


CS-541
Wireless Sensor Networks

Lecture 2: Wireless networks prerequisites and protocol stacks

Spring Semester 2017-2018

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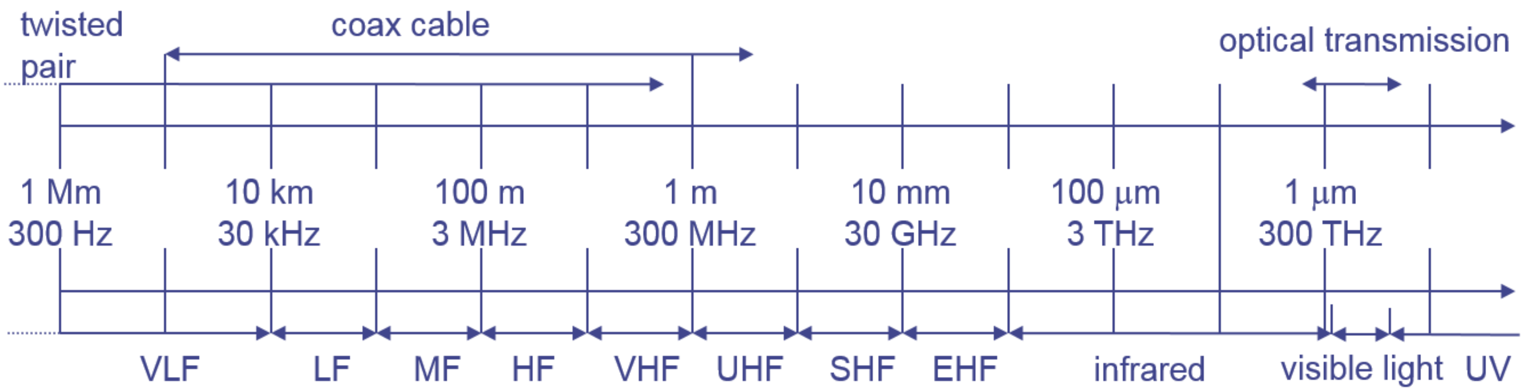
Today's Objectives

- **Part A: Wireless Links: Signal Propagation, Handling the Spectrum, Modelling the PHY performance**

- **Part B: Protocol stack preliminaries for WSN**

Wireless Links – Radio Spectrum

- Radio Spectrum: The part of the electromagnetic spectrum (8.3KHz – 3 THz) **allocated** by ITU for radio communications.



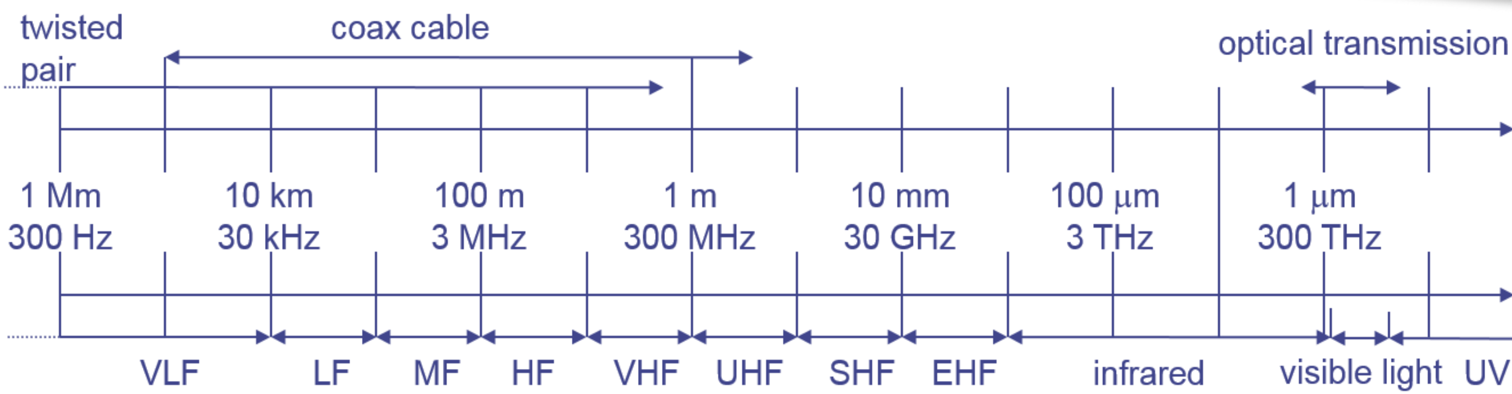
- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

Holger Karl, Andreas Willig, Protocols and Architectures for Wireless Sensor Systems, 2005, Willey, Ch. 4

Wireless Links – Radio Spectrum

Relationship between frequency (f) and wave length (λ):
$\lambda = c/f$
where *c is the speed of light*



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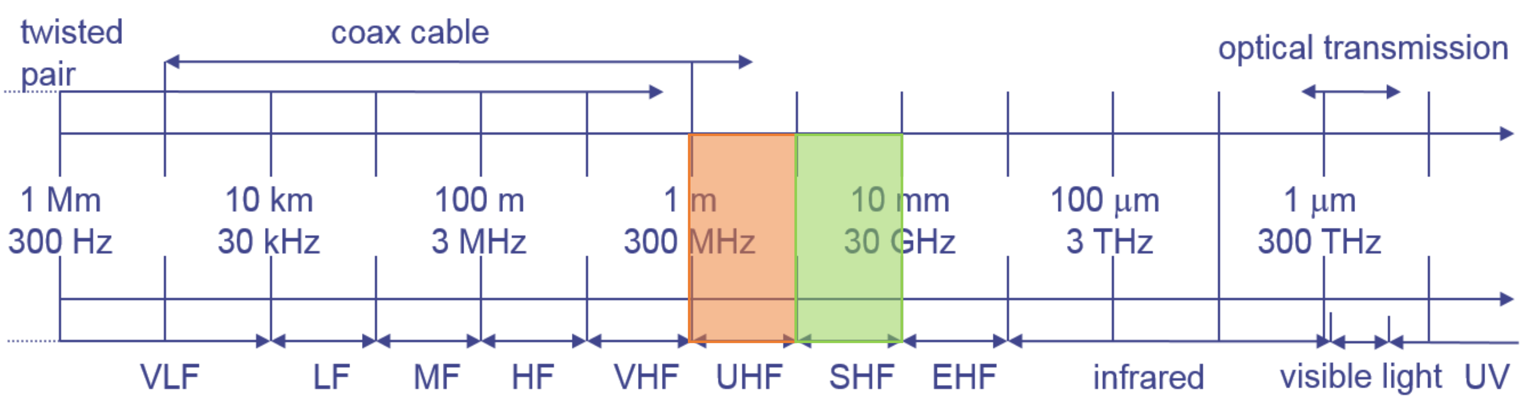
Wireless Links – Radio Spectrum

UHF (300-3000MHz): WLAN, GSM/GPRS
SHF (3-30GHz): radio astronomy, microwaves WLAN, satellites communications, modern mobile telephony

+ WSN



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Wireless Links – Radio Spectrum

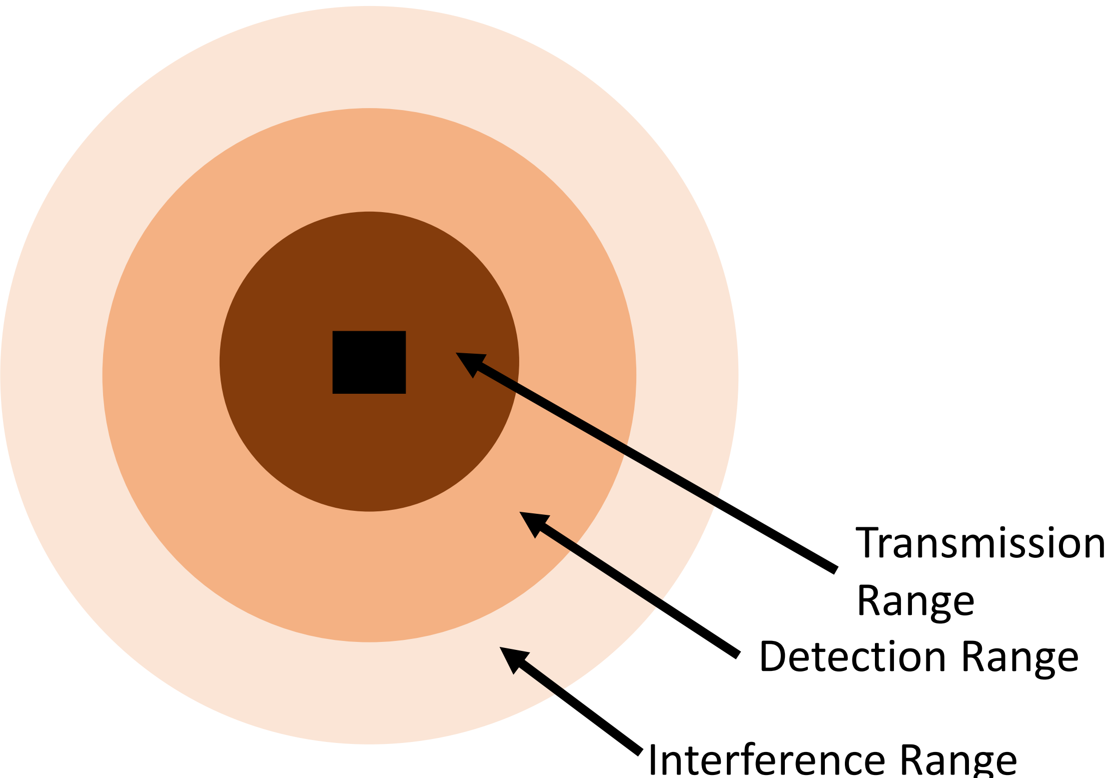
The radio spectrum is not for free or arbitrary use – usage varies w.r.t. the national regulations…

- Some of these bands are reserved, some are licensed and some are open / unlicensed.
- **ISM band – free to use**
- Typical WSN applications & manufacturers exploit this band
- @2.4GH & 5.8GHz bands: coexistence with WiFi devices

Starts	Ends	Range	Center	Availability
6.765 MHz	6.795 MHz	30 kHz	6.780 MHz	Subject to national regulations
13.553 MHz	13.567 MHz	14 kHz	13.560 MHz	Worldwide
26.957 MHz	27.283 MHz	326 kHz	27.120 MHz	Worldwide
40.660 MHz	40.700 MHz	40 kHz	40.680 MHz	Worldwide
433.050 MHz	434.790 MHz	1.74 MHz	433.920 MHz	Europe, Africa, M. East, former SU, Mongolia
902.000 MHz	928.000 MHz	26 MHz	915.000 MHz	US, Greenland, Eastern Pacific Islands
2.400 GHz	2.500 GHz	100 MHz	2.450 GHz	Worldwide
5.725 GHz	5.875 GHz	150 MHz	5.800 GHz	Worldwide

Wireless Links – Signal Propagation

Range in wireless communications:



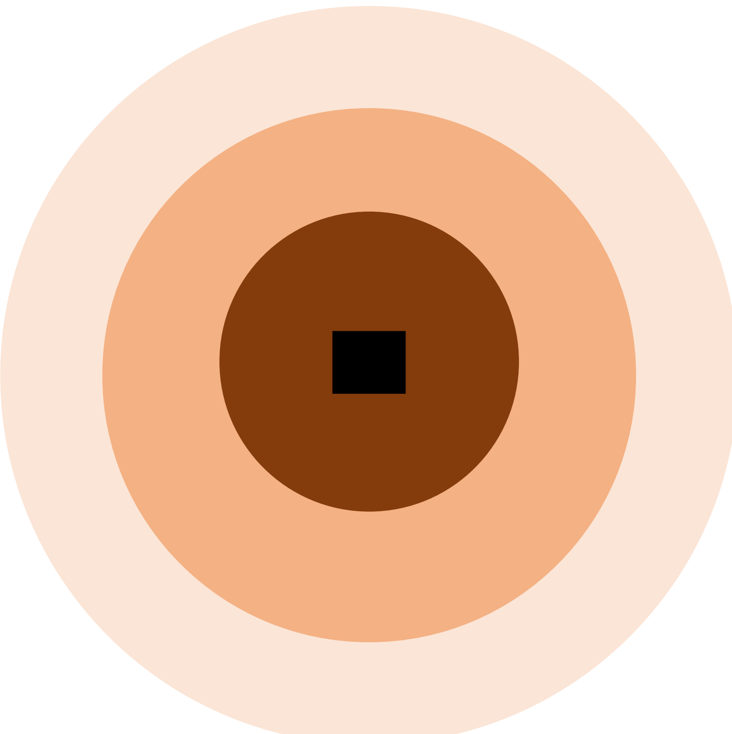
In theory

Depends on:

- Operational frequency
- Transmission power
- Gain / Type of the antenna & hardware differences
- Sensitivity of the receiver **S**
- Type of environment & propagation mechanism
- Ambient conditions & co-existence of other devices

Wireless Links – Signal Propagation

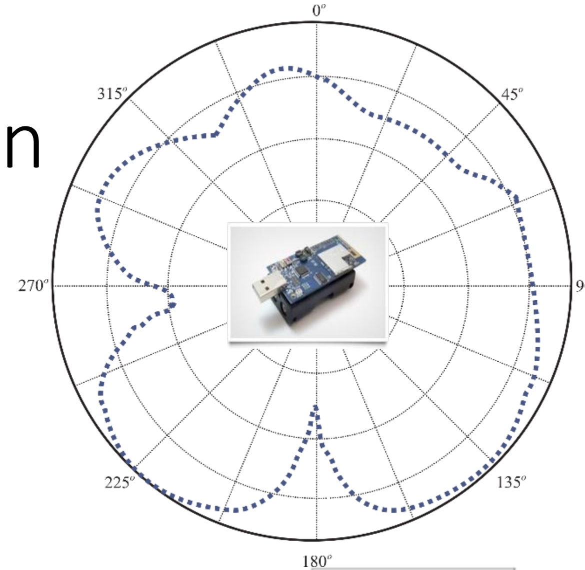
Range in wireless communications:



In theory

In reality

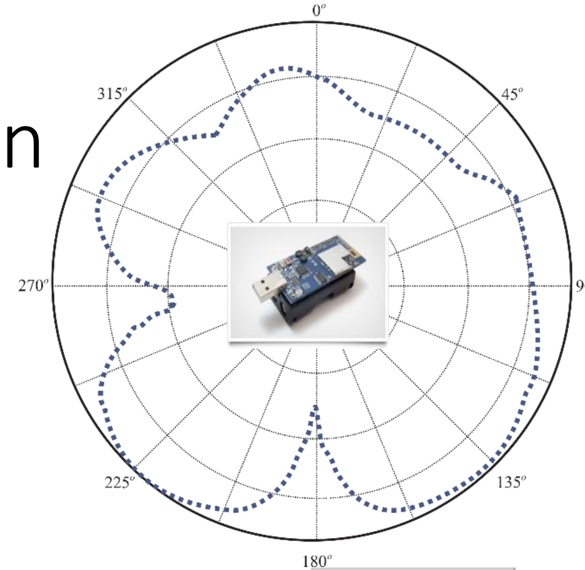
Anisotropic Path Losses



Gang Zhou et. al 2006. Models and solutions for radio irregularity in wireless sensor networks. *ACM Trans. Sen. Netw.* 2, 2 (May 2006), 221-262.

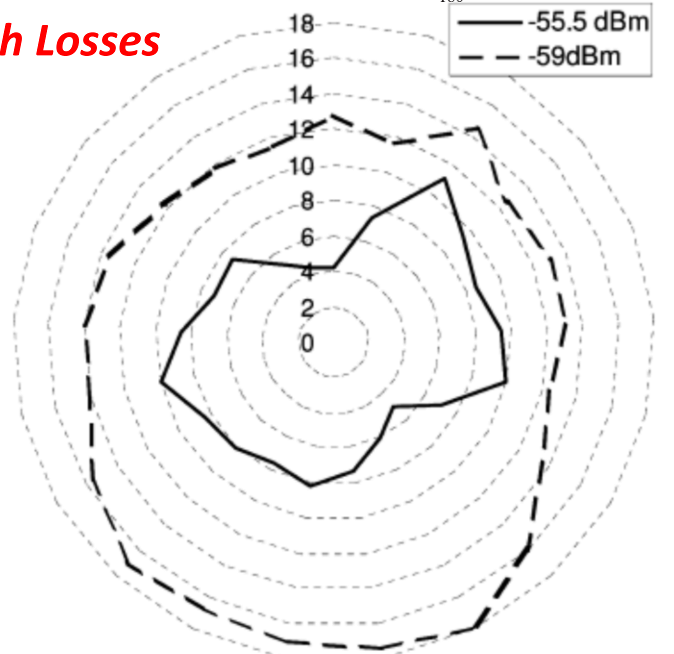
Wireless Links – Signal Propagation

Range in wireless communications:



In reality

Anisotropic Path Losses



- Operational frequency
- **Transmission power: different power yields different range**
- **Gain / Type of the antenna & hardware differences: dipole Vs embedded antennas**
- Sensitivity of the receiver
- **Type of environment & propagation mechanism**: Variance in the signal path loss

Gang Zhou et. al 2006. Models and solutions for radio irregularity in wireless sensor networks. *ACM Trans. Sen. Netw.* 2, 2 (May 2006), 221-262.

Wireless Links – Signal Propagation

Range in wireless communications:

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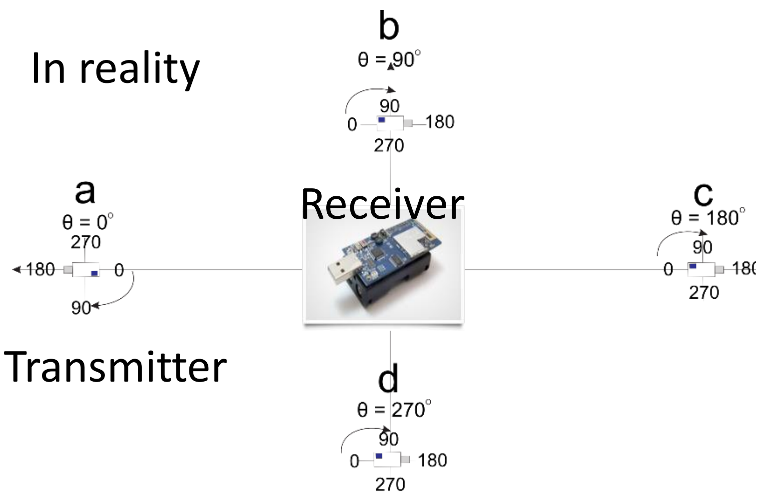
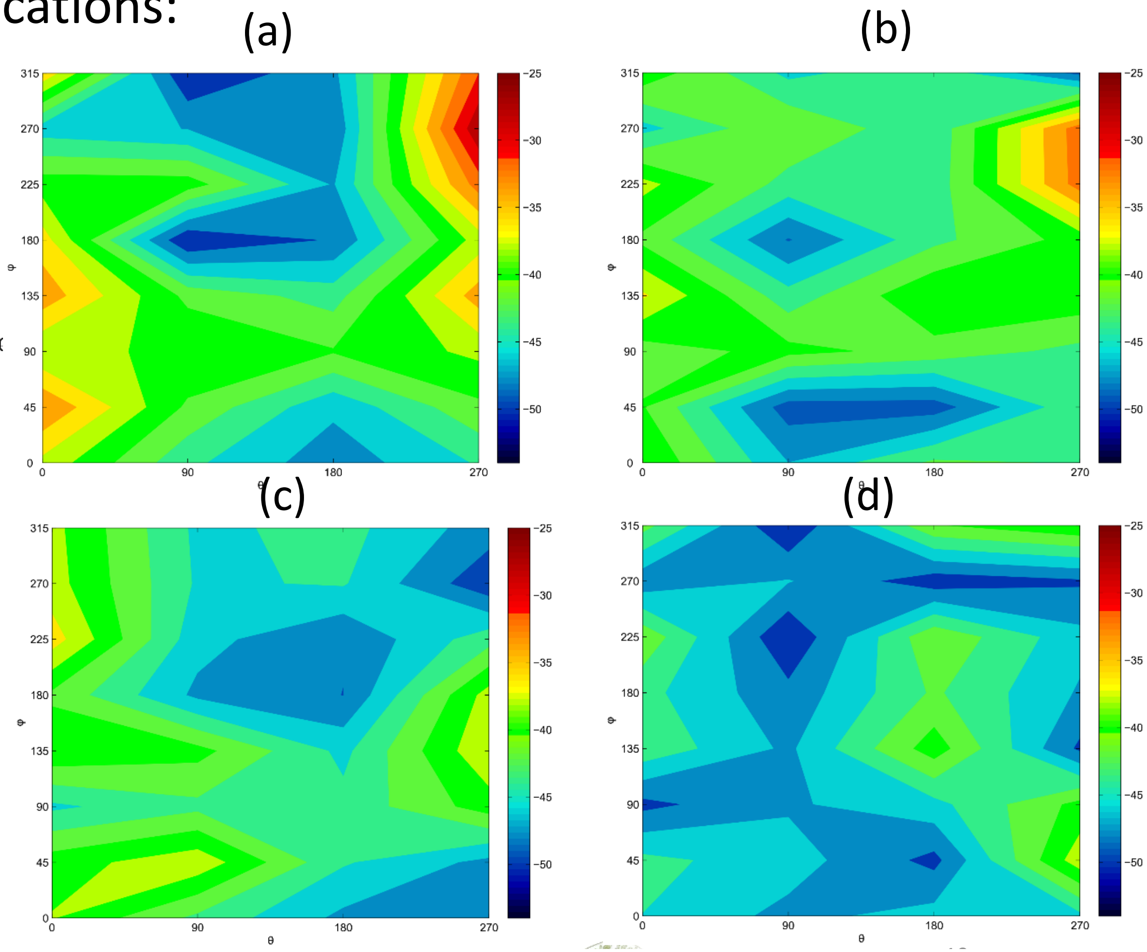




At the same distance & with constant transmission power, even the relative position of the tx-rx pair matters!

Gain / Type of the antenna & hardware differences

Wireless Links – Signal Propagation

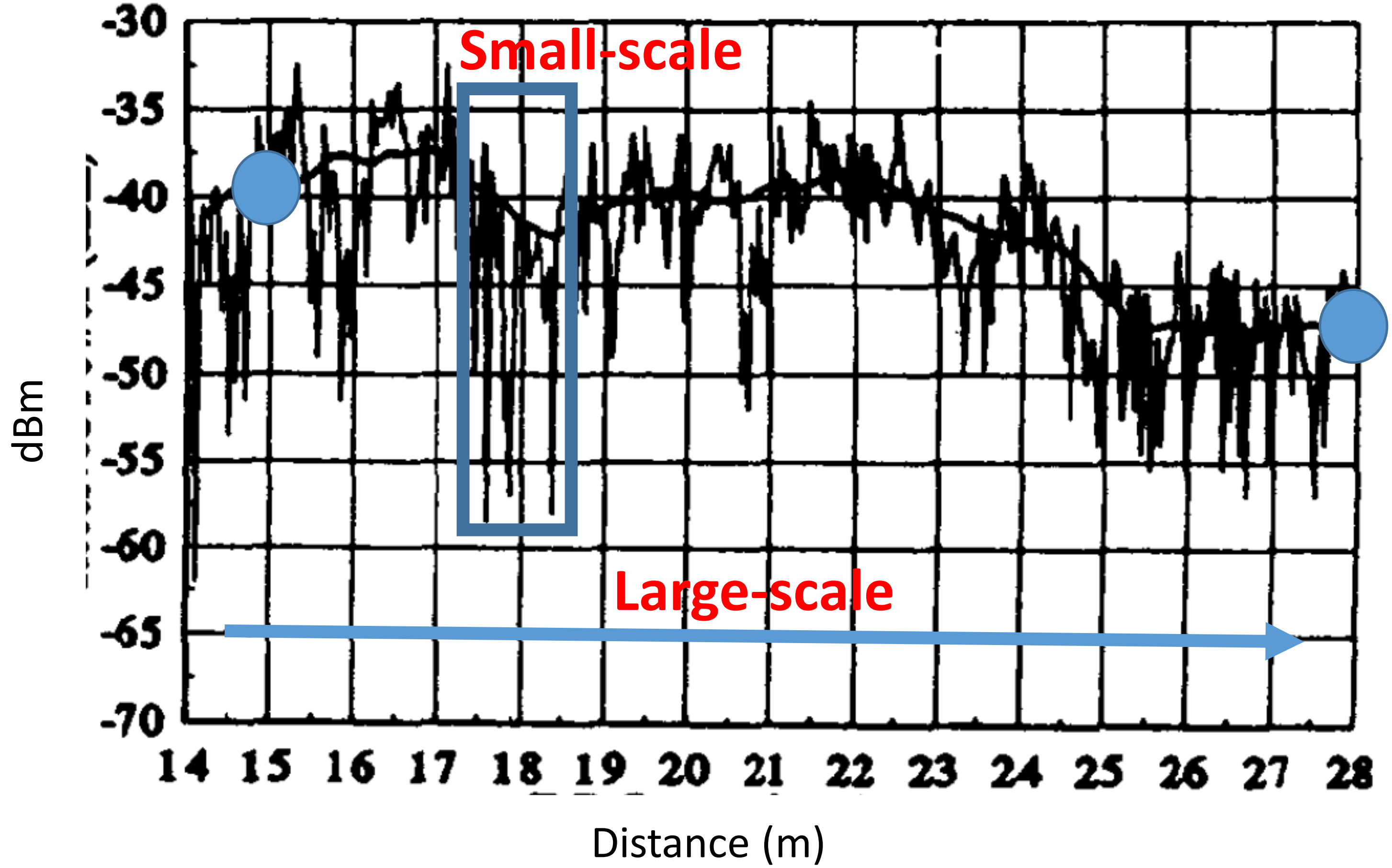
Radio Propagation dictates the behavior of a transmitted radio wave:

- How signal is attenuated with respect to distance between transmitter and receiver
- How signal is affected by the surrounding environment (e.g. line of sight, types of obstacles, etc)
- How signal fluctuates over very short distances or very short time durations.

Radio propagation models: predict the average received signal strength at a given distance from the transmitter, & the time variability of the signal strength at a given location.

- **Large-scale path-loss**: estimating the signal strength Vs distance
- **Small-scale / fading**: variations over very short distances, time, and frequencies

Wireless Links – Signal Propagation



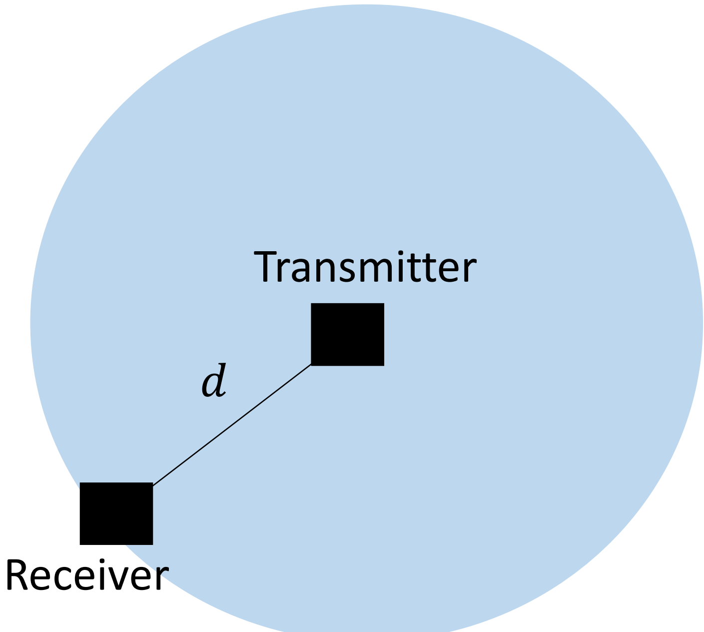
Rappaport T. "Wireless Communications: Theory and Practice", 2nd Edition, 2002

P mW to X dBm:
X dBm = 10log10(P/1mW)

Wireless Links – Signal Propagation

- Large-scale path-loss: Theoretical Model is the Free Space Model

$$P_{rx}(d) = \frac{P_{tx} G_{tx} G_{rx} \lambda^2}{16\pi^2 d^2 L} \quad (W)$$

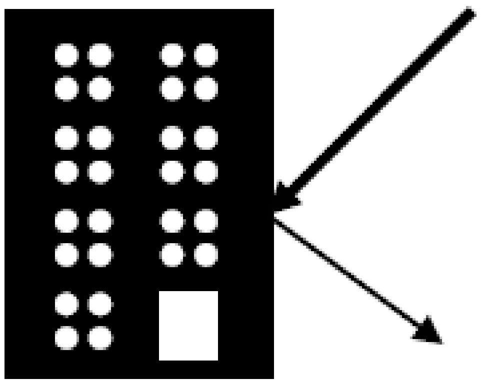


- Path-loss: difference (**in dB**) between the transmission and reception power:

$$PL(dB) = 10log\frac{P_{tx}}{P_{rx}}$$

Wireless Links – Signal Propagation

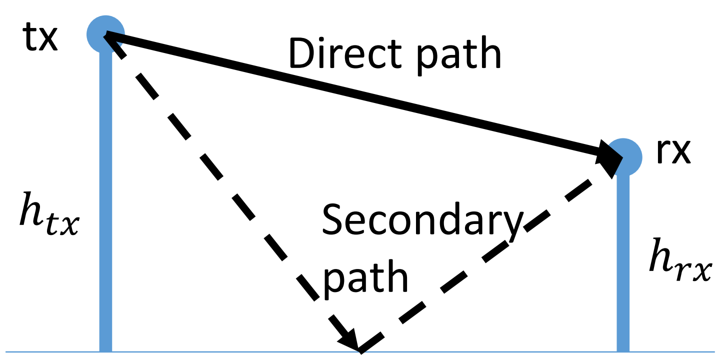
- Large-scale path-loss:
  - Reflection: the wave bounces on an object which has very large dimensions when compared to the **wavelength** of the propagated wave. The signal is partially reflected and partially transmitted **through** the medium (**absorbed**)
    - Material properties
    - Angle of reflection
    - Frequency of wave.



Also:

Ground reflection: direct path and the ground reflected path between a tx-rx pair:

$$P_{rx}(d) = \frac{P_{tx} G_{tx} G_{rx}}{d^4} (h_{tx} h_{rx})^2 \; (W)$$

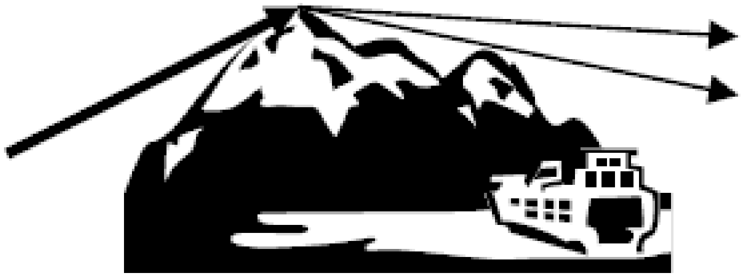


$d \gg h_{tx} + h_{rx}$

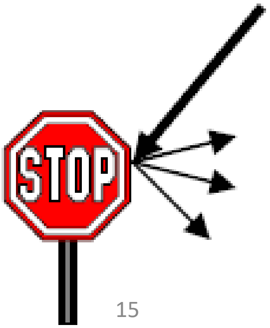
Wireless Links – Signal Propagation

Large-scale path loss:

- Diffraction: the signal encounters an irregular surface, such as a stone with sharp edges.



- Scattering: the medium through which the electromagnetic wave propagates contains a large number of objects with dimensions smaller than the signal wavelength. Signal is diffused in different directions → **Additional radio energy arrives at the receiver**.



Wireless Links – Signal Propagation

Small-scale phenomena:

Caused by the macroscopic behavior of the transmitted wave - reflection, diffraction, scattering -> Fading due to interference of the same signal arriving at the receiver at different times.

↓

Delay spread: the duration of the "echo" generated by the difference in arrival times.

↓

Inter-symbol interference: Second multipath is delayed and is received during next symbol

Wireless Links – Signal Propagation

Analytical & empirical models conclude to the observation that signal attenuates logarithmically to the distance between TX – RX.

Log-normal shadowing model:

Environmental clutter

$$P_{rx}(d)[dBm] = P_{tx}[dBm] - PL(d)\ (dB)$$

$$PL(d) = PL(d_0) + 10nlog10\left(\frac{d}{d_0}\right) + X\sigma\ (dB)$$

n: **path-loss exponent**
σ: std of zero-mean Gausian distributed random variable X (dB)

Wireless Links – Signal Propagation

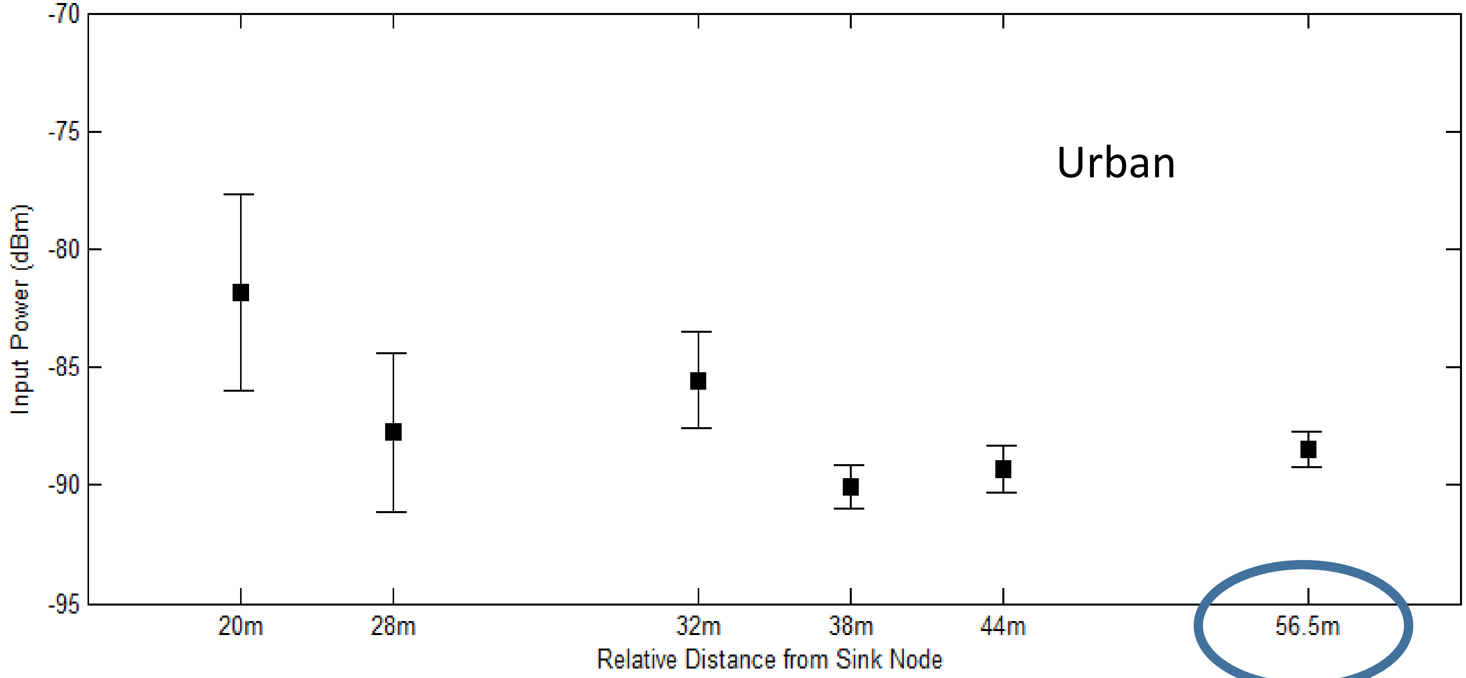
Environment	**path-loss exponent** n
Urban Area	2.7 to 3.5
Suburban Area	3 to 5
Indoors (LOS)	1.6 to 1.8
Indoors (no-LOS)	4 to 6
Industrial (no-LOS)	2 to 3

Wireless Links – Signal Propagation

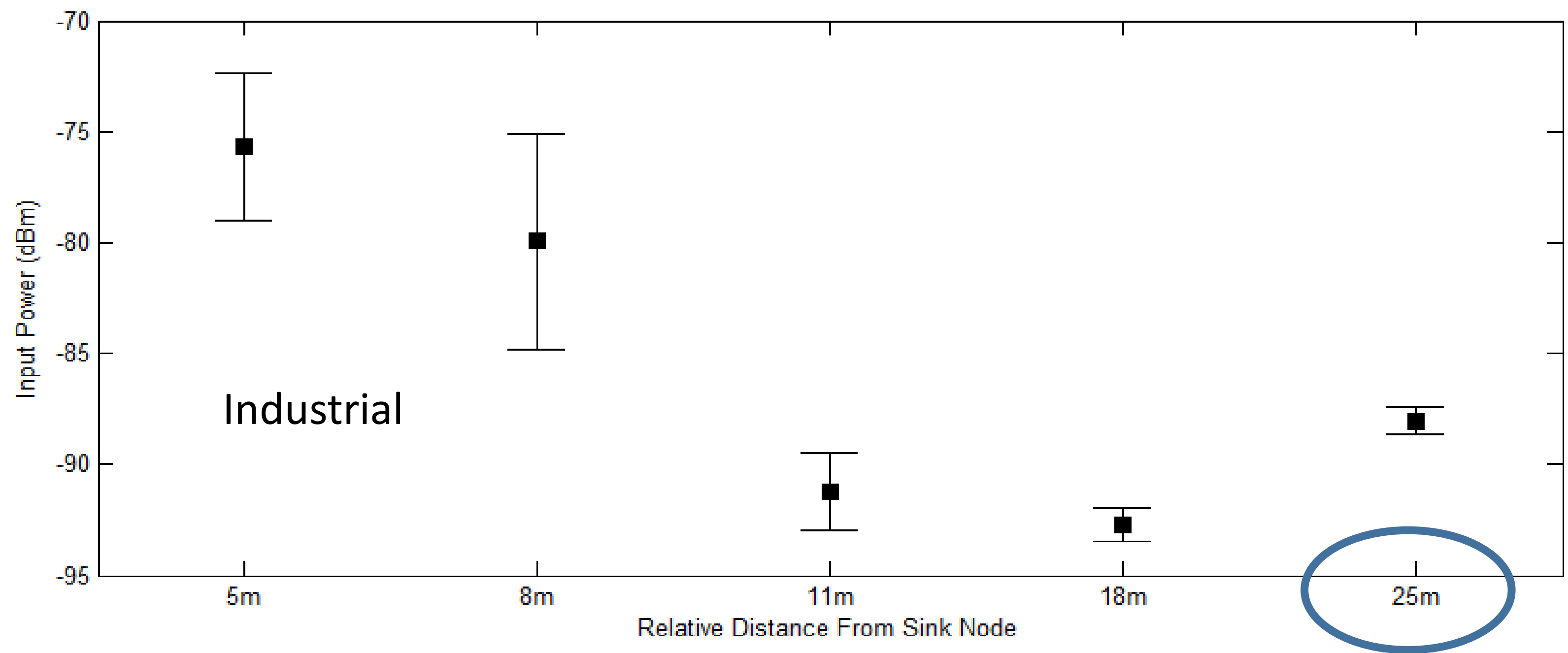
Log-normal shadowing empirical model

n, σ: Data measurements over a wide range of locations and tx-rx distance, then linear regression…

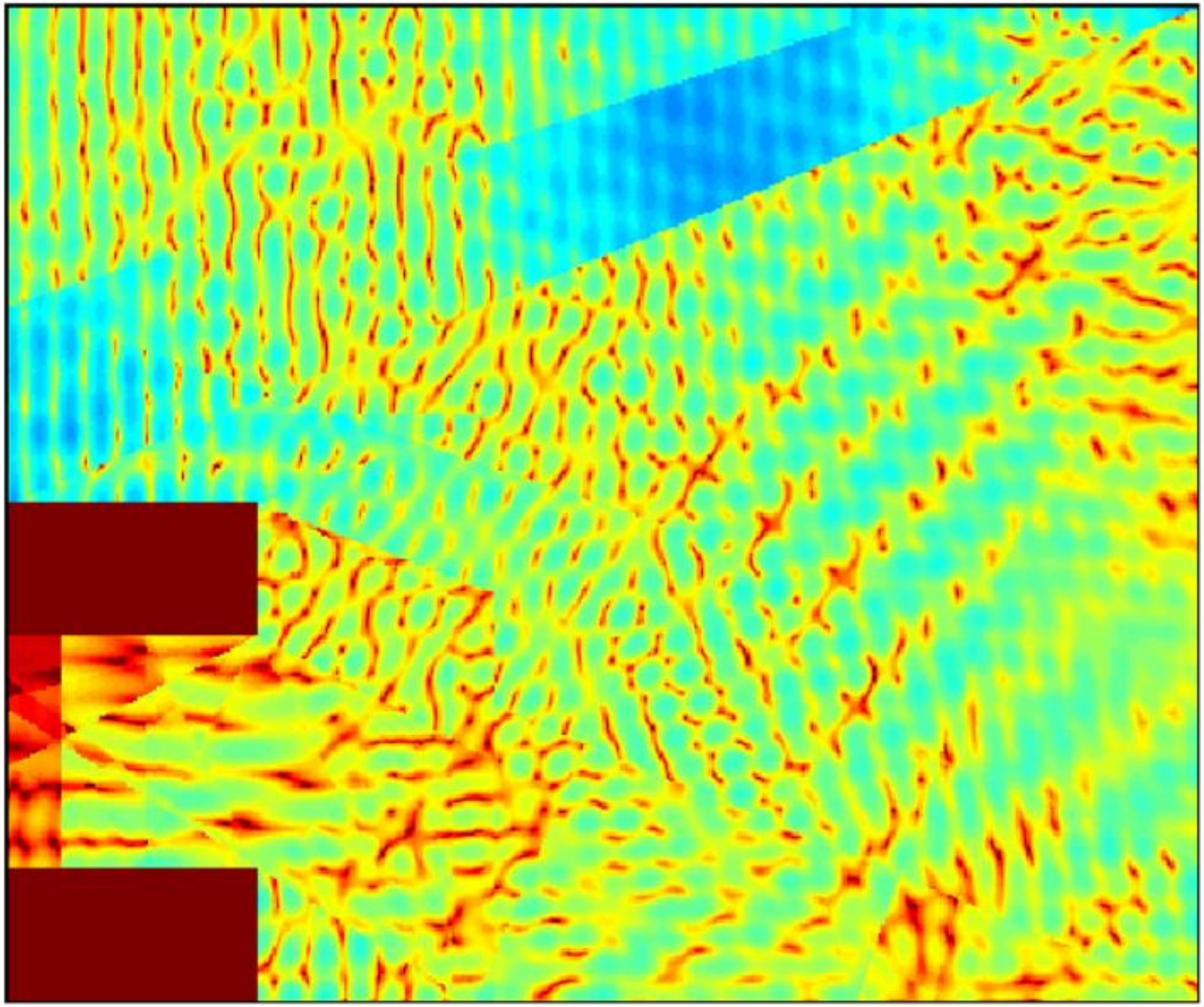
Environment	Frequency	n	σ (dB)
Vacuum, infinite space		2.0	0
Retail store	914 MHz	2.2	8.7
Grocery store	914 MHz	1.8	5.2
Office with hard partition	1.5 GHz	3.0	7
Office with soft partition	900 MHz	2.4	9.6
Office with soft partition	1.9 GHz	2.6	14.1
Textile or chemical	1.3 GHz	2.0	3.0
Textile or chemical	4 GHz	2.1	7.0, 9.7



Hydrobionets



Office Environment



William Stallings, Data and Computer Communications, 7th Edition, Ch. 9.

Wireless Links – PHY performance

- Signal distortion
- Noise due to electronics (RF design) – Additive white noise Gaussian Channel
- Interference:
  - intra network (> 1 users on the same type of network &the same channel)
  - Adjacent channels (HW filters)
  - Inter network: different types of networks (e.g. WSN + WiFi) on overlapping channels

- Additional factors that can affect interference:
  - Transmission power
  - Channel bandwidth
  - **Spectrum spreading mechanism & medium access scheme**

Wireless Links – PHY Performance

- Signal-to-Noise-plus-Interference Ratio

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

The ability of the receiver to decouple the interfering signals

- Bit Error Rate (with respect to type of modulation & data rate R):

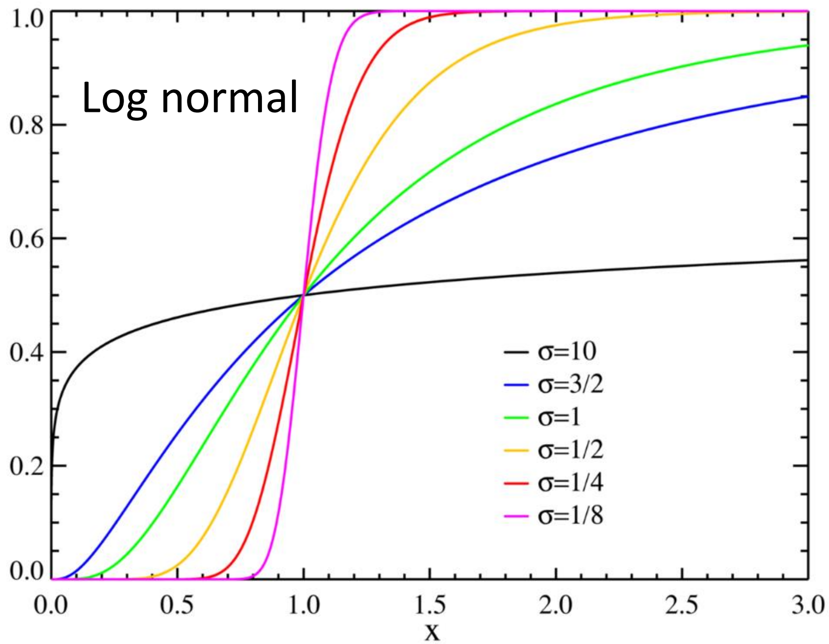
DPSK:

$$\mathrm{BER}(\mathrm{SINR}) = 0.5e^{-\frac{E_b}{N_0}}$$

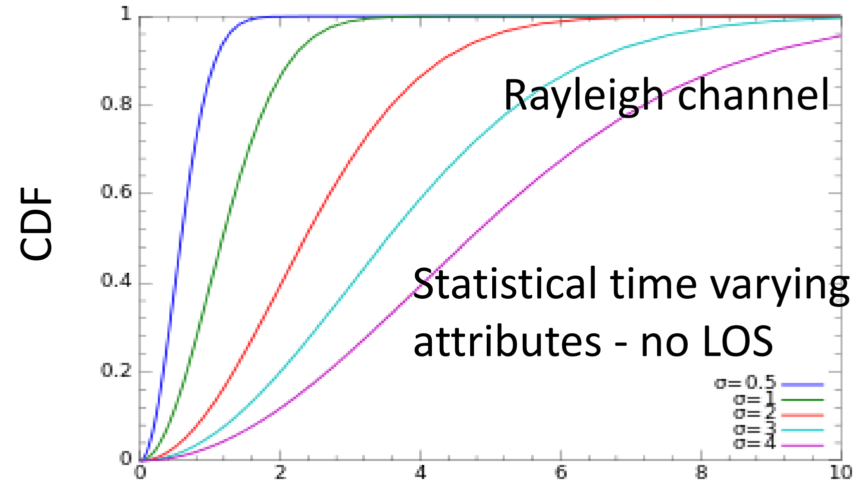
$$E_b/N_0 = \mathrm{SINR} \cdot \frac{1}{R}$$

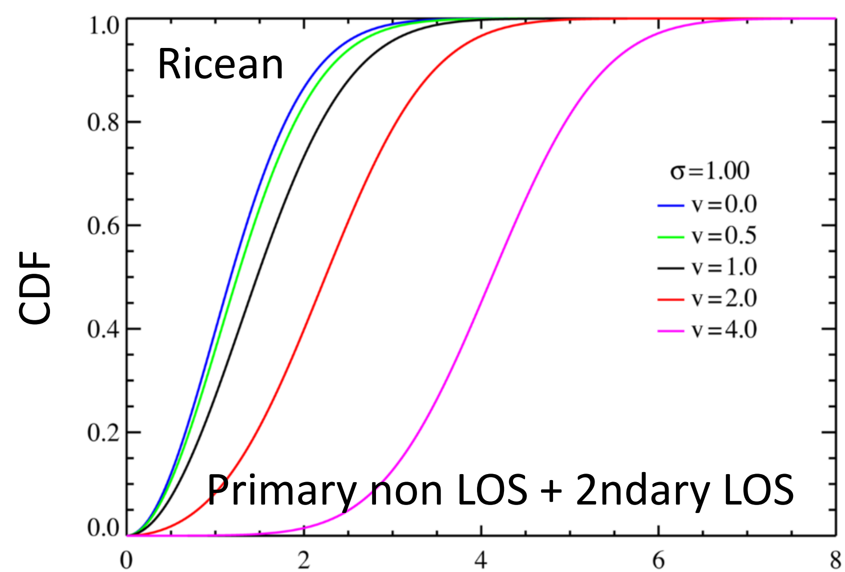
Wireless Links – PHY Performance

- Channel modelling for capturing the temporal behavior of a wireless channel / environment (modeling SNR or BER)



Or design your own model



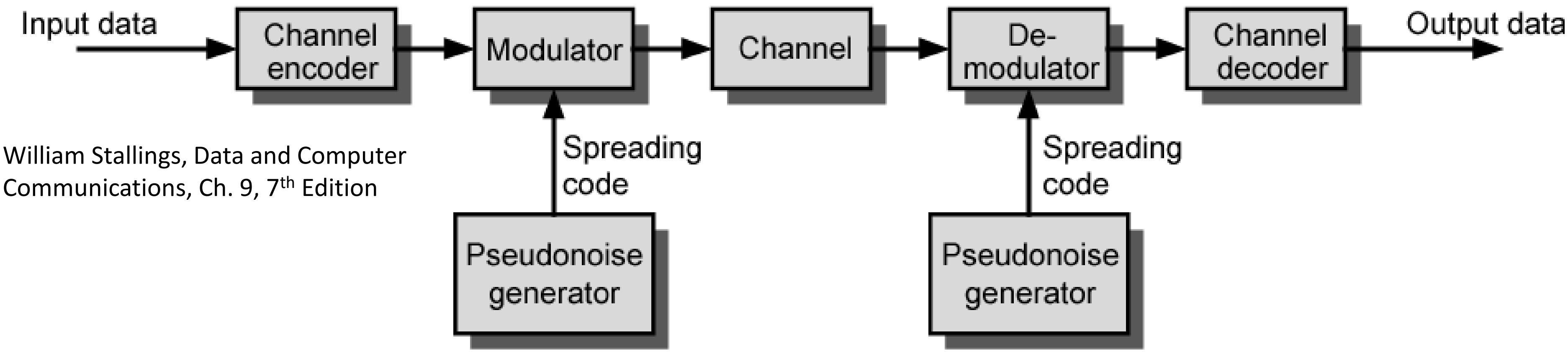


Envelope of fading signal

Wireless Links – How to handle the spectrum

Spread Spectrum:

- Compensates from interference and fading – allows multiple users on the same bandwidth
- The transmission bandwidth >> minimum required signal bandwidth
- Transmitter: pseudo-noise sequence for spreading signal (seed, algorithm)
- Receiver side: cross-correlation with a locally generated pseudo-noise sequence



William Stallings, Data and Computer Communications, Ch. 9, 7th Edition

Multipath fading:

Delayed spread signal will correlate poorly with receiver→ interfering signals will be discarded

Wireless Links – How to handle the spectrum

- Spread Spectrum
  - Direct Sequence Spread Spectrum
  - Frequency Hopping
  - Chirp Sequence Spread Spectrum

Wireless Links – How to handle the spectrum

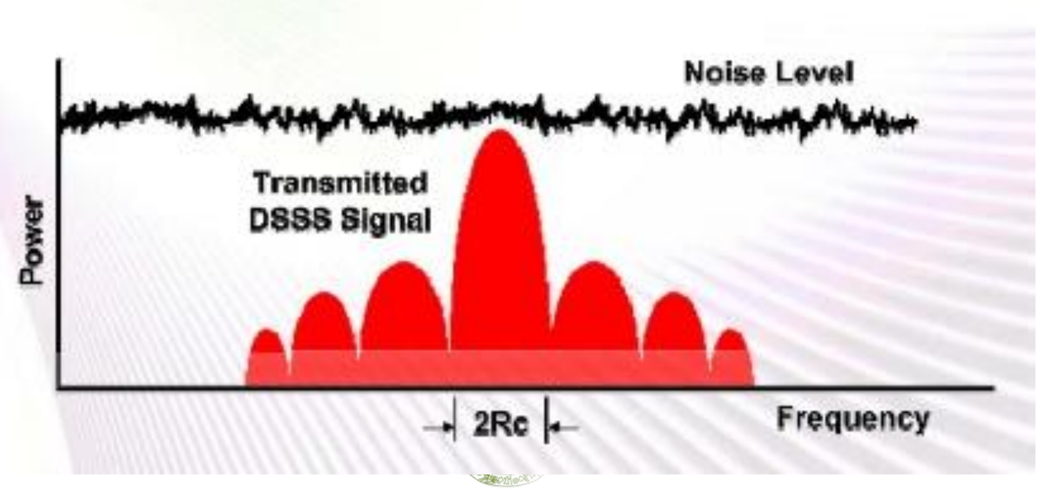
- Spread Spectrum
  - Direct Sequence Spread Spectrum

Widely adopted technique for WSN

The baseband signal is directly multiplied by the pseudo-noise sequence → each bit is represented by multiple bits.

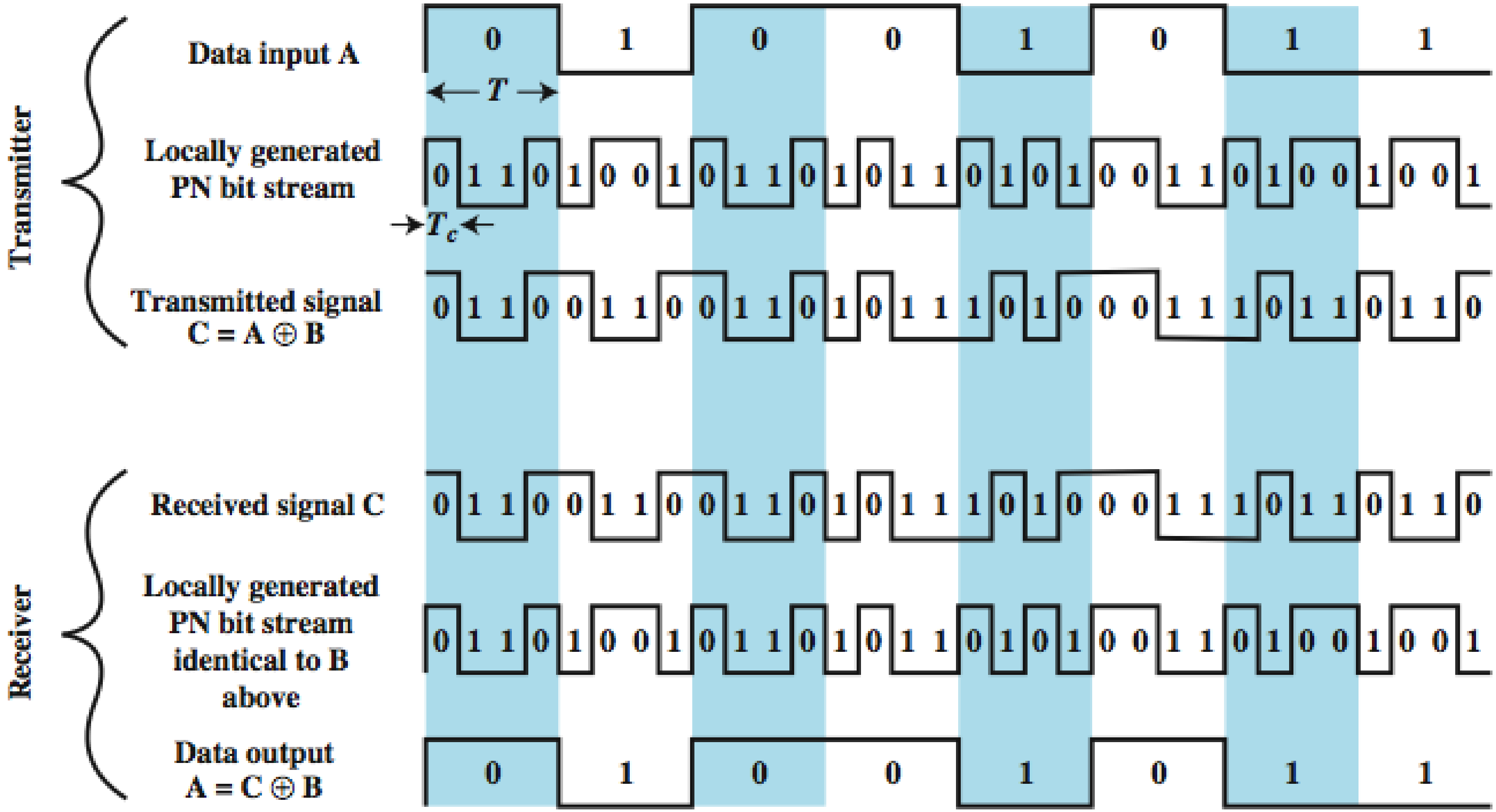
transmitted signal>> information signal

At the receiver: the de-spreading of the signal results at spreading the interference over a larger bandwidth



Wireless Links – How to handle the spectrum

Direct Sequence Spread Spectrum – Example



William Stallings, Data and Computer Communications, 7th Edition, Ch. 9.

Wireless Links – How to handle the spectrum

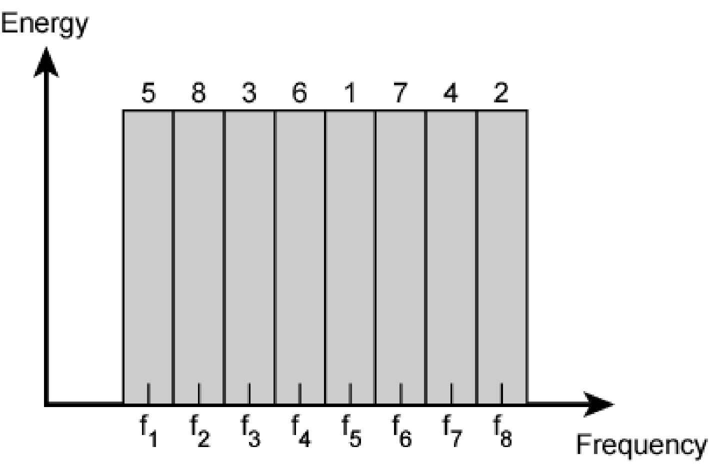
- Spread Spectrum
  - Frequency Hopping Spread Spectrum:

BT & BSN based on BT

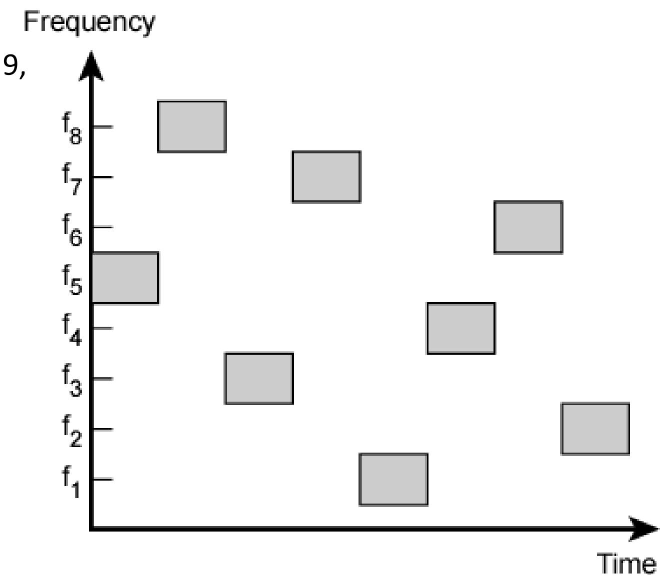
The pseudo-noise sequence is used for changing the transmission frequency ->

Signal broadcast over seemingly random series of frequencies

William Stallings, Data and Computer Communications, Ch. 9, 7th Edition



(a) Channel assignment



(b) Channel use

The transmitted carrier hops from one channel to another – small bursts / channel

Receiver: remain in synchronization with the transmitter for recovering the initial signal.

Wireless Links – How to handle the spectrum

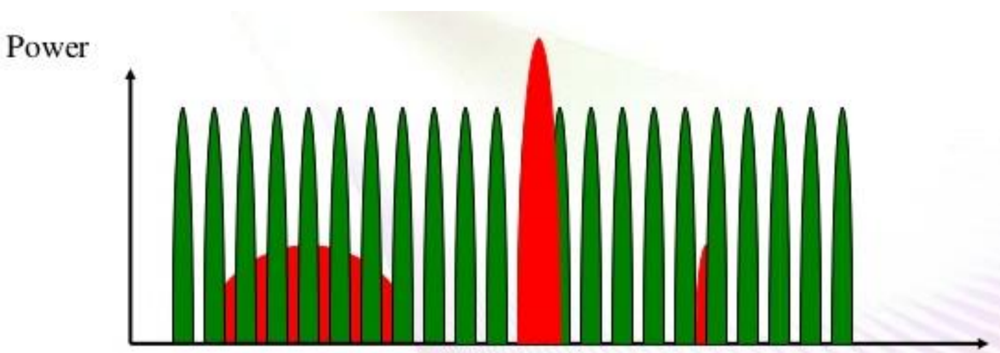
- Spread Spectrum
  - Frequency Hopping Spread Spectrum:

BT & BSN based on BT

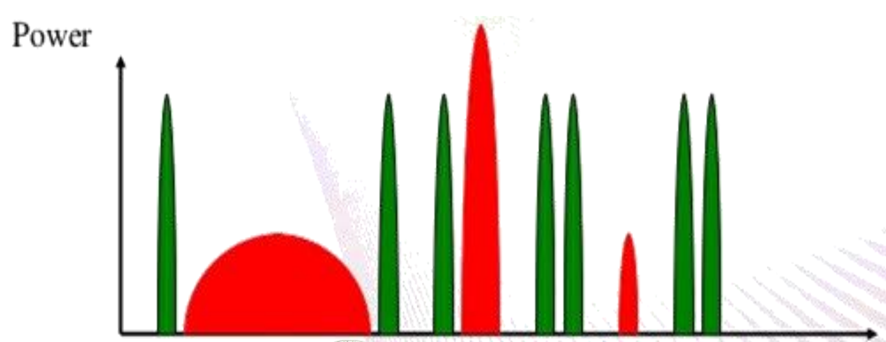
If a signal is send over at the same time & the same channel with another signal then there will be a *collision*

- FH/Time Division: more than one users use the same sequence
- Adaptive FH: allows skipping certain frequencies that are used by non-hopping ISM systems.

Static Frequency Allocation



Adaptive Frequency Allocation

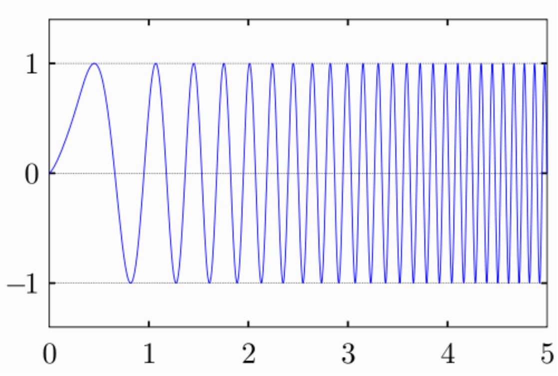


Wireless Links – How to handle the spectrum

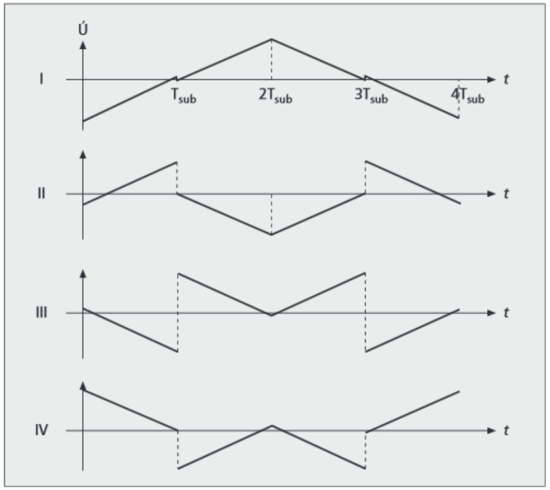
WSN in RF-harsh environments / tracking apps / Long Range WSN!

- Spread Spectrum
  - Chirp Spread Spectrum:

Windowed chirp: a sinusoidal signal whose frequency changes linearly over a time window.



NEW!!!



No pseudo-noise elements (DSSS, FH)

Subchirps: patterns of smaller chirps

Used in different frequency sub-bands with different chirp directions

Concatenated to construct a longer chirp symbol

Wireless Links and WSN

- WSN
  - Small transmission range (most of them)
  - Small delay spread (nanoseconds, compared to micro/milliseconds for symbol duration)

- WSN fading is typically considered **flat** (SS techniques are helping)**:**

BW of signal < BW of the channel
Delay Spread < Symbol period

+ the spectral characteristics of the transmitted signal are preserved at the receiver

- the received signal strength may change over time due to multipath & inter-symbol interference (depending on the type of the environment, antenna & HW **)**

Today's Objectives

- **Part A: Wireless Links: Signal Propagation, Handling the Spectrum, Modelling the PHY performance**

- **Part B: Protocol stack preliminaries for WSN**

OSI Reference Model

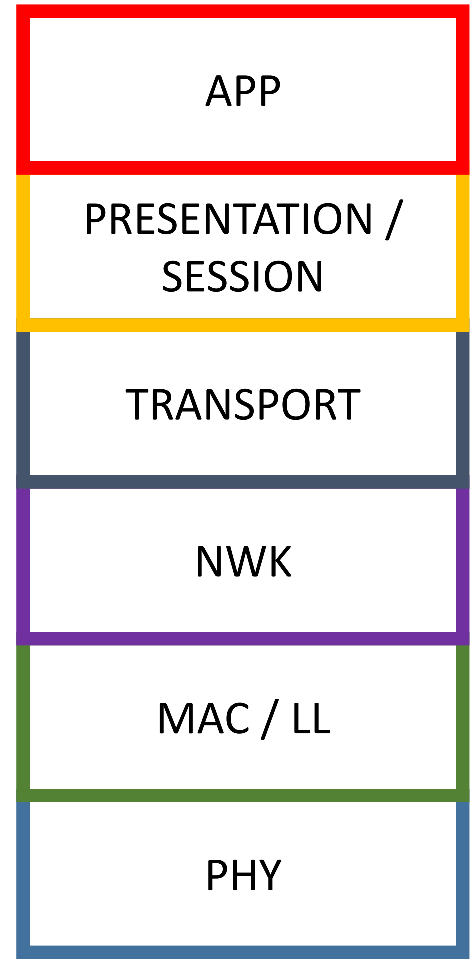
OSI Reference model

Typical data & industrial networks: a stack of vertical planes

Well defined responsibilities @ each plane - well defined roles within the network

Well defined interfaces between different layers

Trade off between layers/range of functionalities and complexity (especially for the industrial protocols)



OSI Reference Model

The more the layers, the higher the complexity

⇩

The higher the computational & memory demands

⇩

The more complex the transmission schemes & energy demands

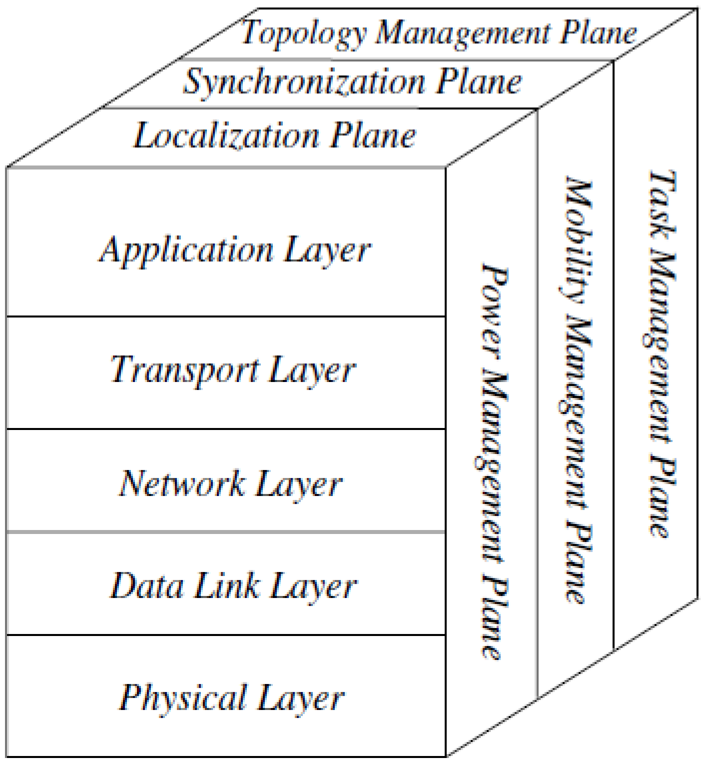
BUT: More scalable, interoperability against low-level differences, and better structured (complex operational conditions)

Protocol Stack Model for WSN

Sensor nodes have multiple roles: (a) data originators, (b) data routers, (c) *sinks and gateways*

Address the challenge of operating in an unattended manner in the field while under several constraints: power limitations, multipath propagation phenomena, exposure/coexistence with other networks, *the demands of the application*, etc.

Protocol stack → combination of vertical and *horizontal* planes



"Wireless Sensor Networks", Ian F. Akyildiz, Mehmet Can Vuran, 2010, Willey, Ch 1

<u>A reference model for WSN</u>

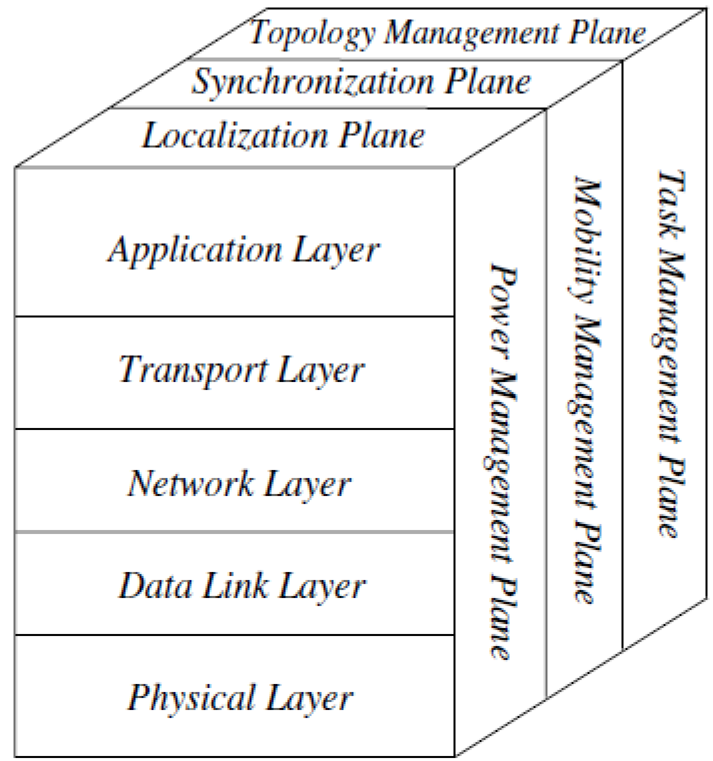
Protocol Stack Model for WSN

Physical Layer: (de)modulation, spectrum allocation, transmission and reception (relying on well defined techniques and **standards**)

Data Link Layer (noisy environment / dynamic topologies): Error Control techniques for reliable communication and manage channel access through the MAC sublayer

Network Layer: (Energy-aware) data routing

Transport layer: Data flow maintenance



"Wireless Sensor Networks", Ian F. Akyildiz, Mehmet Can Vuran, 2010, Willey, Ch 1

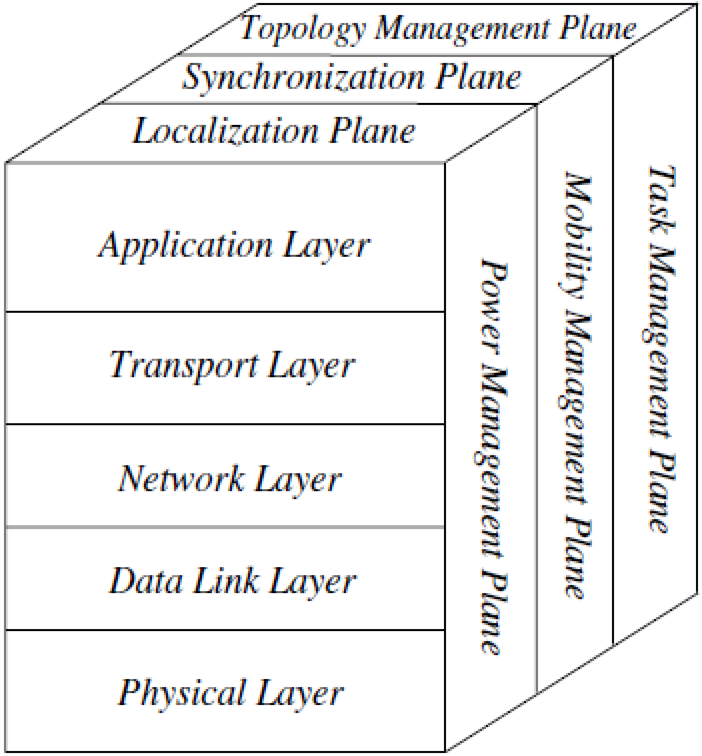
A reference model for WSN

Protocol Stack Model for WSN

Power management: monitoring available energy level & accordingly allocate resources *(e.g. turn of radio after receiving a message or when power is critically low stop all forwarding services.)*

Mobility management plane: detects and registers the movement of sensor nodes (e.g. for routing)

Task management plane: balances and schedules the sensing tasks given to a specific region. $\rightarrow$ **Network-wide collaboration & achieving a global optimum** (e.g. detecting a target, preserving energy)



"Wireless Sensor Networks", Ian F. Akyildiz, Mehmet Can Vuran, 2010, Willey, Ch 1

A reference model for WSN

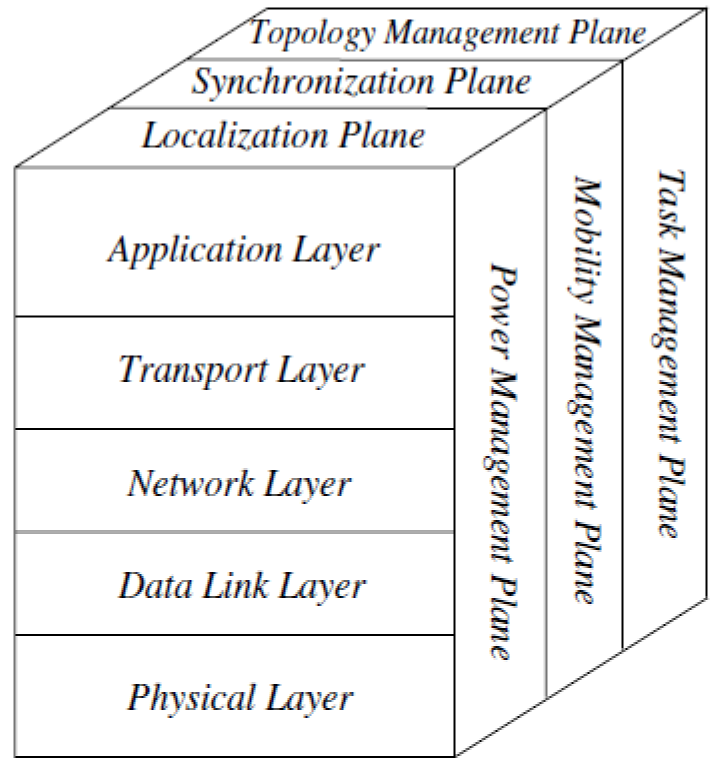
Protocol Stack Model for WSN

At the level of the Application Layer

Localization Plane:
Accurate view of the observed sensor field.
Tracking application & Location-based services

Synchronization Plane:
Local clock for sensing, processing, and communication. Timing information for data consistency. *Collaborative* execution of events (modelling the physical environment).

Topology Management Plane:
Connectivity and Coverage. Formation of clusters. Network deployment for efficient information coverage.



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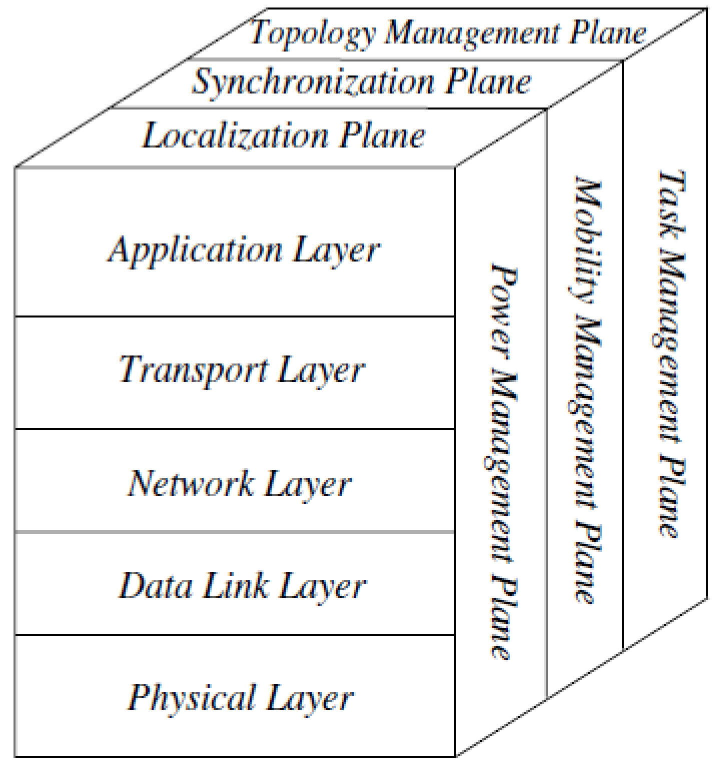
A reference model for WSN

Protocol Stack Model for WSN

Cross-layer design of protocols: tight interaction between different layers of the vertical protocol stack (through the horizontal planes)

Increased efficiency in *code space* and operating overhead

Structured design – *different instances* with respect to the application demands



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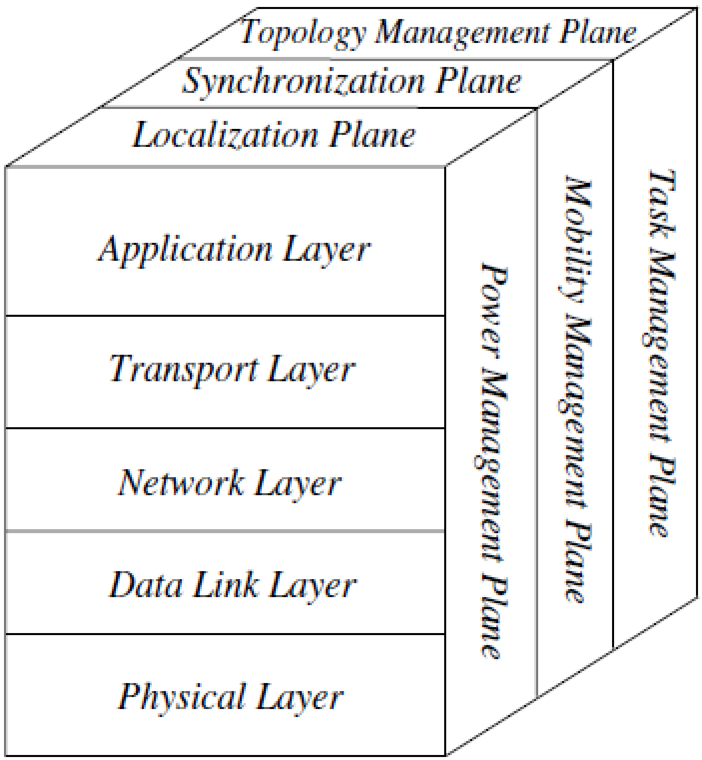
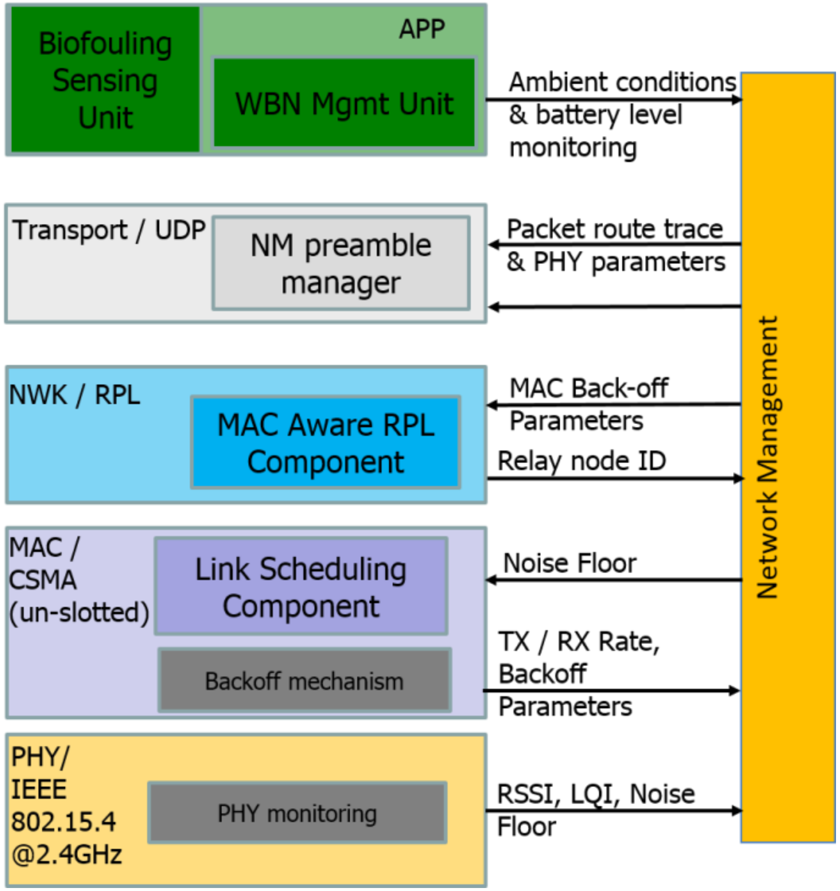
A reference model for WSN

Protocol Stack Model for WSN

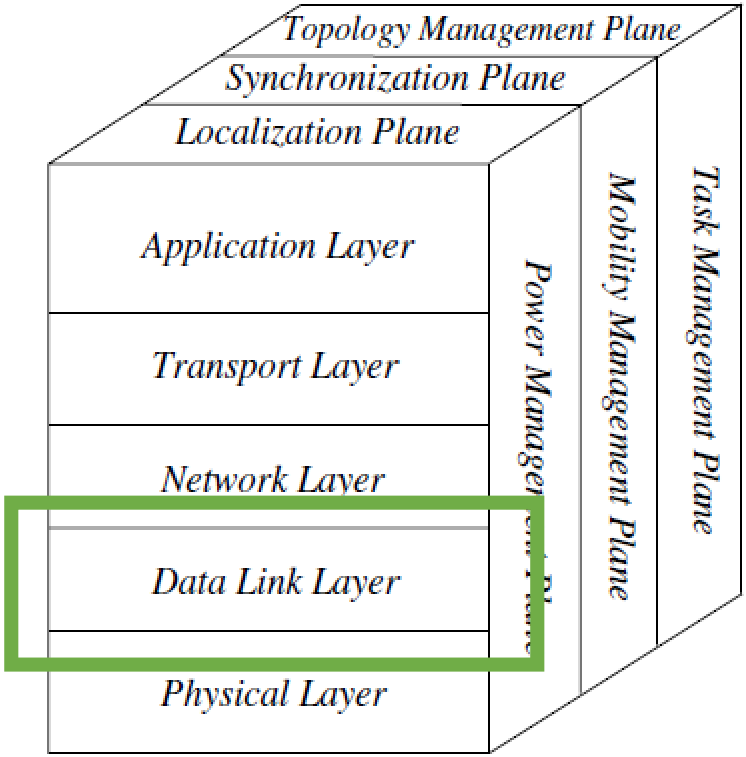
An example of instantiation…





Protocol Stack Model for WSN

- MAC approaches – design considerations for WSN
  - Create the network infrastructure (dense deployment, self-organizing ability)
  - Allow fair and efficient sharing of the wireless communication medium between sensor nodes.
  - **Energy (communication is the most expensive aspect of WSN) -> Balance between smart radio control and protocol design**



- Error control of transmission data:
  - Forward error correction (FEC): @ HW level, simple encoding / decoding techniques
  - Automatic repeat request (ARQ): **Retransmission cost and overhead**. On the other hand, decoding complexity is greater in FEC, as error correction capabilities need to be built in.

Techniques for WSN MAC

- MAC approaches

Contention-based

- CSMA and its variations
- On-demand allocation for those that have frames for transmission
- Sensing the carrier before attempting a transmission
- **Scalable / no need for central authority**
- **Idle listening / Interference / Collisions / Traffic fluctuations -> Energy consumption**
- **Multi-hop topologies (hidden / exposed terminal problem)**

Scheduled-based

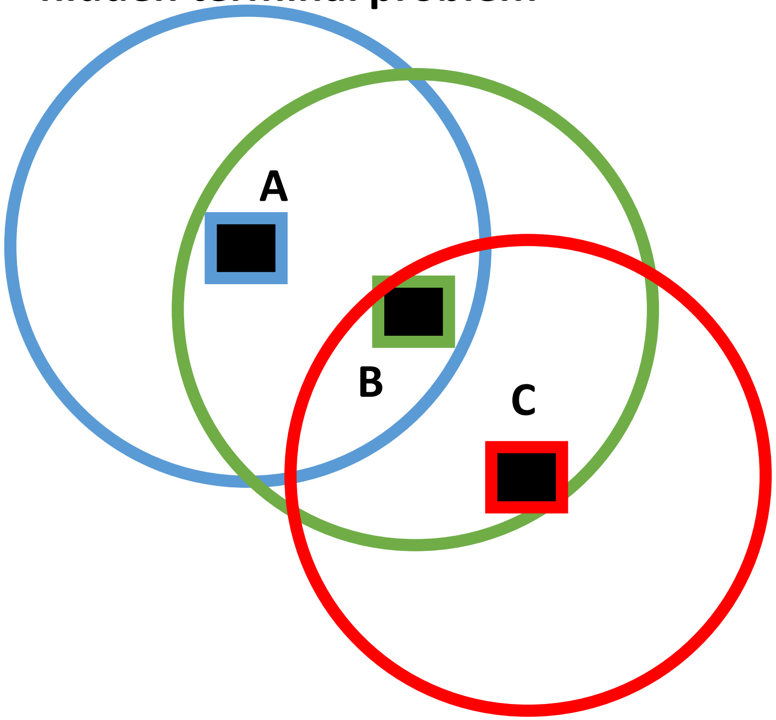
→ **Fixed assignment**

- Schedule that specifies when, and for how long, each node may transmit over the shared medium
- **Energy efficient**
- **Interference, collisions are not a problem**
- **Synchronization**
- **Central authority**

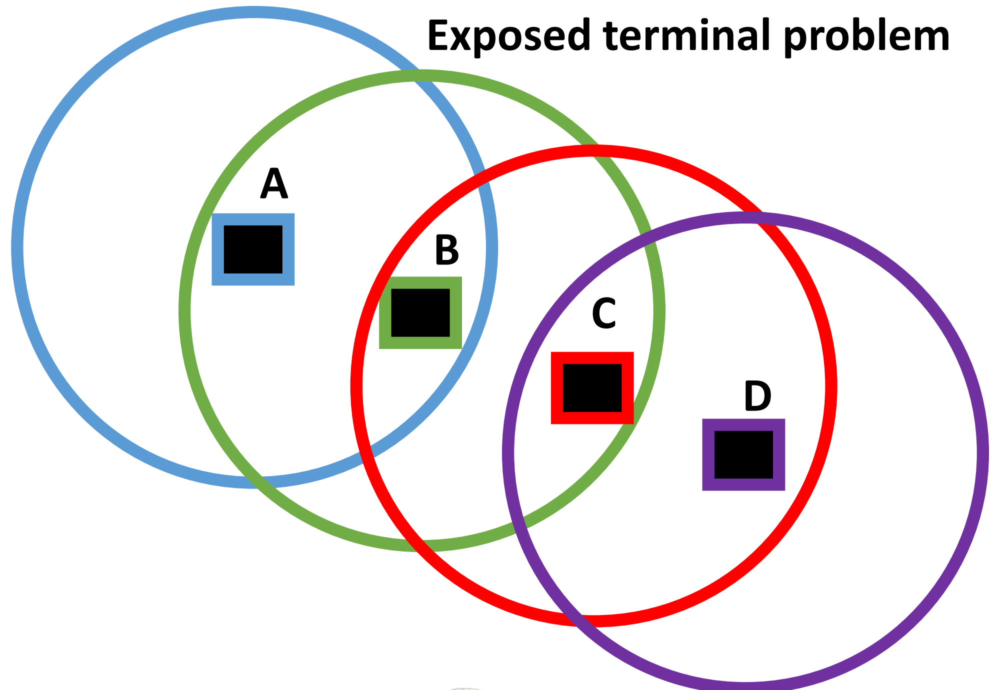
→ **On demand**

Techniques for WSN MAC

hidden terminal problem

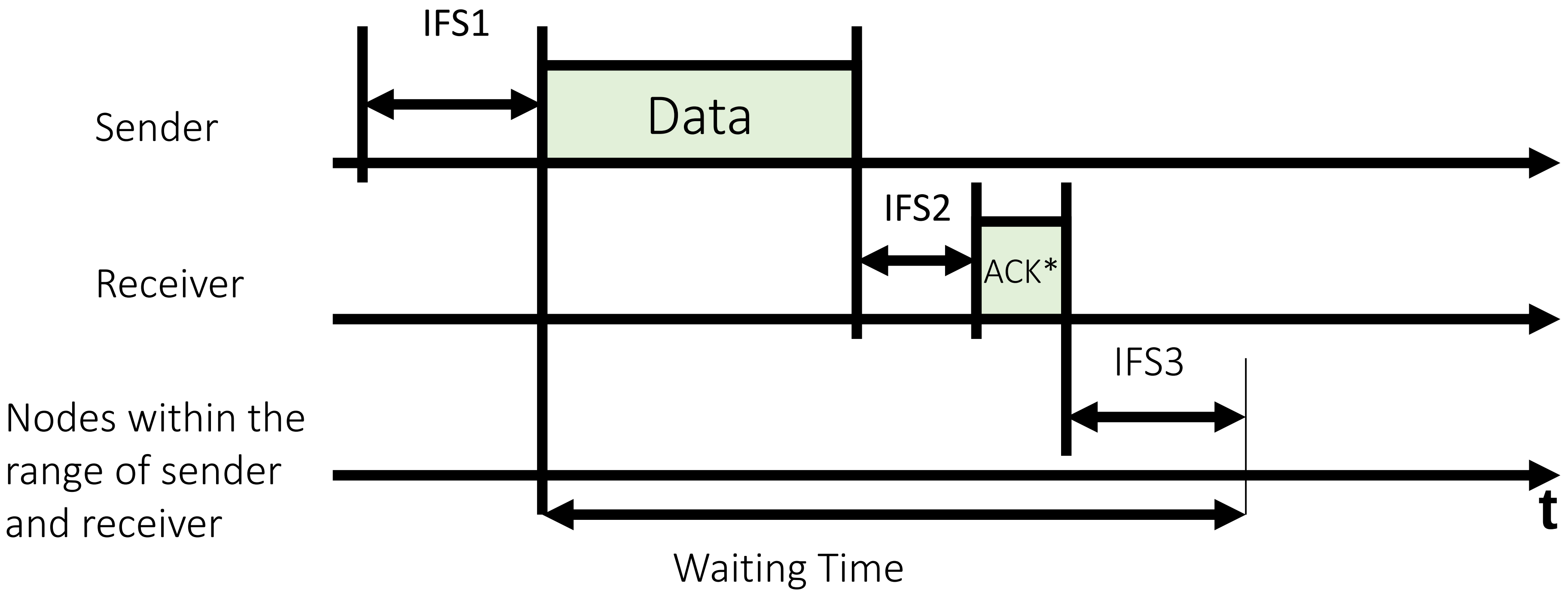


Exposed terminal problem



Techniques for WSN MAC

Basic CSMA/CA



Inter-frame Space: waiting time, after the carrier has been found idle

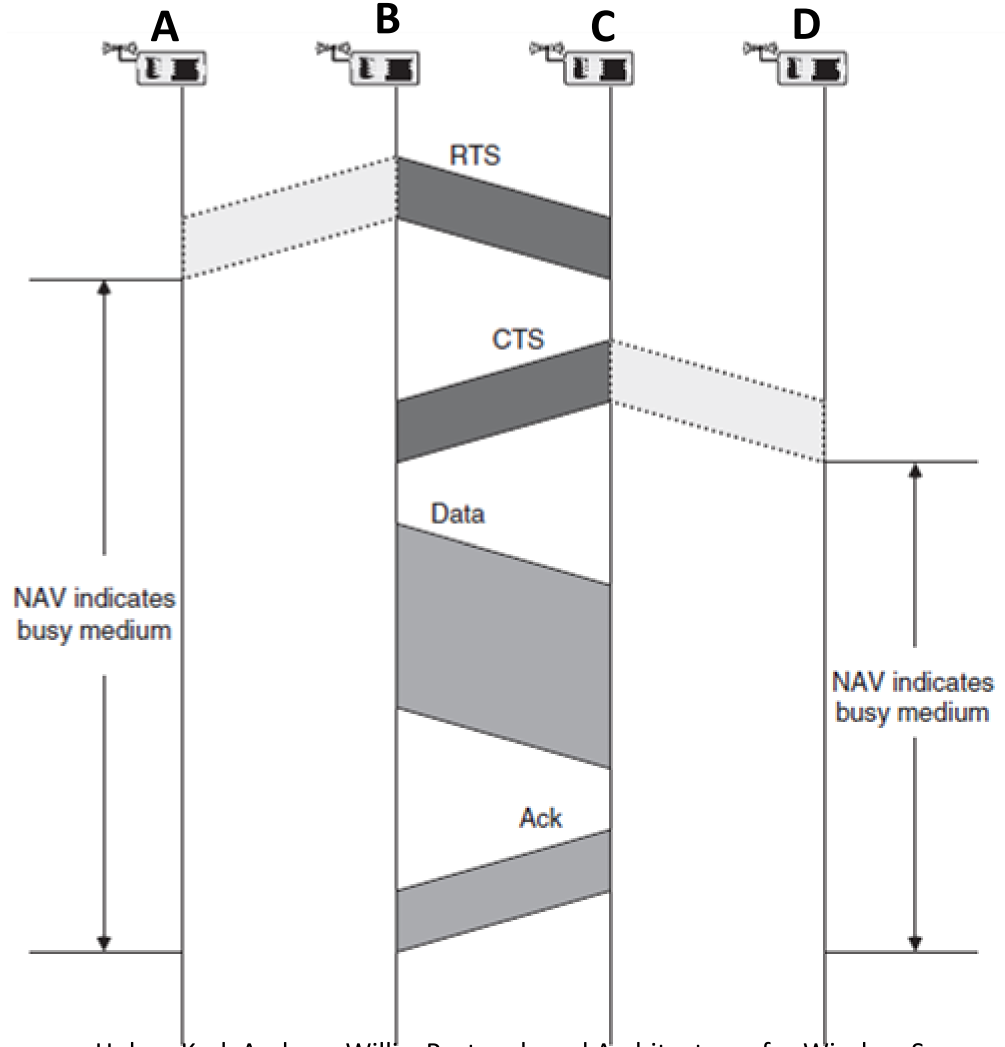
*: ACK is optional

Techniques for WSN MAC

- Contention-based
  - RTS / CTS before transmission
  - Low-level carrier sense method at PHY
    - Transmitter: preamble (no data) to notify receivers for turning on their radio and potential transmitters that the channel is busy
    - Receivers can be on sleep mode and periodically sample the carrier
  - Clear Channel Assessment

Techniques for WSN MAC

- Contention-based: RTS/CTS
  - RTS / CTS before the actual transmission between the transmitter and receiver pair for reserving the transmission medium
  - Combined with carrier sense for mitigating (not solving) the hidden/exposed terminal problem



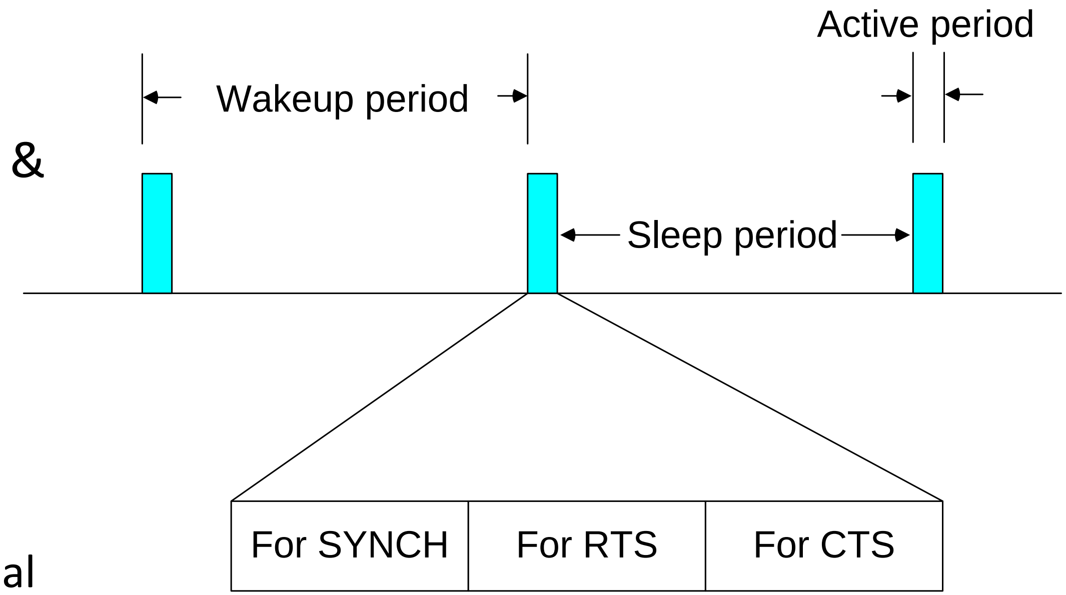
Holger Karl, Andreas Willig, Protocols and Architectures for Wireless Sensor Systems, 2005, Willey, Ch. 5

Techniques for WSN MAC

Contention-based: RTS/CTS

For WSN: idle listening with RTS/CTS is not energy-conservative → combined with **sleep and wake up schedules** between the nodes

- Wakeup schedule between neighbors
- Active period << wakeup period & sleep period
- Use SYNCH, RTS, CTS phases
  - SYNCH: for synchronization on wakeup and sleep (and drifting)
  - RTS/CTS: for data transmission
  - If RTS/CTS: the packet exchange continues, extending the nominal sleep time.

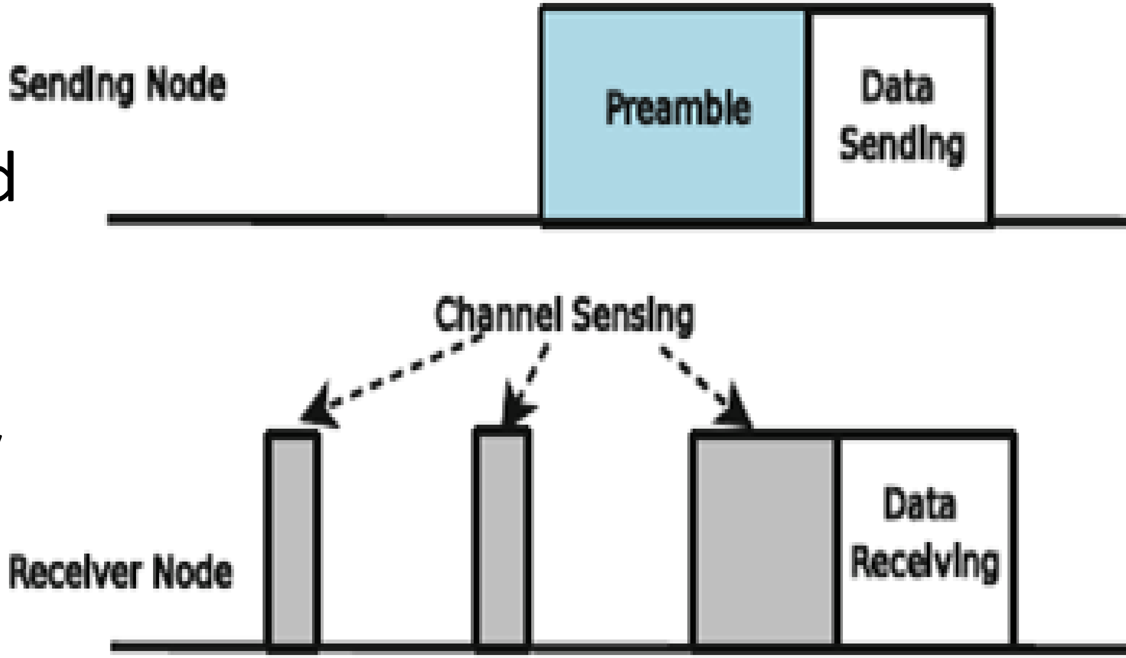


Holger Karl, Andreas Willig, Protocols and Architectures for Wireless Sensor Systems, 2005, Willey, Ch. 5

Techniques for WSN MAC

Contention-based: Low-level carrier sense

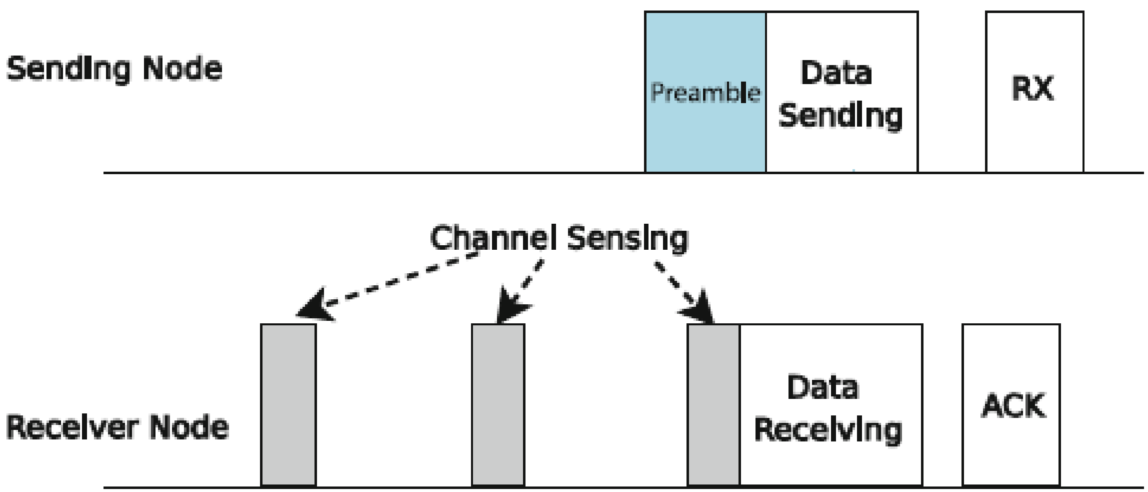
@ PHY header:
TX: Preamble that is used to notify receivers of the transfer
RX: Adjust their circuitry to the current channel conditions.



"Guide to Wireless Sensor Networks", S. Misra, I. Woungang, S. C. Misra, 2009, Springer, Ch 16

Techniques for WSN MAC

Contention-based: Low-level carrier sense



"Guide to Wireless Sensor Networks", S. Misra, I. Woungang, S. C. Misra, 2009, Springer, Ch 16

WiseMAC: CSMA-based + piggyback information in the ACK related to sleep time for deciding the time and duration of preamble

Transmitter schedules transmissions s.t. the receiving node's sampling time corresponds to the middle of the sender's preamble

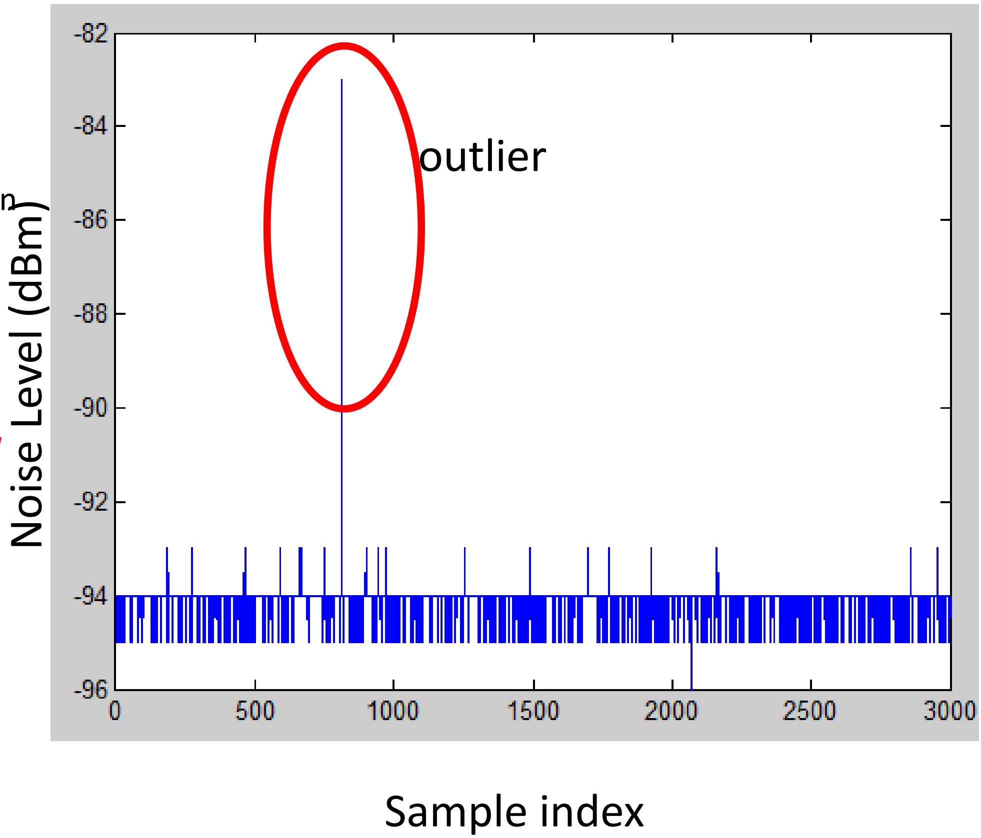
Adapting preamble duration with respect to traffic conditions:
Light traffic: longer preambles
Heavy traffic: short preambles

Clock drift: the preamble is extended with a time proportional to the length of the interval since the last message exchange.

Techniques for WSN MAC

Contention-based: Clear Channel Assessment

- What is noise and what is data (in terms of received signal strength)
  - Ambient noise may change significantly depending on the environment
  - Packet reception has fairly constant channel energy
- Take a signal strength sample when the channel is assumed to be free/idle
  - ***Right after a packet is transmitted or when no valid data is received***
- Samples are exponentially averaged, in order to decide on thresholds of free channel
- Random backoff if channel is found busy (+Immediate ACK for received packets)



Techniques for WSN MAC

Scheduled-based

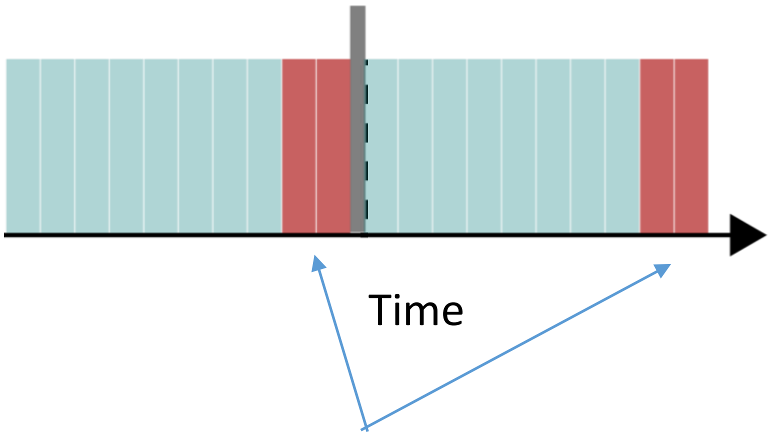
- TDMA & variations
- Clustering & Hierarchical approaches

Techniques for WSN MAC

Scheduled-based: TDMA & variations

- Direct single-hop communication with a central node (Base Station)
- How the coordinator pre-allocates the slots (based on negotiation or not, based on previous performance)
- On-demand polling for data (initiated by the coordinator)
- Pre-allocation of slots for retransmissions or priority traffic

Suitable for small scale WSN (e.g., body area networks)

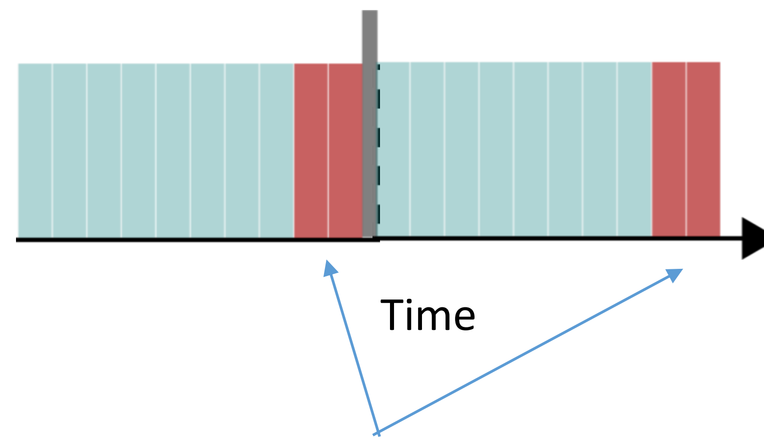


Techniques for WSN MAC

Scheduled-based: TDMA & variations

Suitable for small scale WSN (e.g., body area networks)

- Simple / Limited requirements on computational efficiency
- Power efficiency (strict master-slave mode)
- Coordinator has a leading role (single point failures)
- Assumption of perfect synchronisation



Reserved for high priority packets

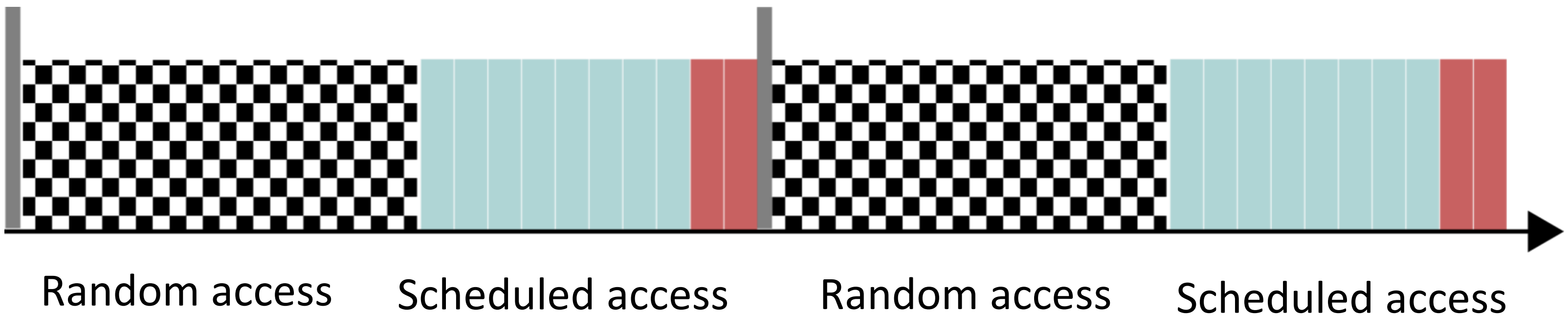
Techniques for WSN MAC

Scheduled-based: TDMA & variations

combine with contention-based

TRAMA

- Nodes are synchronized – no central entity



Nodes exchange neighborhood information: 2-hop neighborhood
Nodes exchange schedules of transmission (point to point links)
Nodes with little traffic: release their slots for the remainder of the frame for use by other nodes with heavy traffic

Techniques for WSN MAC

Scheduled-based: TDMA & variations

TRAMA

- Slot allocation
  - ***node identifier*** x & ***hash function*** h (globally known)
  - For time slot t: ***priority*** $p = h(x \oplus t)$
  - Compute this priority for next k time slots for node x and all two-hop neighbors
  - Node uses those time slots for which it has the highest priority

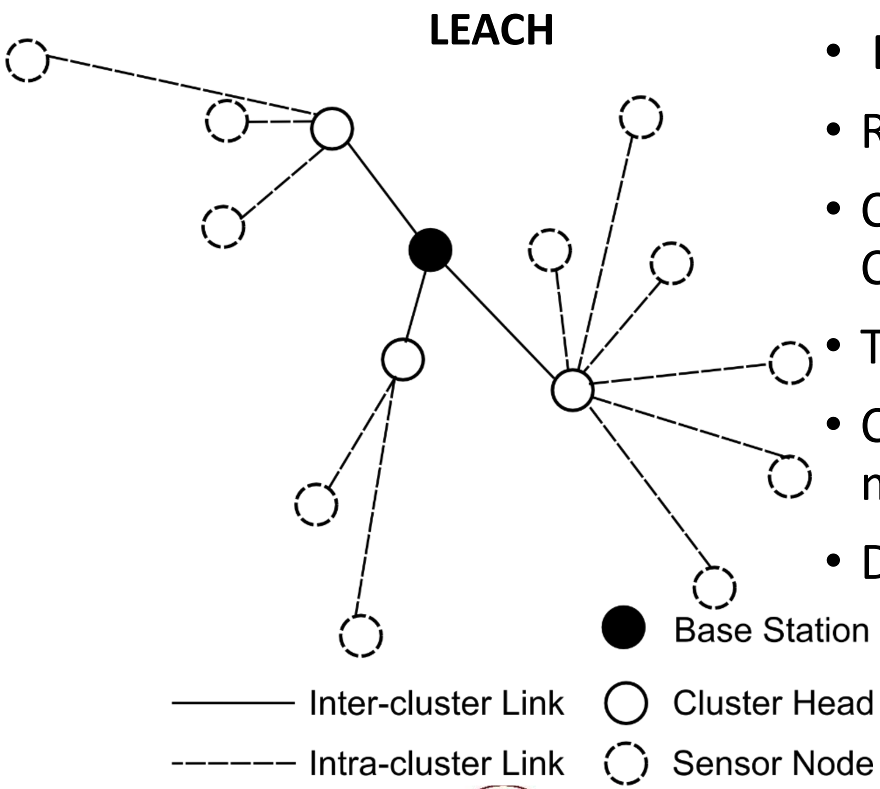
Knowledge of all priorities within the 2-hop neighborhood. Significant computation and memory in dense sensor networks

	t = 0	t = 1	t = 2	t=3	t = 4	t = 5
A	14	23	9	**56**	3	26
B	33	**64**	8	12	44	6
C	**53**	18	6	33	**57**	2

Priorities of node A and its two neighbors B & C

Techniques for WSN MAC

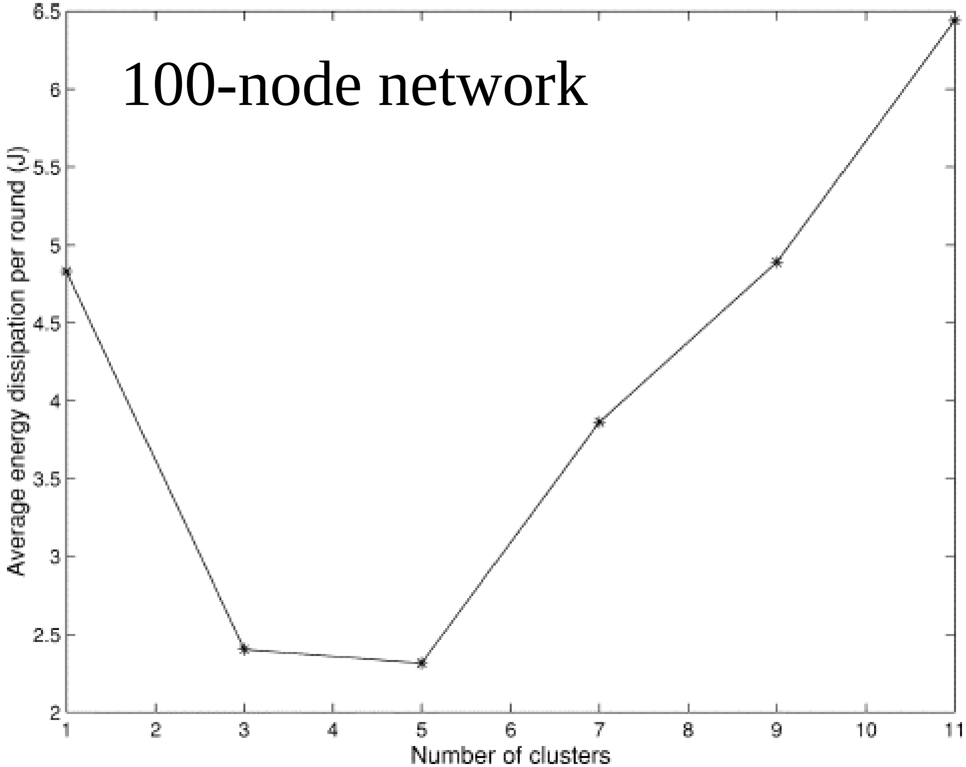
Scheduled-based: Clustering & Hierarchical approaches



- Dense network of nodes, reporting to a BS
- **Each node can directly reach BS**
- Round-robin CH selection
- CH advertise themselves, ordinary nodes join CH with strongest signal
- TDMA within a cluster – **no peer to peer**
- CHs collect & aggregate data from all cluster members
- DSSS for inter-cluster

Techniques for WSN MAC

Scheduled-based: Clustering & Hierarchical approaches



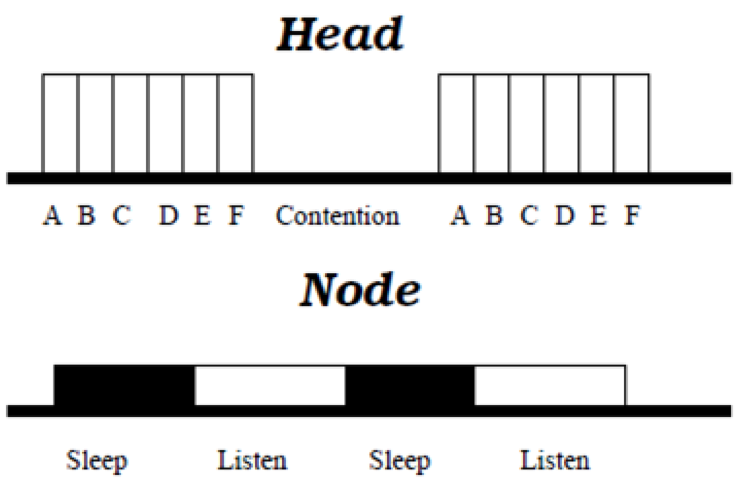
- 7-8 times lower overall energy dissipation, compared to the case where each node transmits its data directly to the sink
- 4-8 lower energy than in a scenario where packets are relayed in a multihop fashion.

Heinzelman, Wendi B., et al. "An application-specific protocol architecture for wireless microsensor networks." IEEE Transactions on wireless communications 1.4 (2002): 660-670.

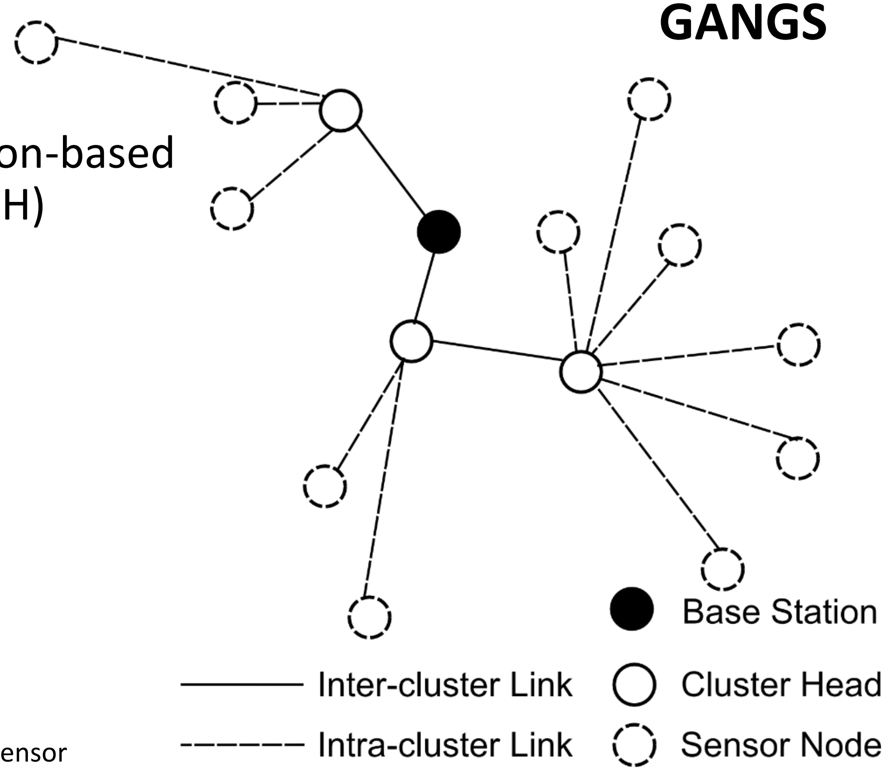
Techniques for WSN MAC

Scheduled-based: Clustering & Hierarchical approaches

- CH selection: available energy resources
- CH form the network backbone (multi-hop)
- Sensor Nodes follow their CH & use a contention-based mechanism to transmit (sleep on the slots of CH)



GANGS



S. Biaz and Y. Dai Barowski. 2004. "GANGS": an energy efficient MAC protocol for sensor networks”

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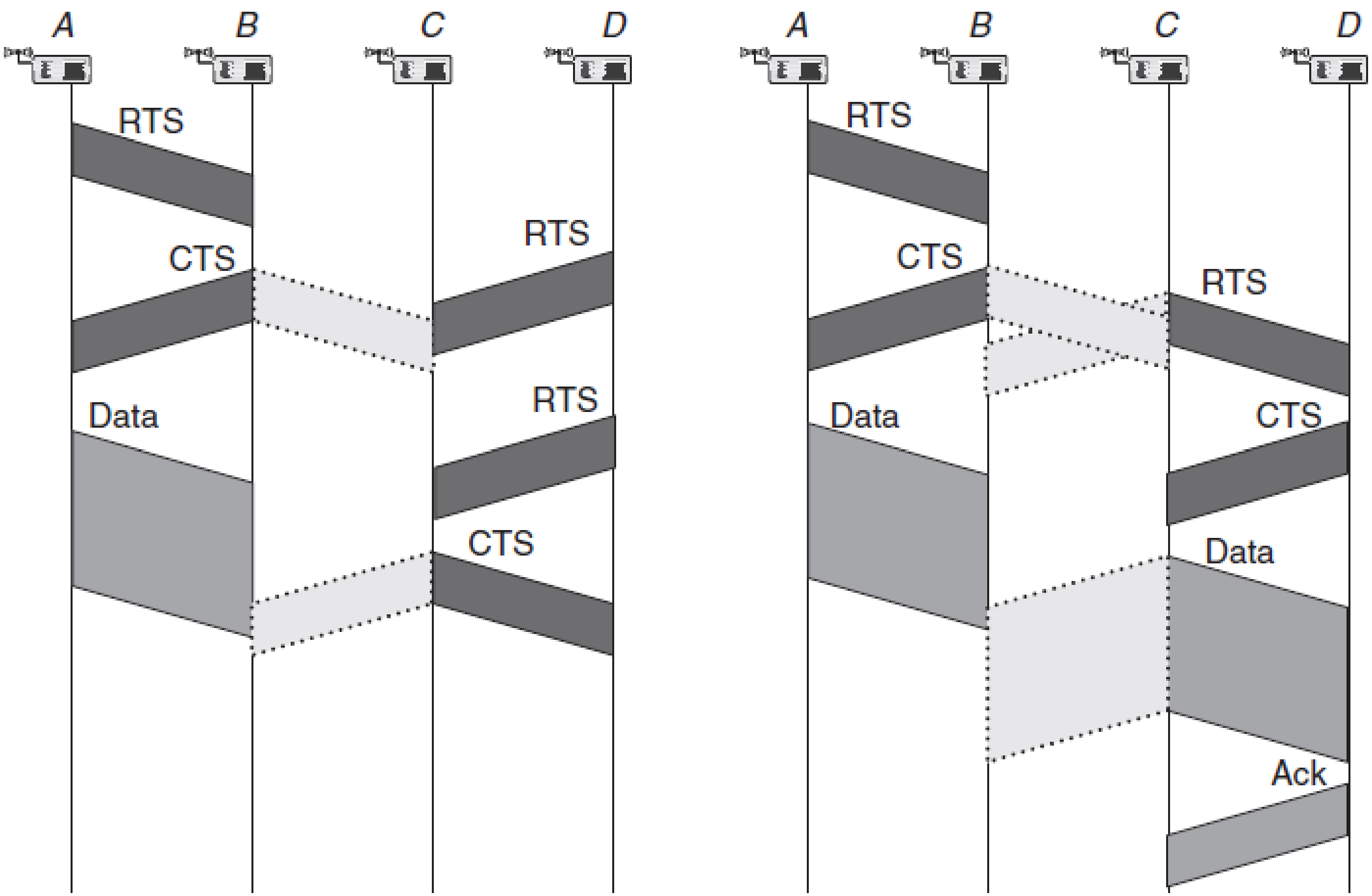
Techniques for WSN MAC



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