- **Applications: home automation, industrial, medical, data collection, non-real-time control**
- **ZigBee builds on 802.15.4 PHY/MAC layer and adds network and application layers**
  - Adds routing, security, application profiles

- **ZigBee has been created and is maintained by an industry consortium: ZigBee Alliance (>300 member companies)**
  - **2002** : Foundation of the ZigBee Alliance as industry consortium
  - **2003** : Completion of the IEEE 802.15.4 standard (ratified Dec. 2004)
  - **2004** : ZigBee 1.0 (also known as ZigBee 2004) announced (now obsolete)
  - **2006/2007/…:** further releases supersede previous versions
  - **Latest version:** ZigBee 3.0 (since 2015)

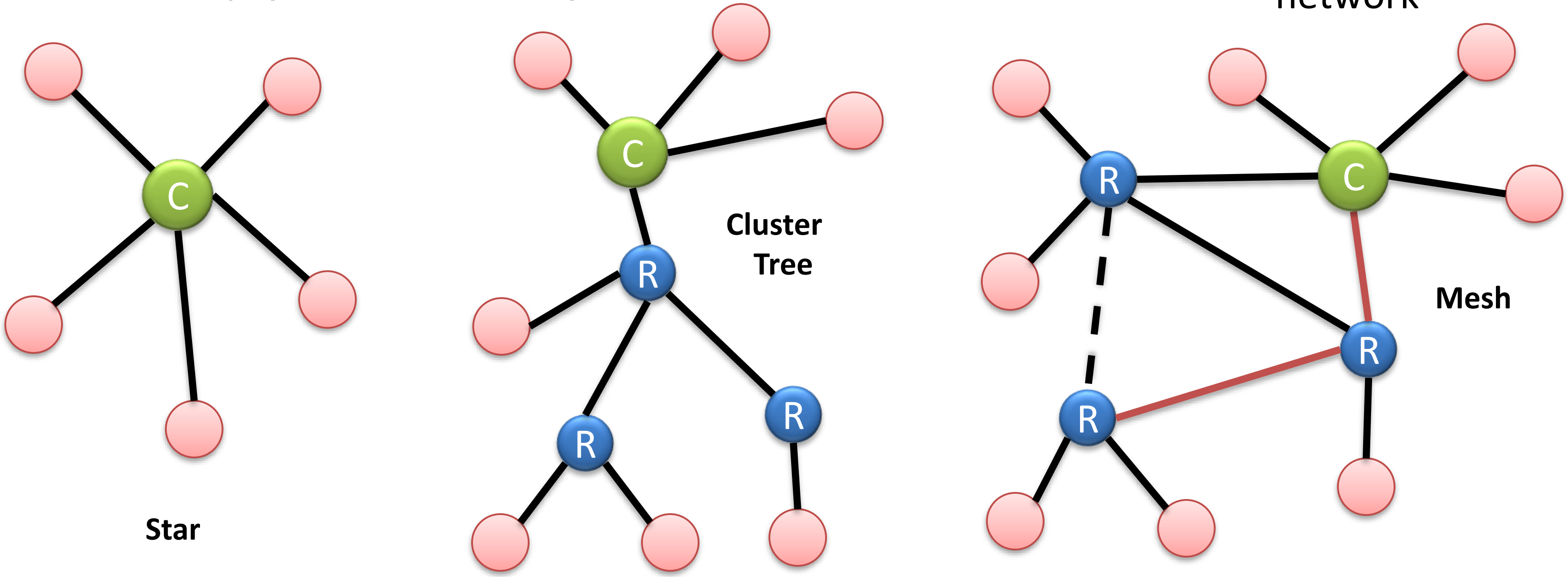
- **Main non-technical advantage of ZigBee:** rigorous certification process for device interoperability (in practice, still many hurdles)

- **Drawback**: costly certification process and complex (close-source stack) & licensing costs

ZigBee Network Topologies

- **Self organizing ad-hoc network with 3 different roles**
  - Star
  - Cluster Tree
  - Mesh Network
    - Routers connect to multiple other routers (and endpoints)
    - Improved reliability (alternate routes)

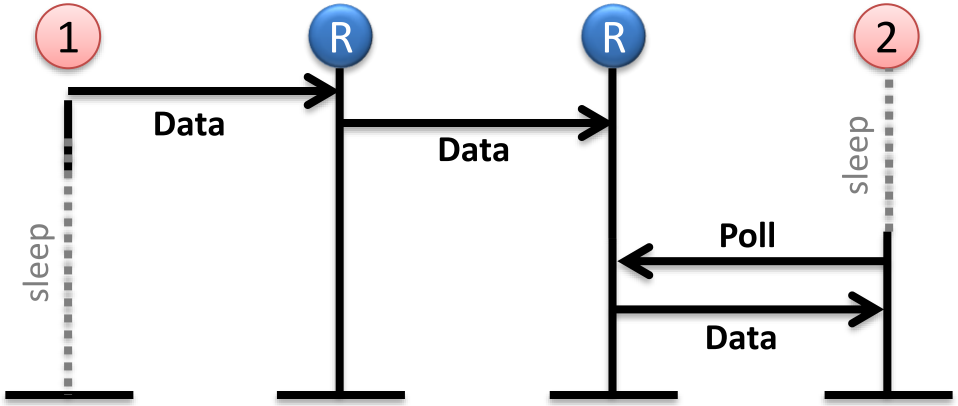
- **End device**: connects only to one and only one router
- **Router**: multiple connections to other routers and multiple end devices
- **Coordinator**: only one per network

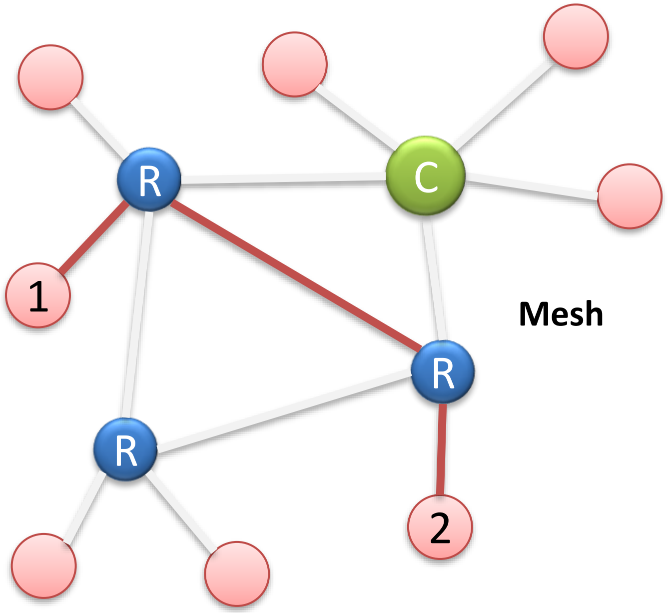


ZigBee Network Topologies

- **Self organizing ad-hoc network** with 3 different roles
  - Star
  - Cluster Tree
  - Mesh Network
- **Communication in the network**
  - **Coordinator** creates and manages the network
  - **End devices** sleep most of the time and *initiate communication* by sending data or polling a router
  - **Routers** buffer traffic for their connected end devices

- **End device**: connects only to one and only one router
- **Router**: multiple connections to other routers and multiple end devices
- **Coordinator**: only one per network





ZigBee Devices

- **Transceivers are typically available as modules or highly integrated SoCs with MCU/ROM/flash/memory**
- **Receiver sensitivity (1% PER) typically -90 to -100dBm**

NXP JN5139-Z01-M/03
30 x 18mm,
>15 USD

- **Typical power consumption**
  - Standby: < 8uW
  - Active: 60-120mW (@3V)

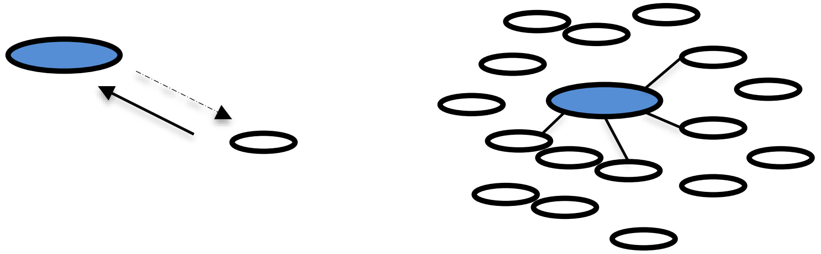
TI CC-2420/2430/2431
ZigBee Radio + MCU
6 x 6 mm, ~4-8 USD

M. Varchola, M. Drutarovsky, "ZigBee Based Home Automation Wireless Sensor Network," Acta Electronica Et Informatica, Vol. 7, No. 4, 2007

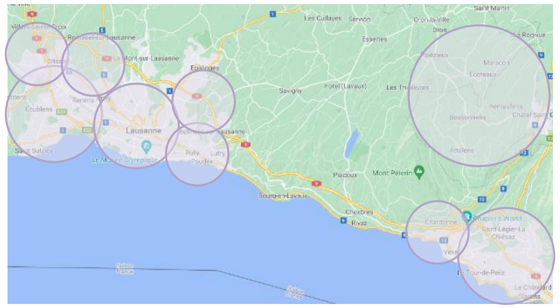
	Vendor	Atmel	Ember		Freescale				Jennic		Microchip	Texas Instruments		
	ZigBee Chip	AT86 RF230	EM 250	EM 260	MC 13193	MC 13203	MC 13213	MC 13225	JN 5121	JN 5139	MRF 24J40	CC 2420	CC 2430	CC 2431
IEEE 802.15.4 Features	Sleep Current [uA]	0.1	1	1	1	1	1	NA	5	1.3	2	2	1	1
	RX Current [mA]	16	36	36	42	42	42	20	50	34	18	20	27	27
	TX Current [mA]	17	36	36	35	35	35	20	45	34	22	18	27	27
	RX Sensitivity [dBm]	-101	-98	-98	-92	-92	-92	NA	-90	-97	-91	-95	-92	-92
	TX Power [dBm]	+3	+5	+5	+4	+3	+3	NA	0	+3	+5	0	0	0
MCU Features	In Package		X	The ZigBee Coprocessor			X	X	X	X			X	X
	External	X			X	X					X	X		
	Core	AVR	XAP2b		HCS08	Coldfire	HCS08	ARM7	RISC	RISC	PIC	MSP430	x51	x51
	Bus Width [bits]	8	16		8	32	8	32	32	32	8	16	8	8
	RAM [kB]	8	5		4	~32	4	NA	to 96	to 96			8	8
	ROM [kB]	256	128		60	~256	60	NA	64	192			128	128
	Core Freq. [MHz]	16	12		20	50	40	26	16	16			32	32
ZB Stack	Availability	yes	yes	in ROM	yes	soon	yes	soon	yes	yes	yes	yes	yes	yes
	License Price				995 $		995 $				free	free	free	free
	Latest Version	PRO	2006	2006	2006	2006	2006	2006	2006	2006	2004	2006	2006	2006

Long Range Low Power Wide Area Networks (LPWANs)

- **Highly optimized for low-cost IoT sensor nodes**
  - Support only very low data rates with very short duty cycles
  - Focused on Upling (sensor-to-cloud) traffic
  - Large number of devices per gateway (hundreds)



- **Radio access and modulation**
  - Often based on open radio standards
  - Operation in unlicensed (ISM) frequency bands
  - Mostly ad-hoc network deployment (rather unplanned)
  - Low cost and low power physical layer modems
  - Long range radio reach to minimize infrastructure needs
  - Very basic radio access protocol, optimized for ULP only



- **Low medium cost infrastructure (gateways & core network)**
  - Relatively low cost gateways (300-1000 USD)
  - Basic core network with simple radio-network protocols
  - Builds on public IP network (no dedicated fiber links or networks)

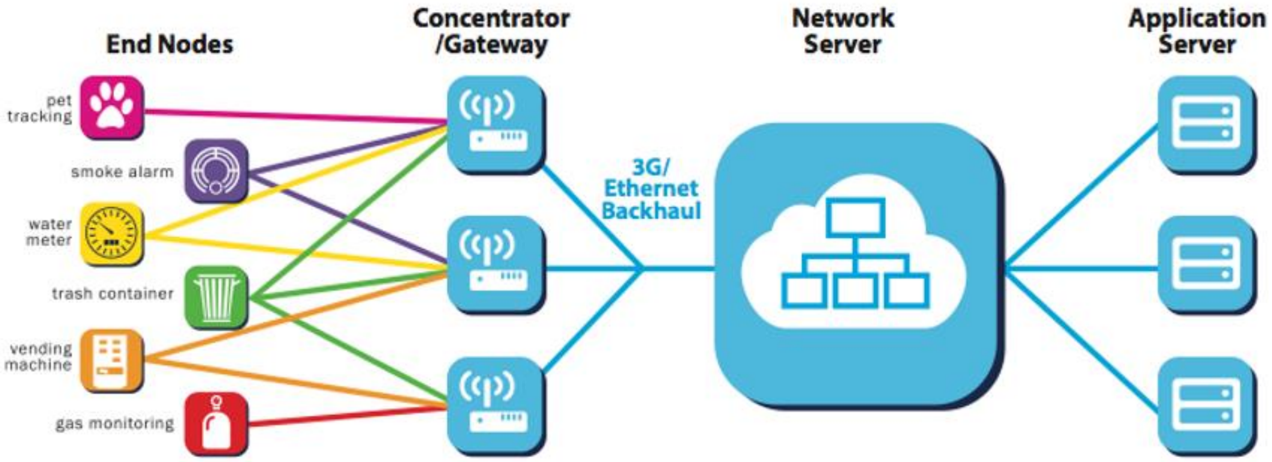
LoRa

- **Alliance between multiple companies on different levels of the stack**
- **Multiple vendor offering based on cooperation between various companies offering services around a common open concept**
- **Technology was originally developed by Cycleo (Grenoble, France) and later acquired by *Semtech (Neuchatel, Switzerland)* in 2012**
- **Semtech broadly licenses the IP to other chip manufacturers**
- **LoRa Alliance provides a certification process for new products**

- **Targets low data rates: 290 bps – 11 kbps (125 kHz), 1.16 kbps – 50 kbps (500 kHz)**
  - Symmetric up and downlink
- **Modulation provides multiple data rates using spread spectrum modulation**
  - Robustness to interferers
  - Tradeoffs between data rate and range
  - Codes of different spreading factors are almost orthogonal
- **Coverage per gateway: rural=5-10 km, urban=1-3 km**
  - Multiple gateways extend coverage area and improve robustness (diversity)
  - Network server filters duplicate packets (received by multiple gateways)

The LoRa System Architecture

- **Gateways (Connectors):**
  - Receive and demodulate long-range wireless transmissions using LoRa PHY protocol and serve as interface between the wireless connection and a Network Server with almost no further intelligence
- **Network Server (intelligence):**
  - Collects receptions from multiple gateways (diversity), filters duplicate packets, schedules acknowledgements, controls data rates and checks security. They can process messages directly or act as Cloud Server to provide services to a further layer of customers (depending on the business model)



LoRa Modulation

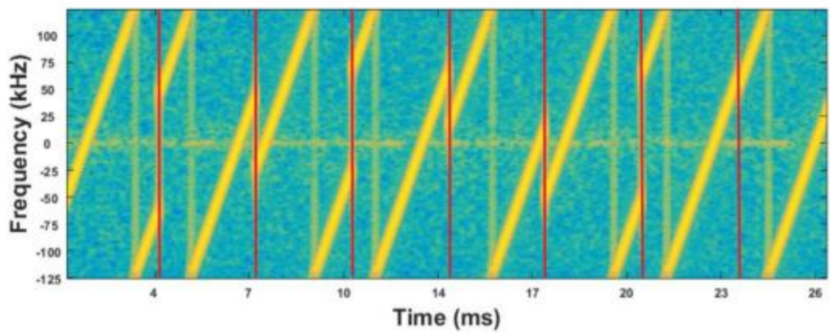
- **To cover a wide range of distances, LoRa requires a modulation that allows to adapt the energy per bit (at the cost of throughput)**
  - Spread-spectrum frequency chirp
  - Symbols are distinguished by the starting frequency

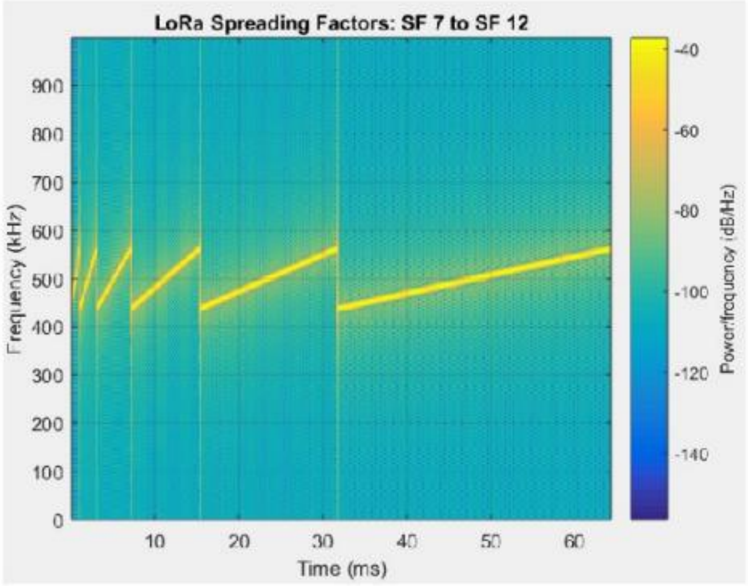
$$x[n] = e^{j2\pi\left(\frac{n^2}{2N}+\left(\frac{s}{N}-\frac{1}{2}\right)n\right)}$$

  - Six possible spreading factors adjust the symbol duration (i.e., the rate) $T_s = \frac{1}{BW}2^{SF}$
    - Each symbol carries SF bits of information

PHY Data Rate [bps]

$$R_b = SF \cdot \frac{\frac{4}{4+CR}}{2^{SF}} \cdot BW$$





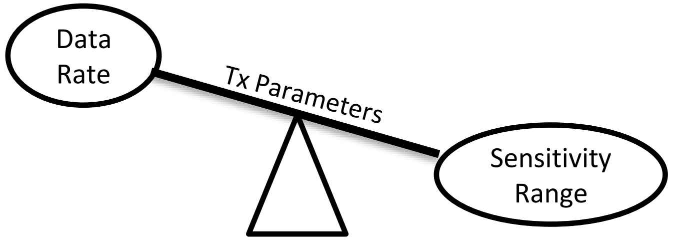
LoRa Chirps for Different Spreading Factors [1]

LoRa: RF and Physical Layer Sensitivity Examples

- **Doubling BW doubles data rate, but reduces sensitivity by 3 dB**
- **Example, based on Semtech SX1272 (860 – 1020 MHz)**

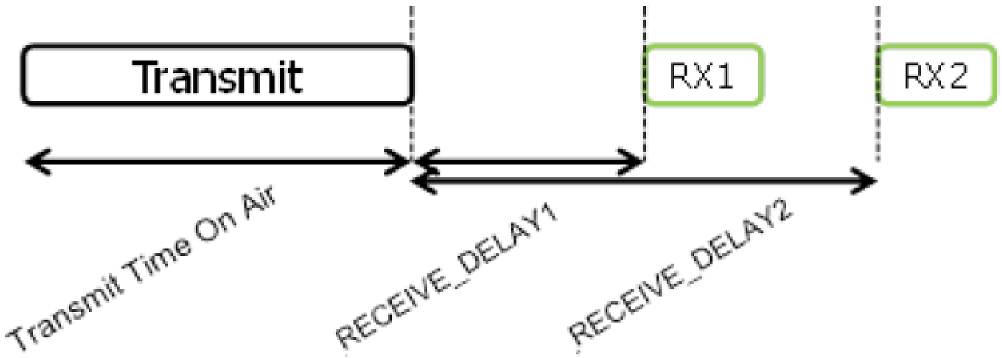
Bandwidth	SF	Code rate	Bit rate (bps)	Sensitivity [dB]
125	6	4/5	9380	-122
125	12	4/5	293	-137
250	6	4/5	18750	-119
250	12	4/5	586	-134
500	6	4/5	37500	-116
500	12	4/5	1172	-131

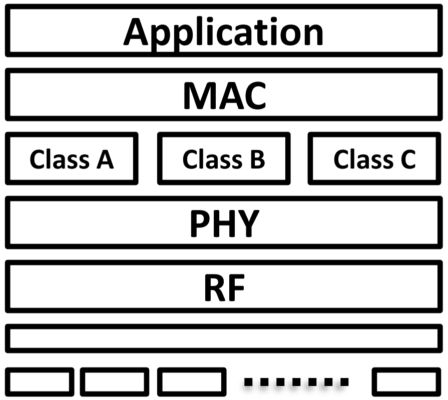
- **Range:**
  - In LOS scenario: 6 dB better sensitivity doubles the range
  - Urban environment: 12 dB better sensitivity needed for doubling the range



LoRa: Multiple Access (Class A)

- **LoRa Class A is based on the ALOHA protocol for multiple access**
  - Class A is the most frequently used type of devices with all communication initiated by end-user device with uplink msg.





  - Orthogonality between spreading codes of different lengths allows collisions between devices that use different SFs
  - Collisions are resolved by missing ACK and retransmissions with random transmission slots
  - Target duty cycle of <1% and limited number of packets per day ensures low collision probability
  - Typical ALOHA network capacity ~18% of its maximum

  - Encryption and authentication using AES-128