Building Robust Wireless LAN for Industrial Control with DSSS-CDMA Cell Phone Network Paradigm

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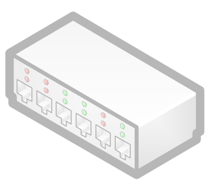
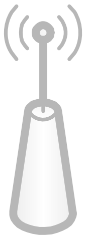
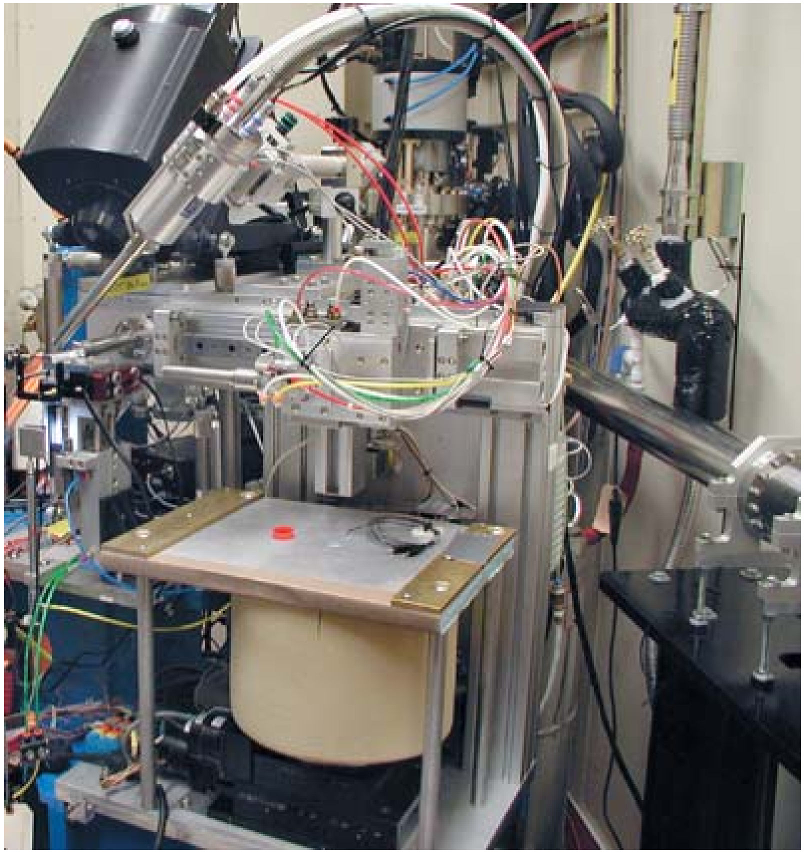




The demand for real-time wireless communication is increasing.

Mechanical Freedom / Mobility

Ease of Deployment / Flexibility



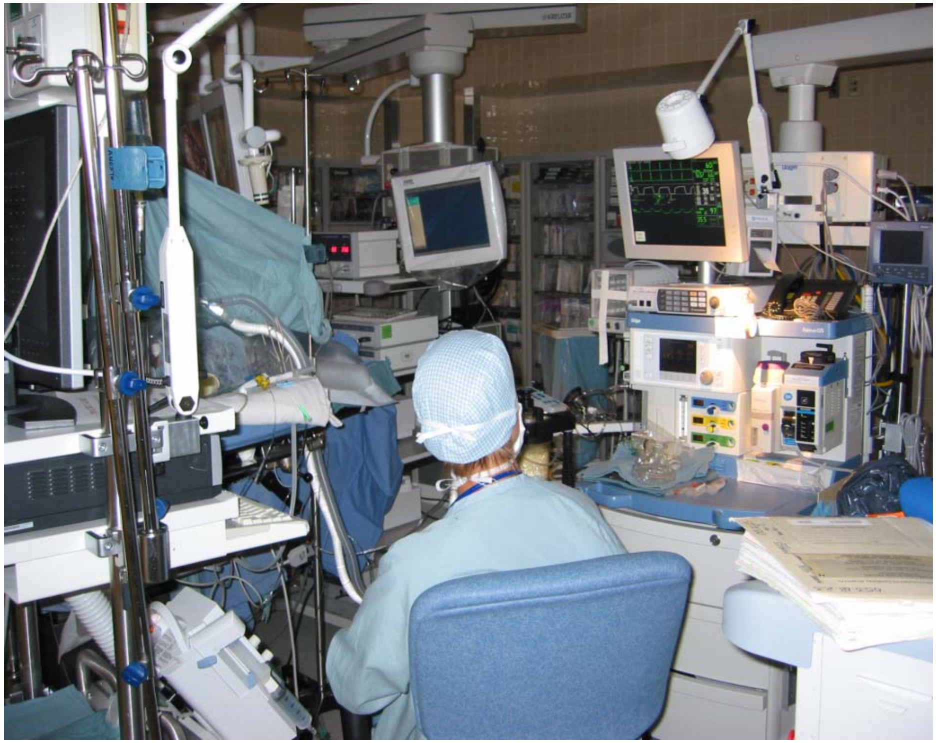
The demand for real-time wireless communication is increasing.

Cables for connecting various monitors to anesthesia EMR

The demand for real-time wireless communication is increasing.

Reduce the risk of tripping over wires

Future

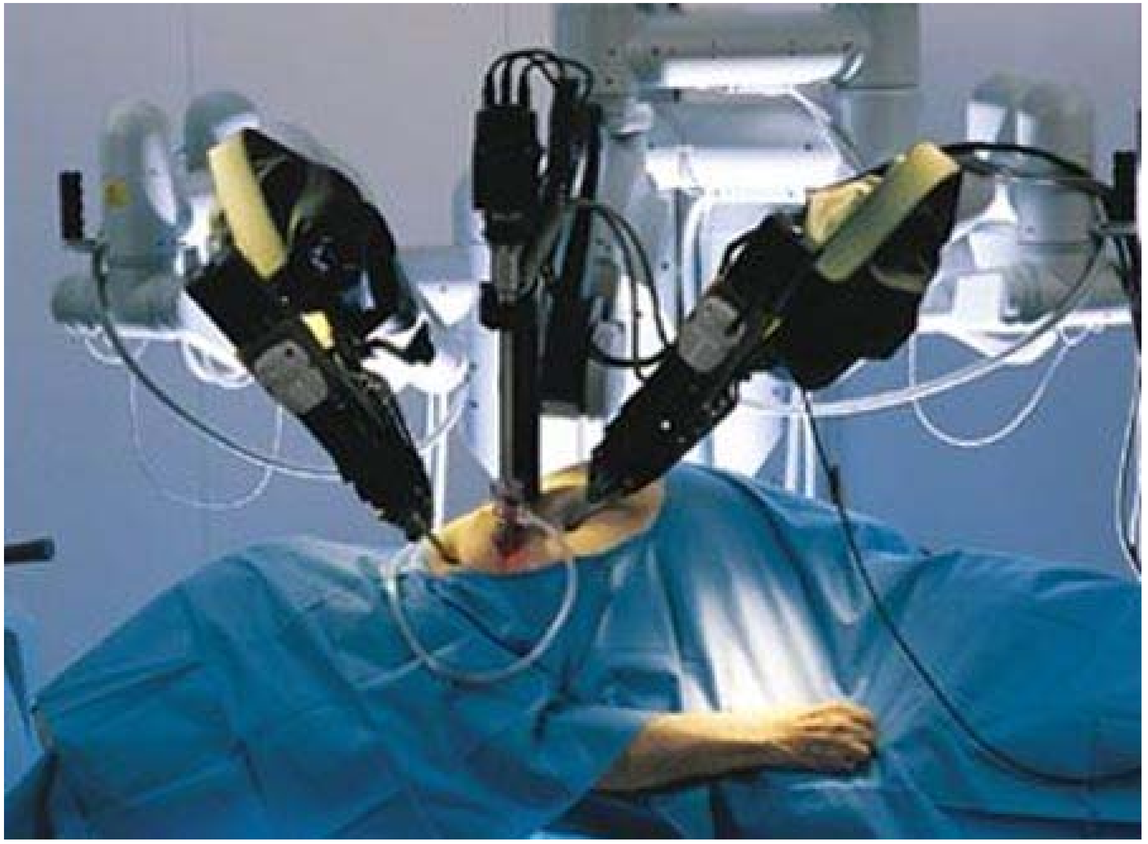


Today

What is real-time? Robotic Surgery: each task is a continuous loop of sensing (or actuating) jobs

Each job:

1. Must catch deadline
2. Does not have to be fast



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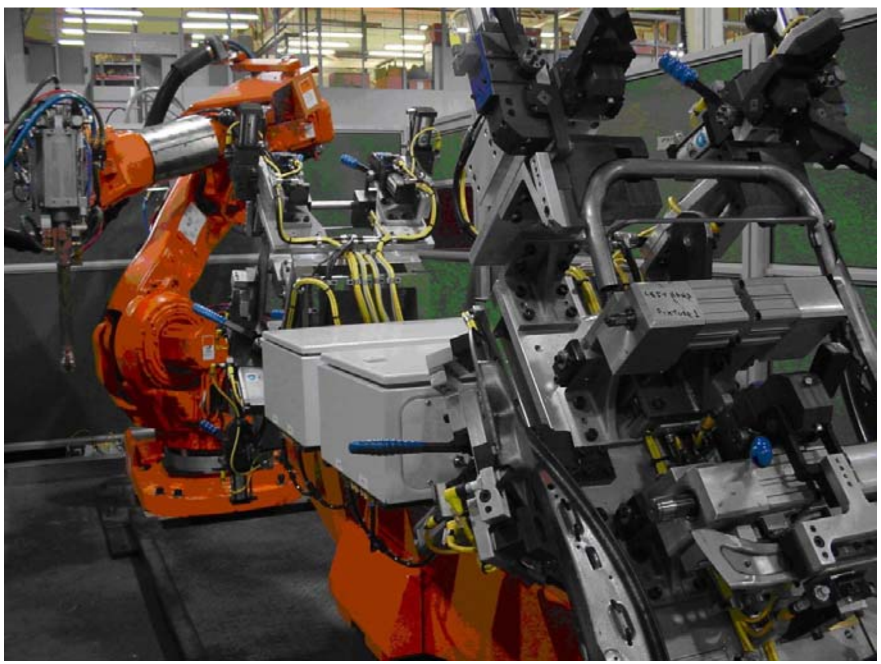
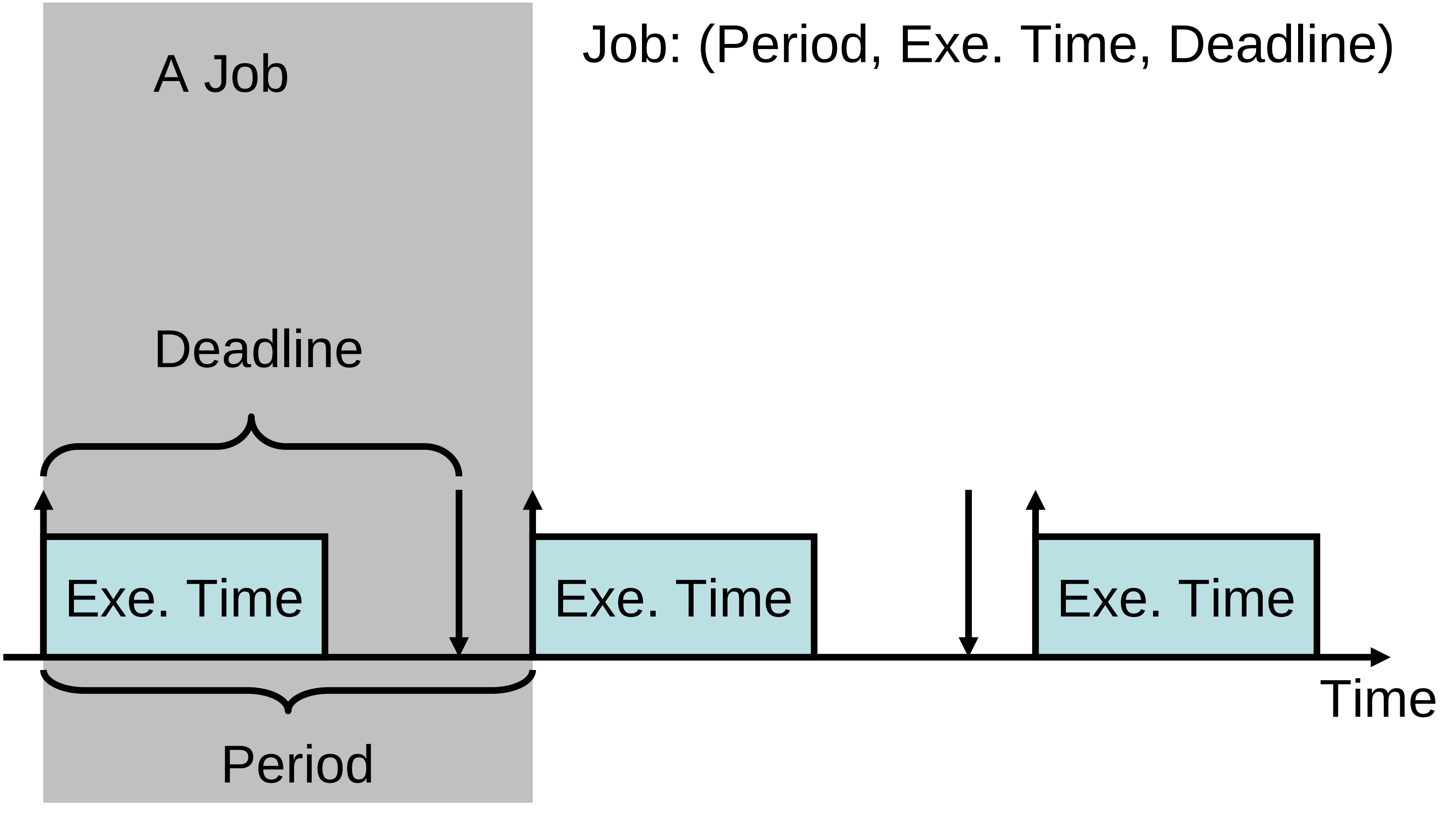


What is real-time? A typical real-time task is a continuous loop of periodic jobs.



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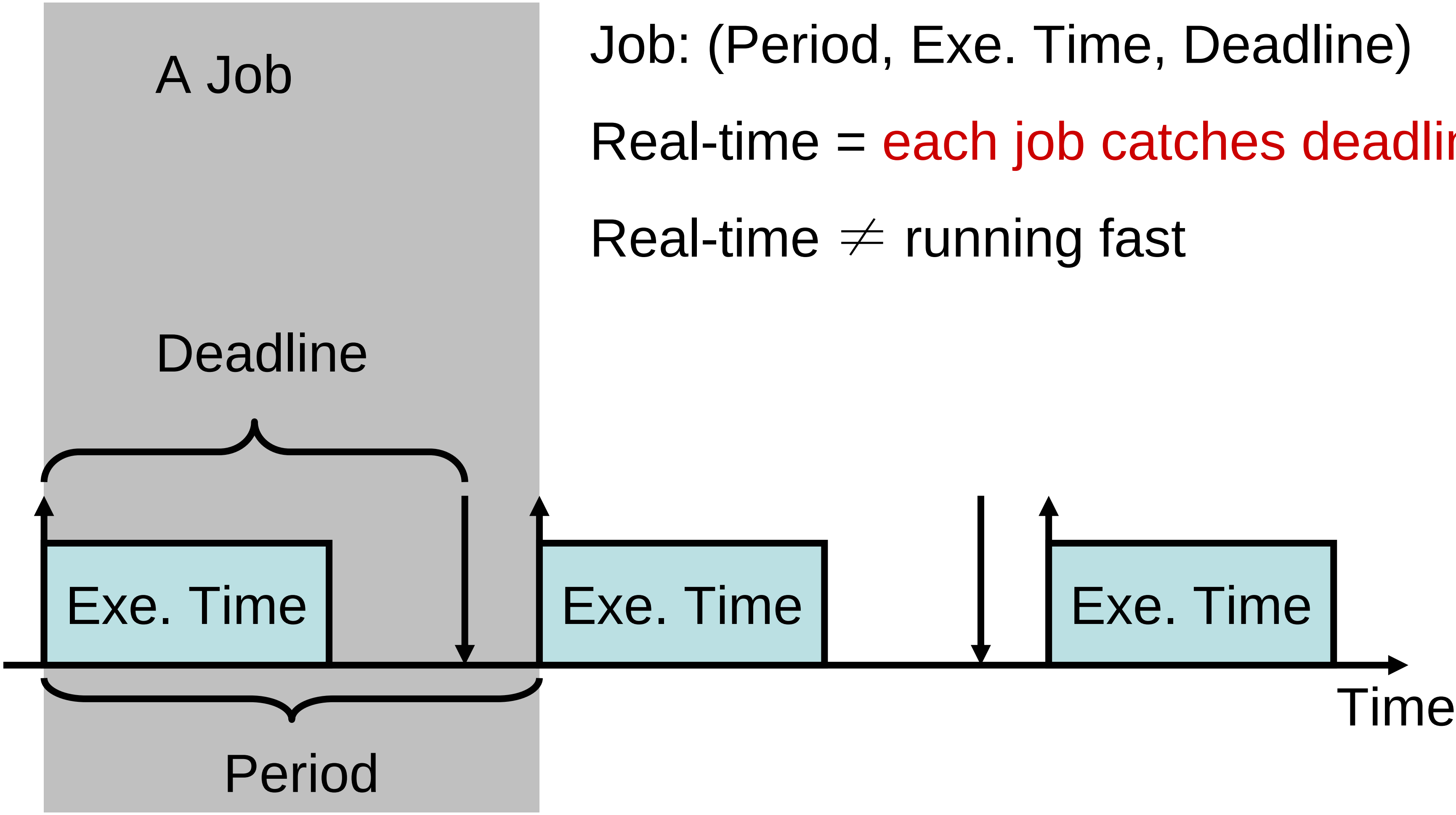
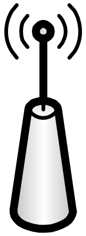
Job: (Period, Exe. Time, Deadline)

Real-time = each job catches deadline

Real-time ≠ running fast





Reliability and Robustness is the top concern for real-time wireless communication.

Cannot back off under adverse wireless channel conditions

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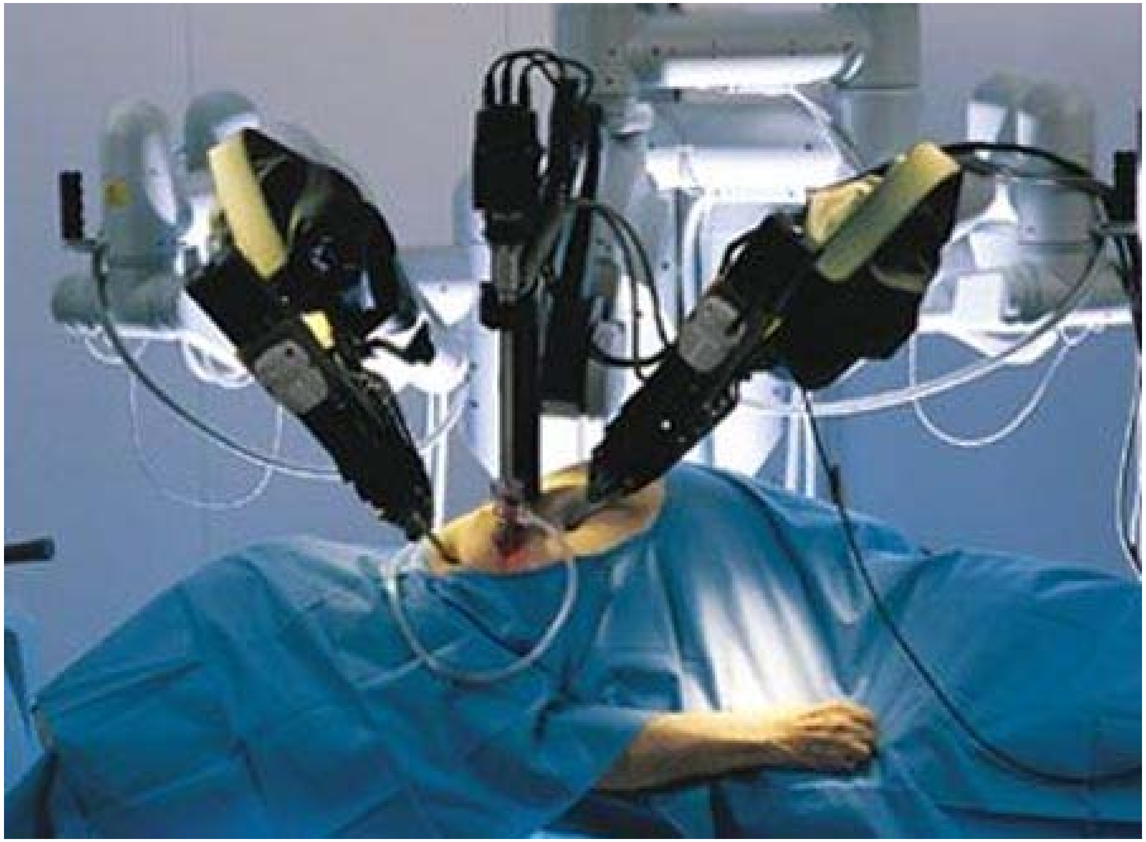
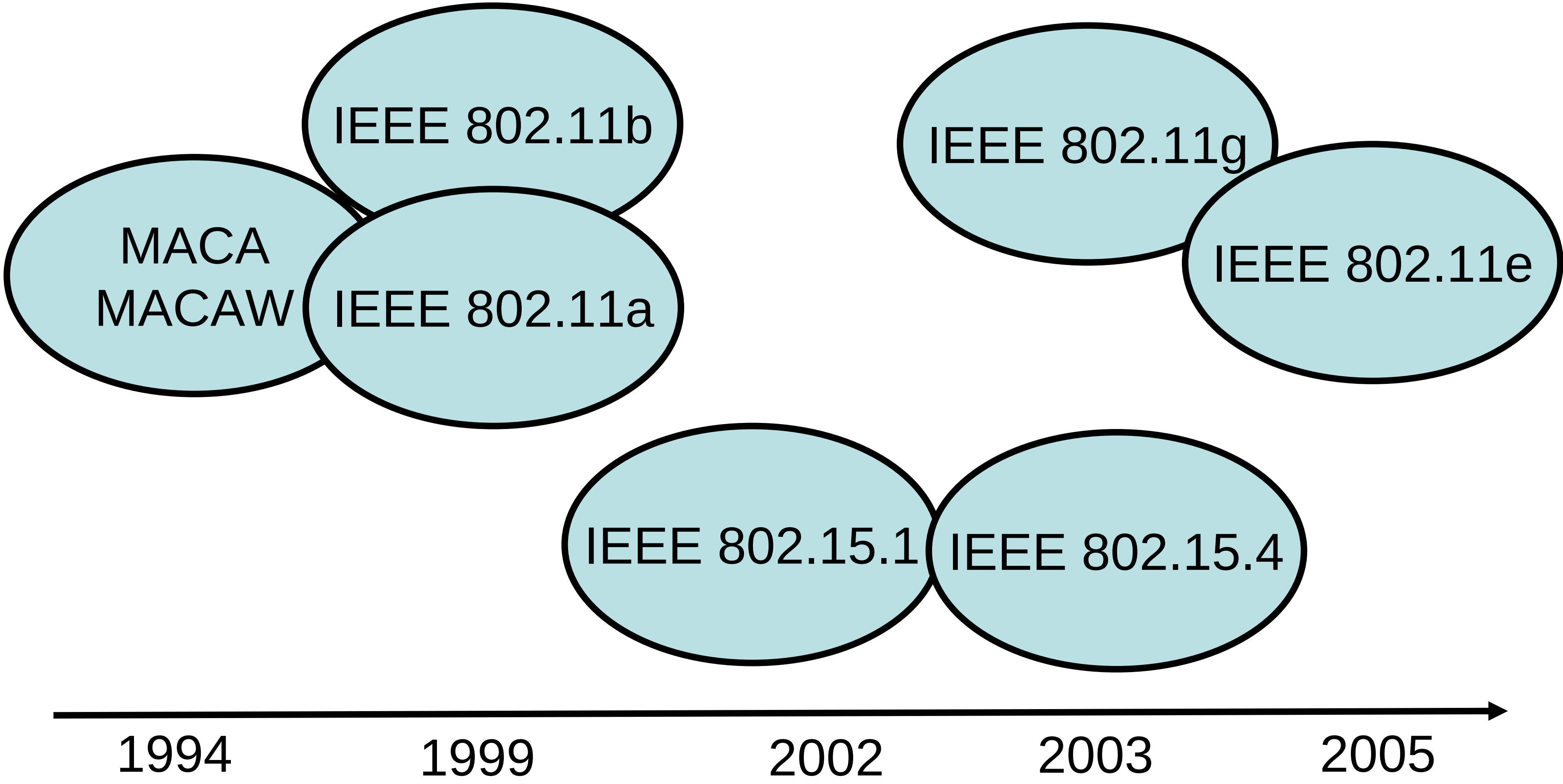


Reliability and Robustness is the top concern for real-time wireless communication.

Adverse wireless medium

- Large scale path-loss
- Multipath
- Persistent electric-magnetic interference
- Same-band / adjacent-band RF devices

Nowadays wireless LANs are NOT real-time.



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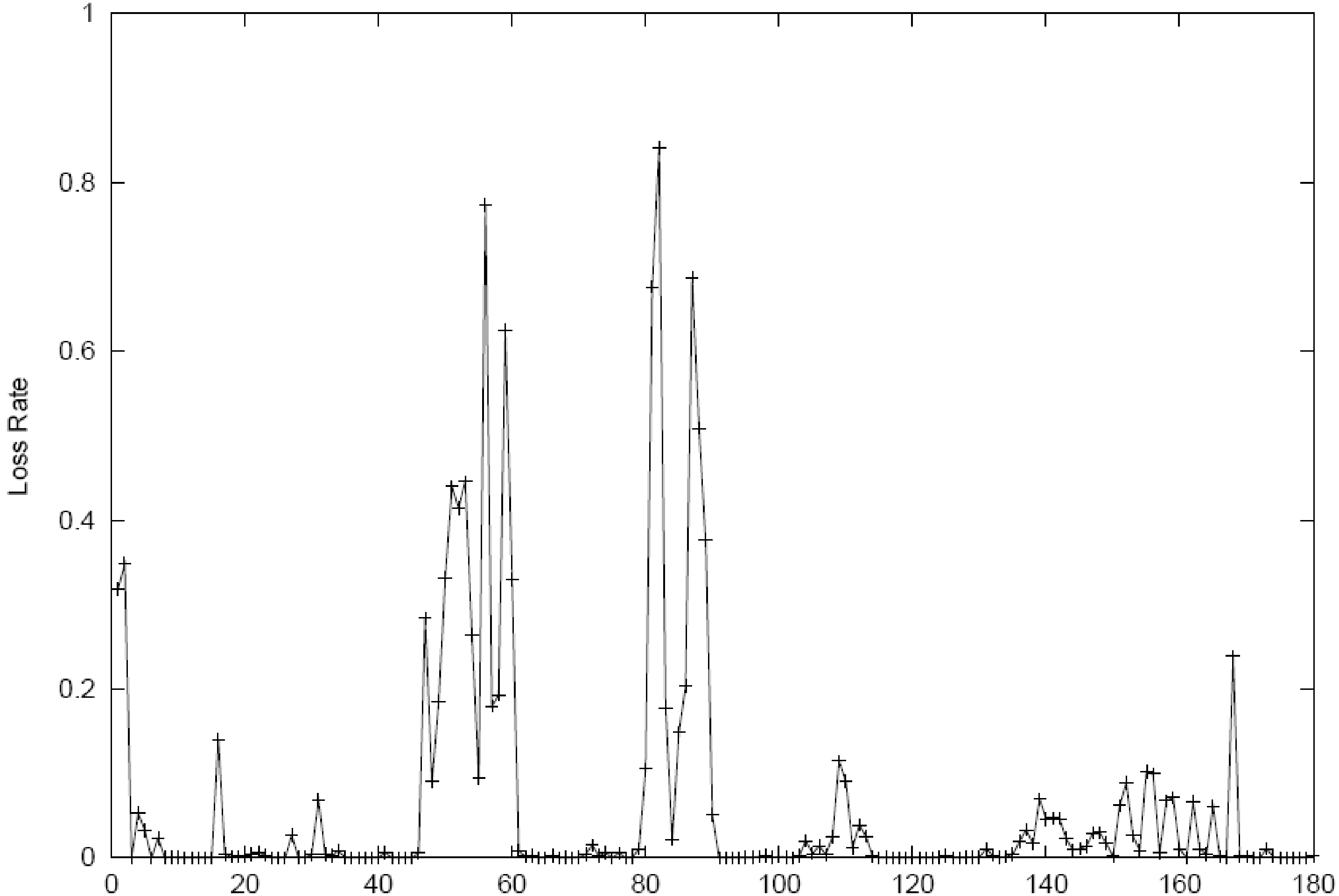
IEEE 802.11 packet loss rate in an industrial environment [Willig02]



Trace ID (87sec/trace)

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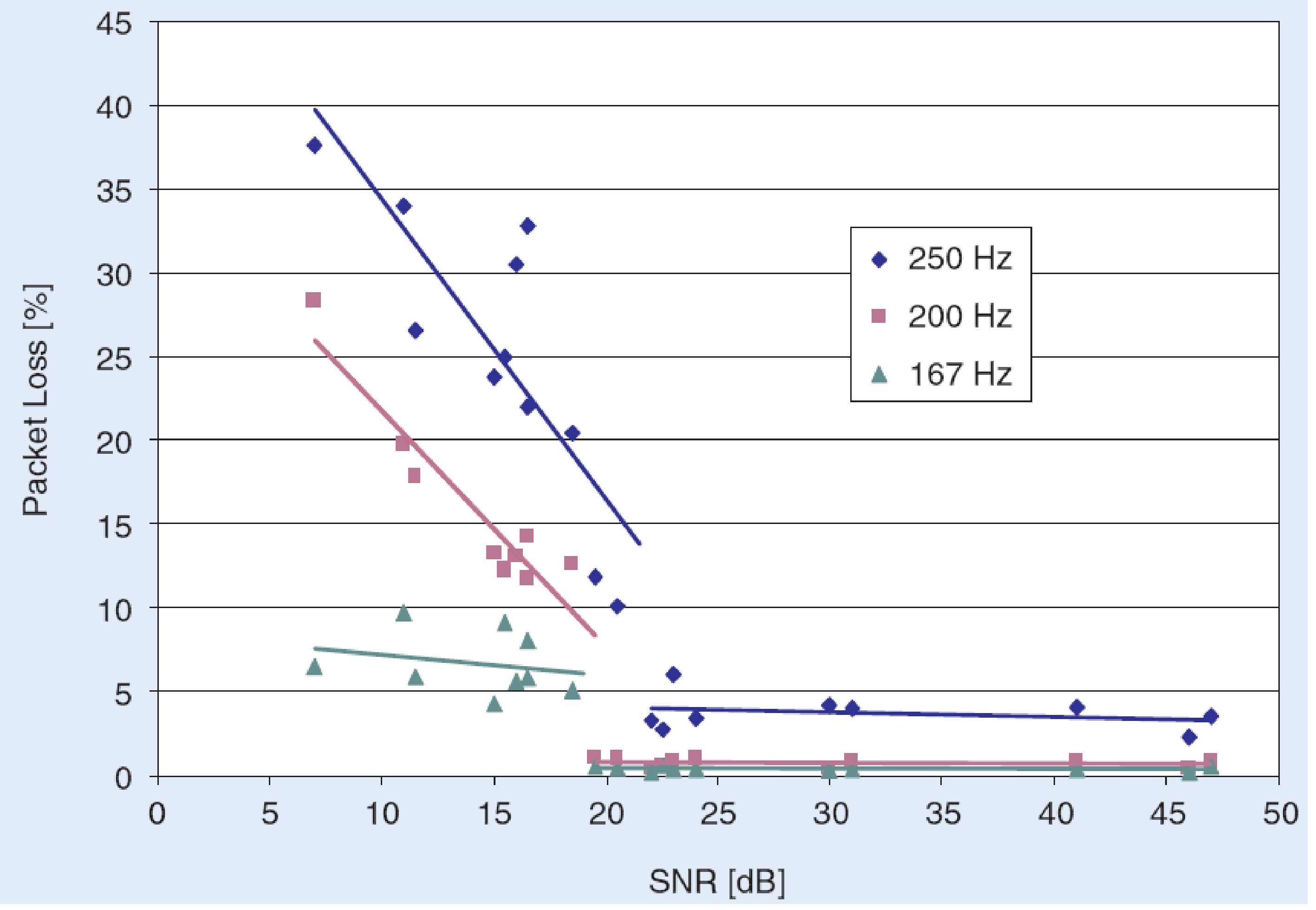

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Design philosophy mismatch: pursuing large data throughput & short delay

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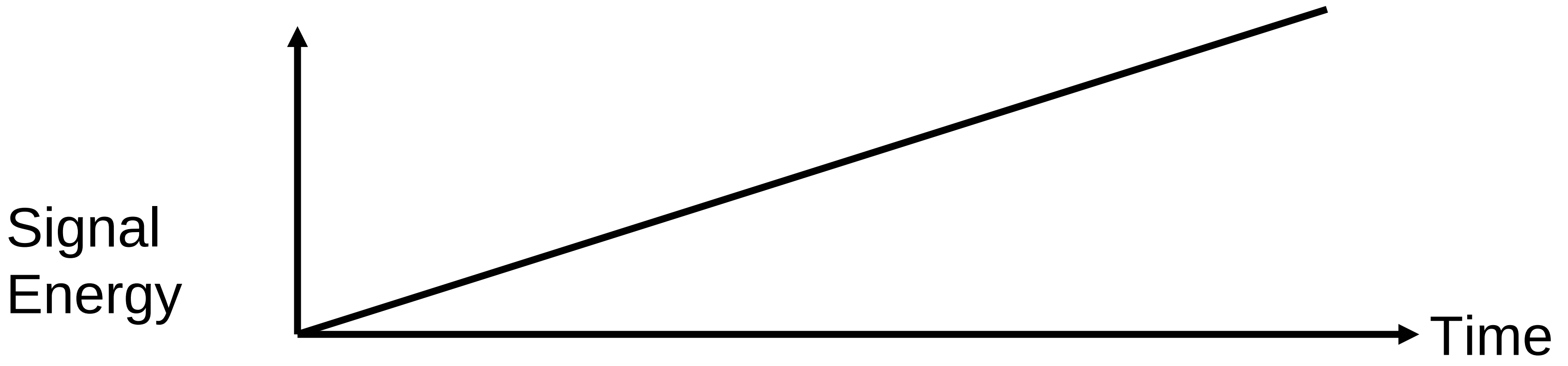
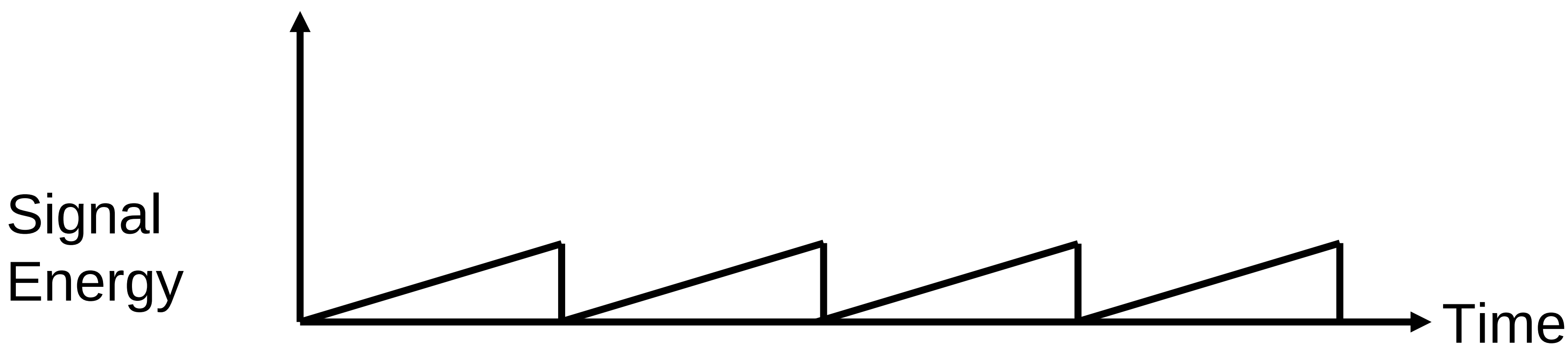


Design philosophy mismatch: pursuing large data throughput & short delay

Send packet fast

Do not spend much time accumulate strength



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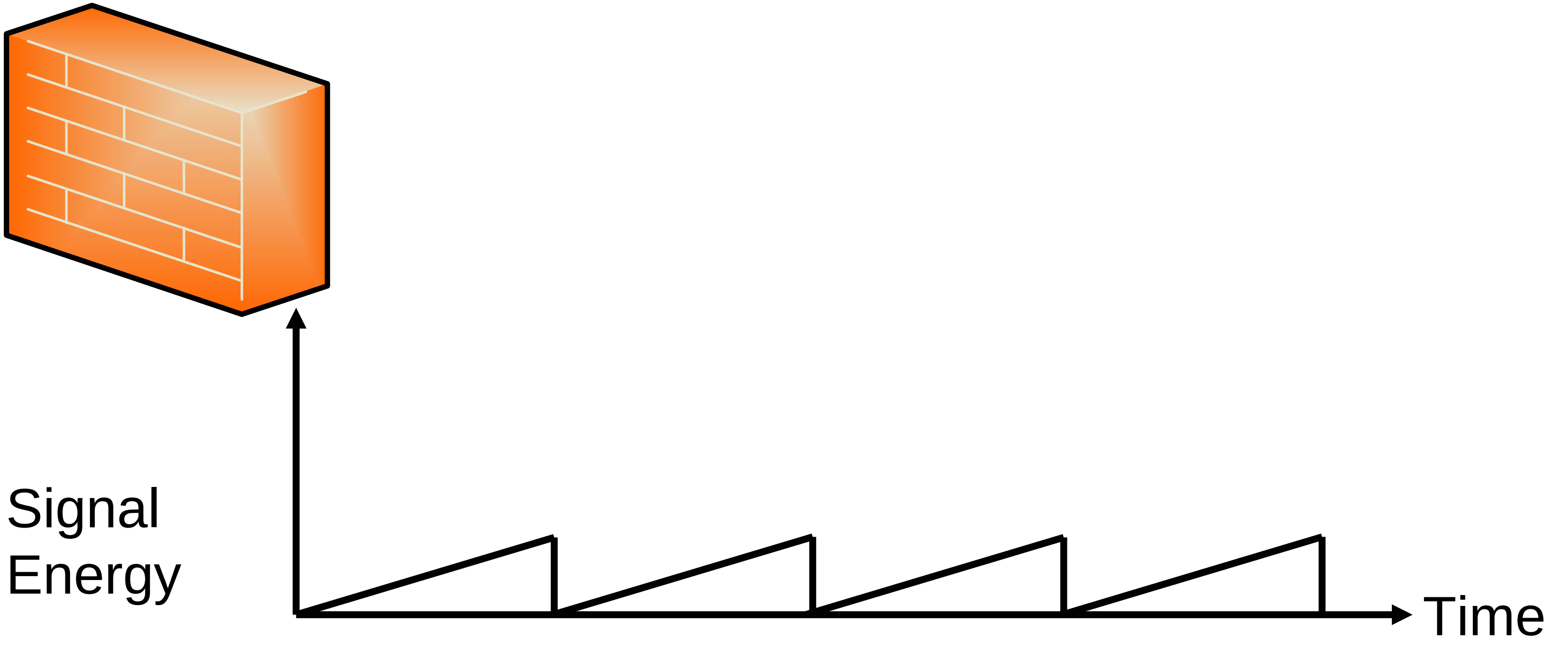

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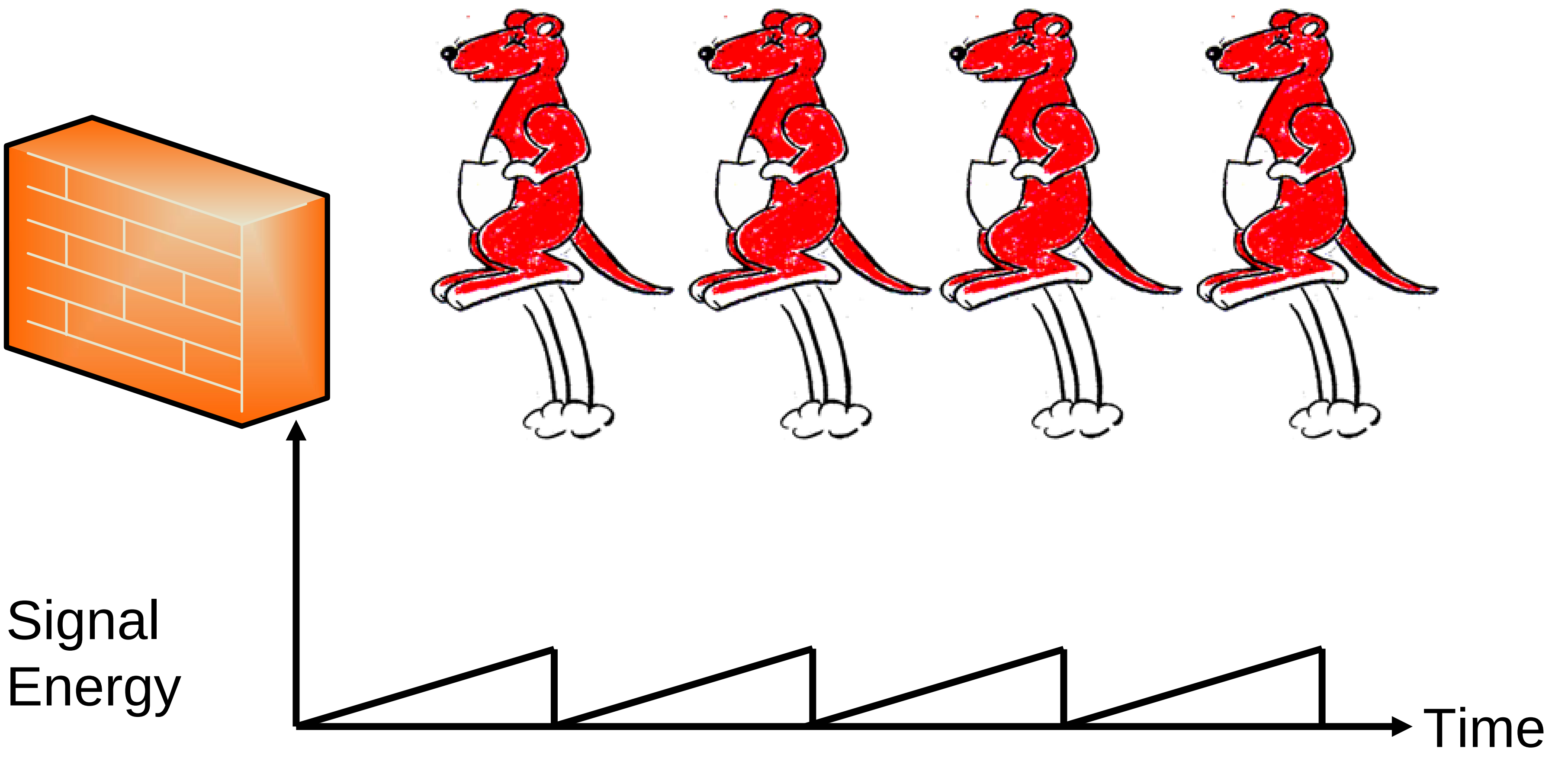

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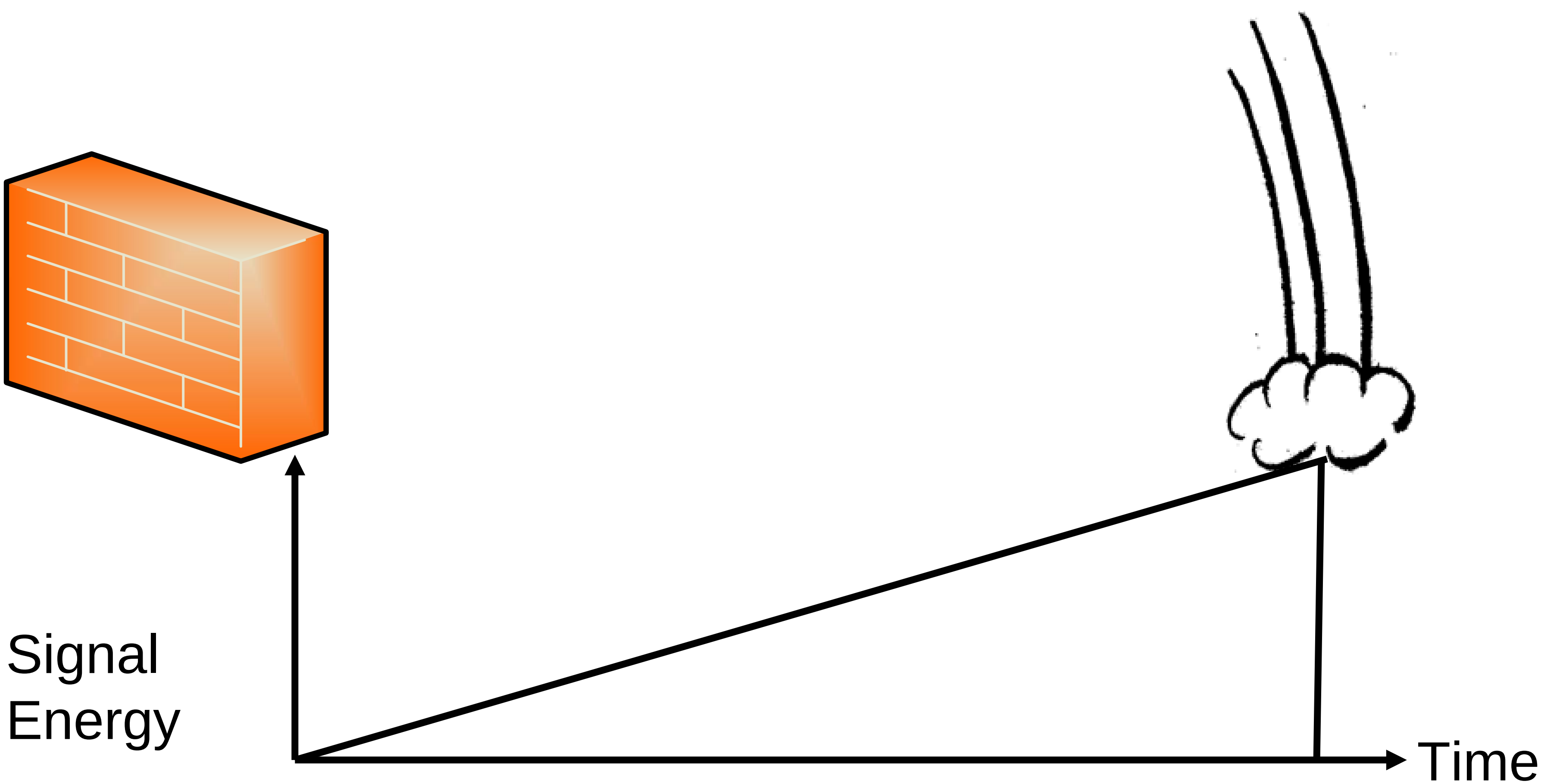

Observation: Real-time communications are usually persistent connections with low data rate

Typical inter-node traffic:

100~200 bit/pkt, 10~1 pkt/sec per connection.

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Information Theory:

Lower data rate ➔ higher robustness.

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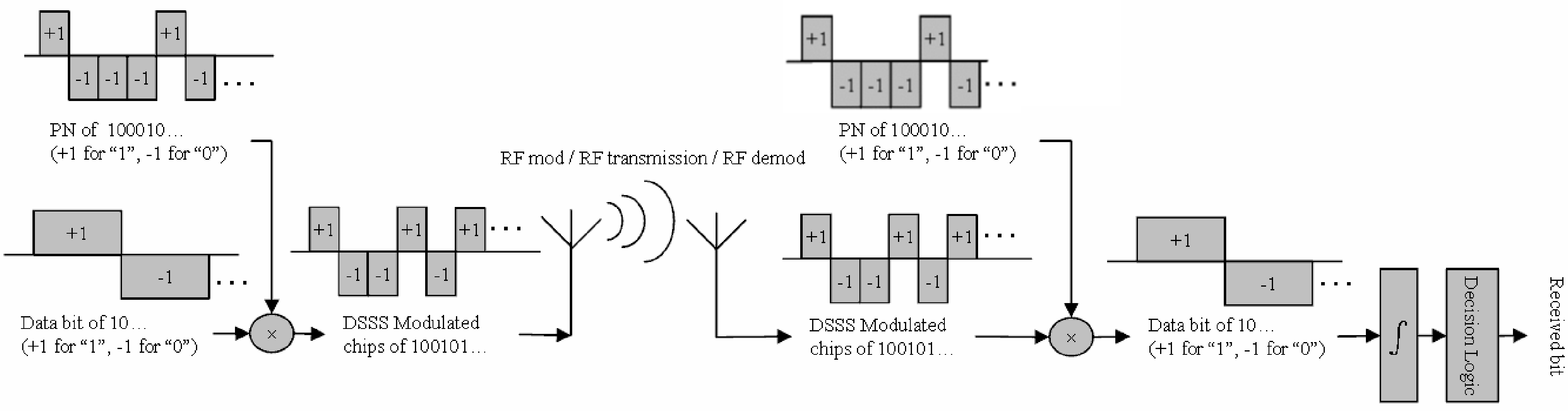
Direct Sequence Spread Spectrum (DSSS) Technology:

Lower data rate ⬅➔ Higher robustness

Tutorial on DSSS



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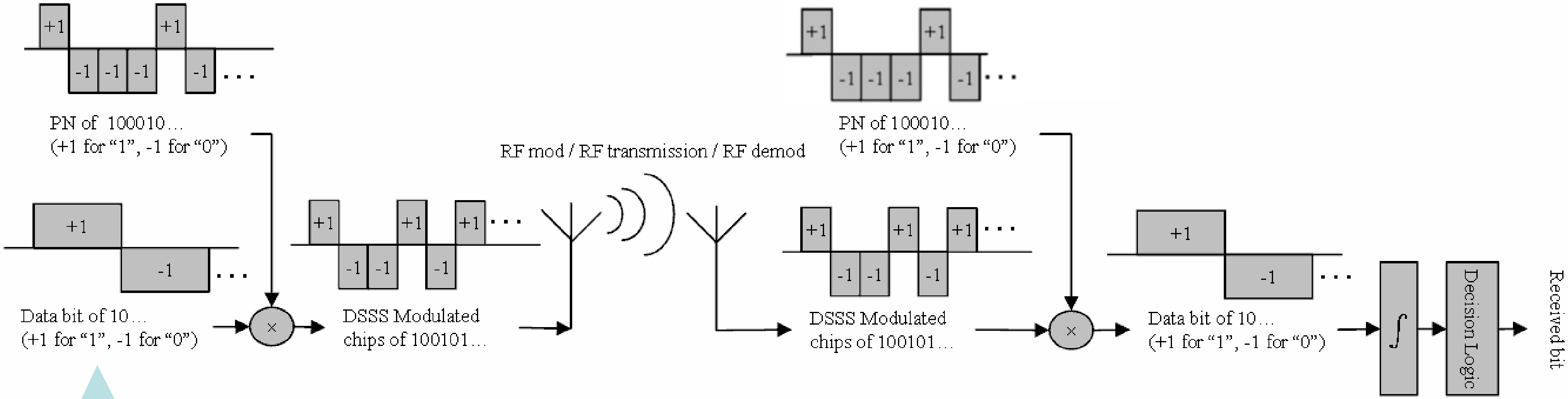
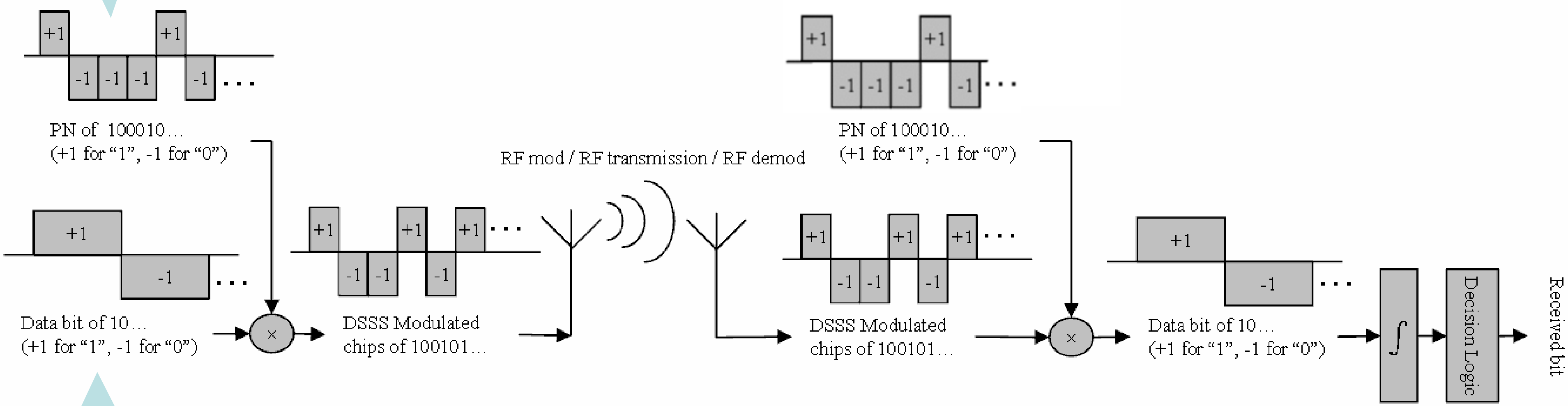


Data stream, a.k.a bit stream. Bit rate: r_b .

Tutorial on DSSS

Pseudo Noise Sequence (PN) Stream, a.k.a chip stream. Chip rate: R_c.



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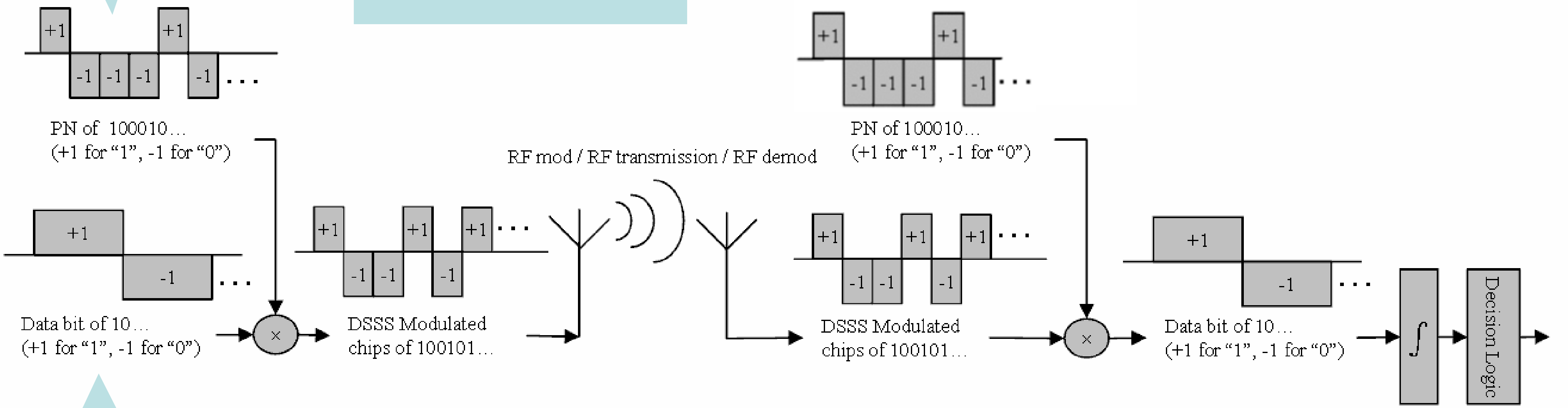

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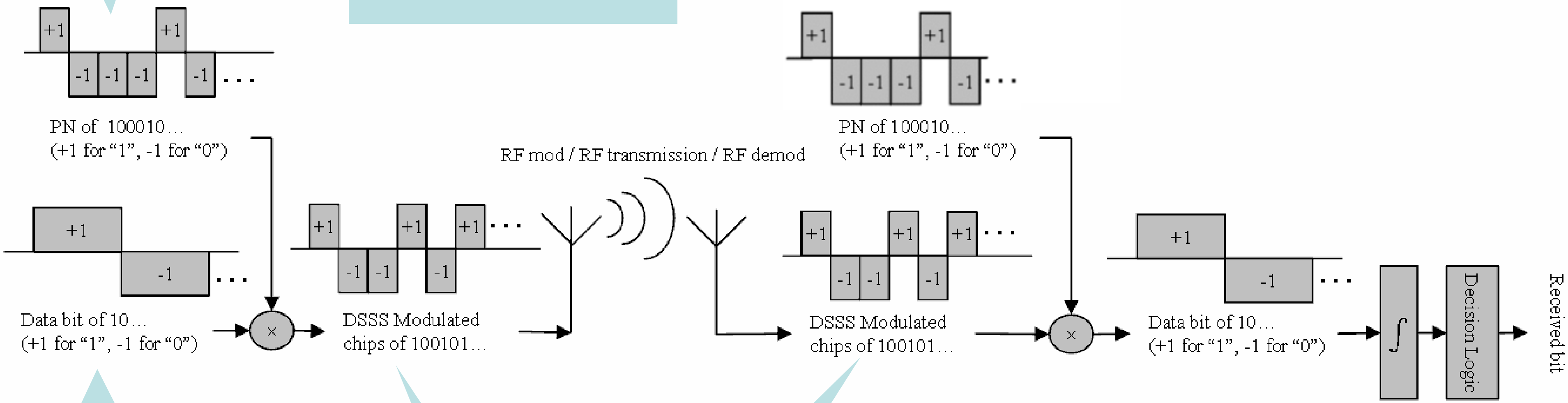

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DSSS Modulated Stream, a.k.a Scrambled Stream

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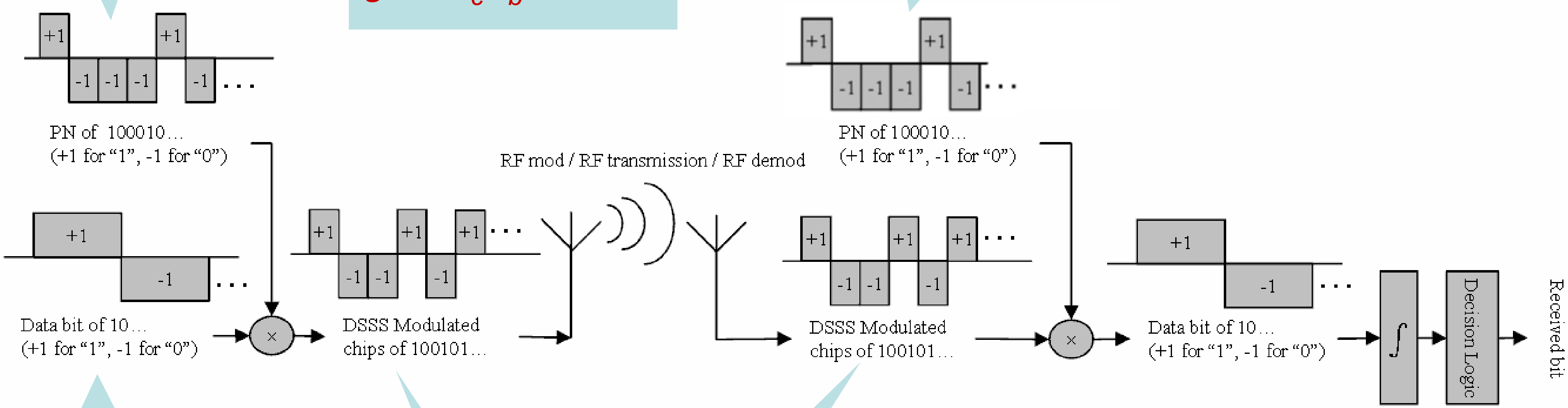

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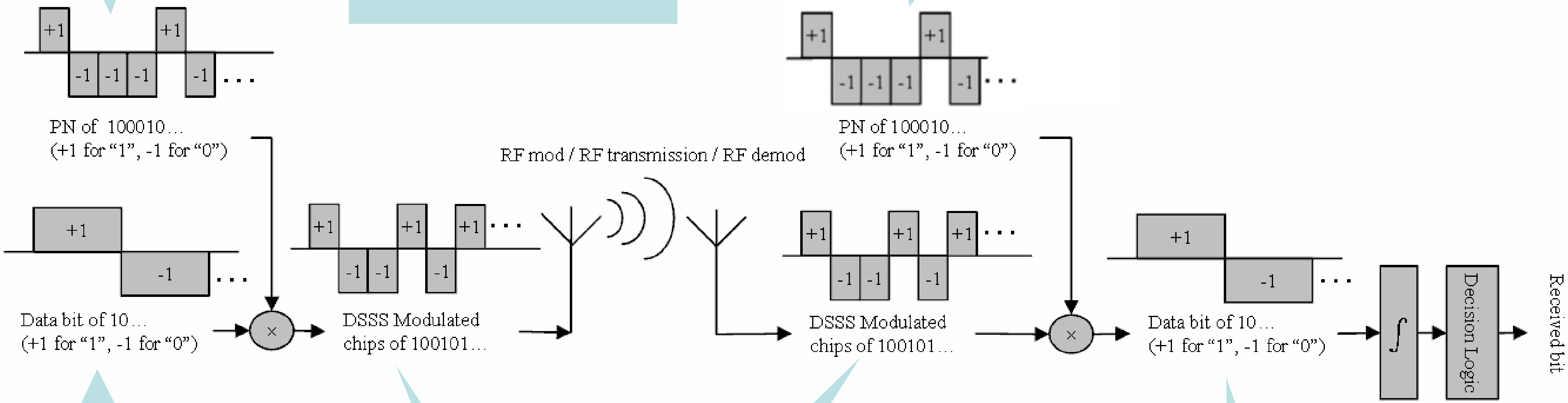

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Original Data

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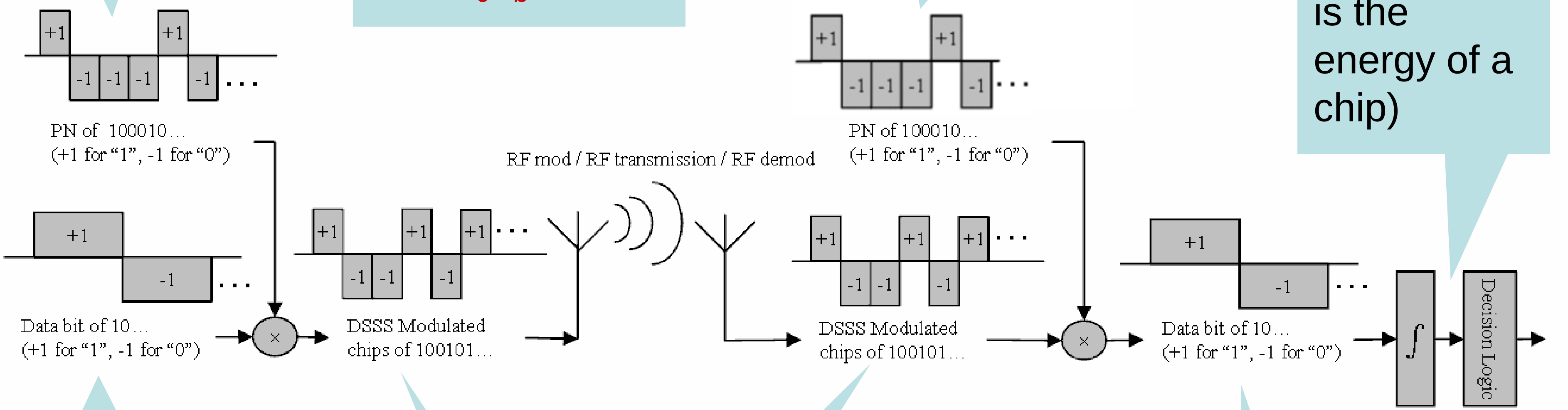
Same PN Sequence

Integration $= gE_c$ for each bit (E_c is the energy of a chip)



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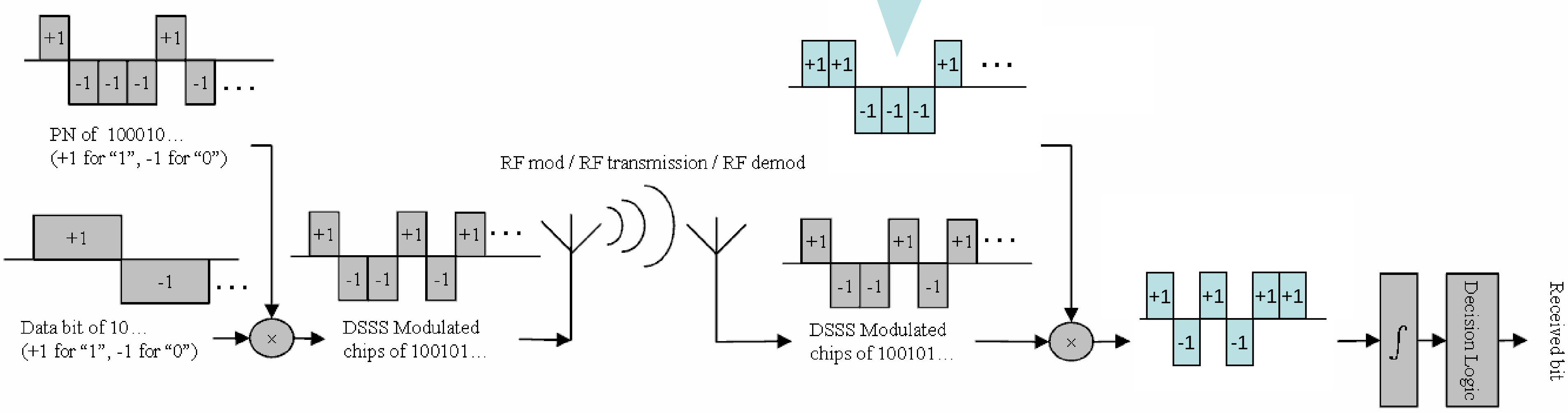
If a different PN Sequence is applied



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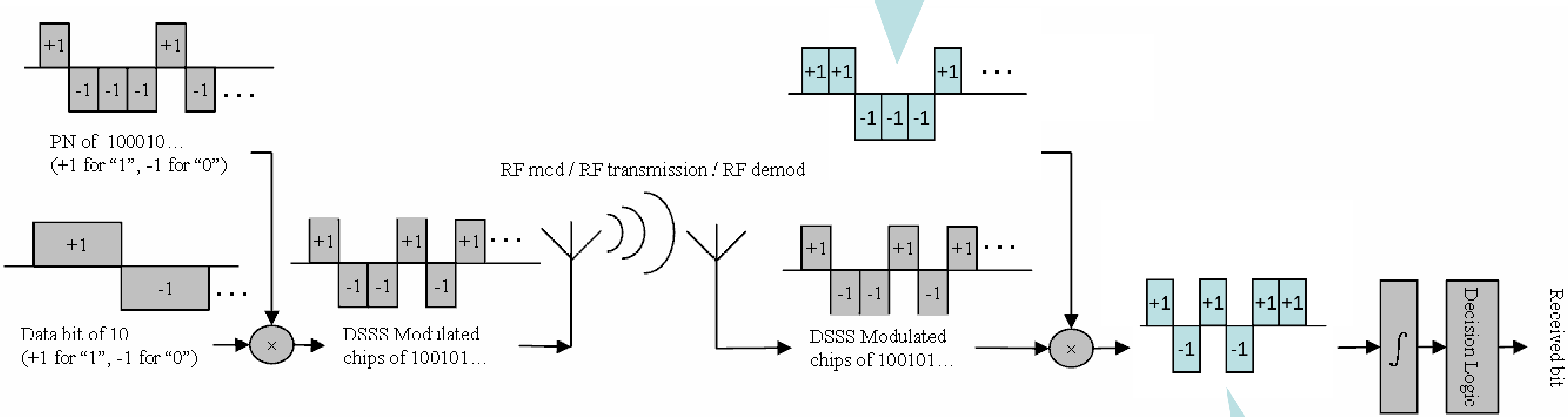
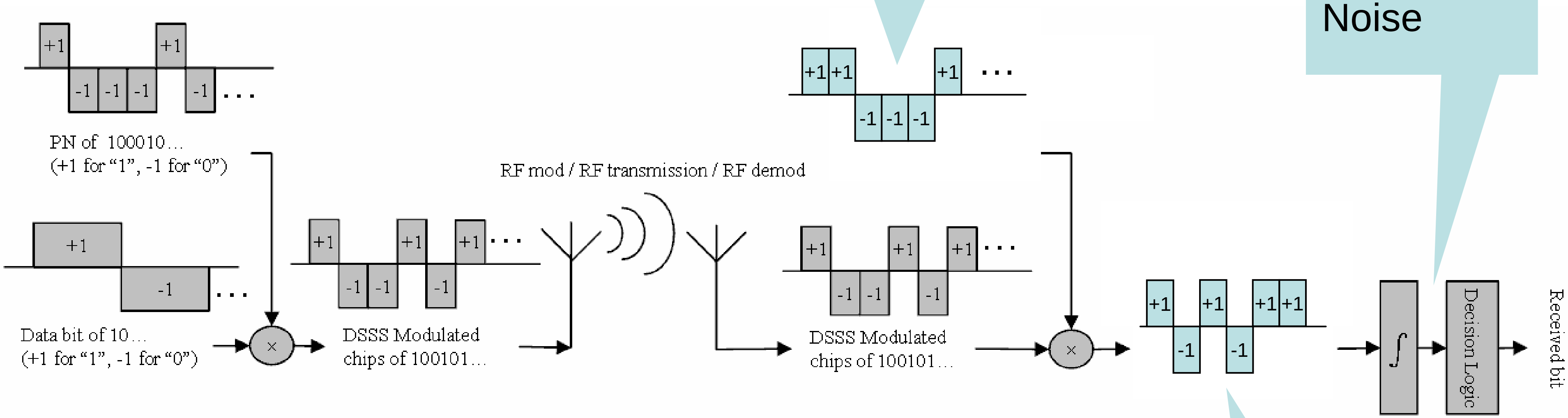


Another scrambled sequence

Tutorial on DSSS



If a different PN Sequence is applied

Integration = Gaussian Noise

Another scrambled sequence

Observation

Bit Error Rate

Processing Gain

$$\mathcal{P}_{ber} \leq \exp\left(-\frac{gP_u}{J+\sum_{i=1,i\neq u}^{\Xi} P_i + \sum_{h=1}^{H} A_h + P_u}\right)$$

- DSSS Technology:

  Larger Processing Gain *g* ⇔ Lower data rate ⇔ Lower Bit Error Rate (Higher robustness)

Observation: DSSS can exploit low data rate to achieve higher robustness

$$P_{BER} \le \exp\left(-gK\right) = \exp\left(-\frac{K}{r_b}\right)$$

DSSS BER Upper Bound

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Bit Error Rate (P_{BER})

Processing Gain (g)

Constant (K)

Bit Rate (r_b)

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Bit Rate

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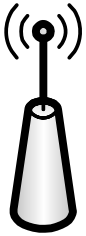
- Lower data rate $\boldsymbol{r_b}$ ←→ Larger Processing Gain $\boldsymbol{g}$ ←→ Lower Bit Error Rate $\boldsymbol{P_{BER}}$ (higher robustness)



Key Idea: How to configure for max robustness for adverse wireless medium?

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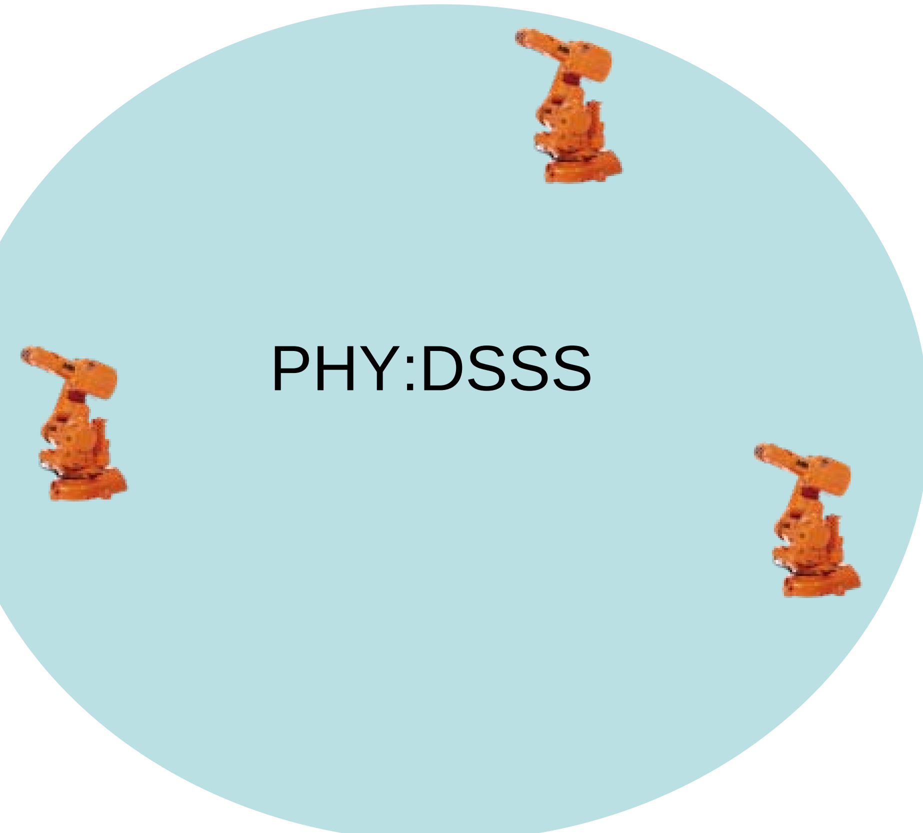
Answer: Use DSSS, deploy as slow data rate $\boldsymbol{r_b}$ (i.e., as large processing gain $\boldsymbol{g}$) as the application allows.

$$P_{BER} \leq \exp(-gK) = \exp\left(-\frac{K}{r_b}\right)$$

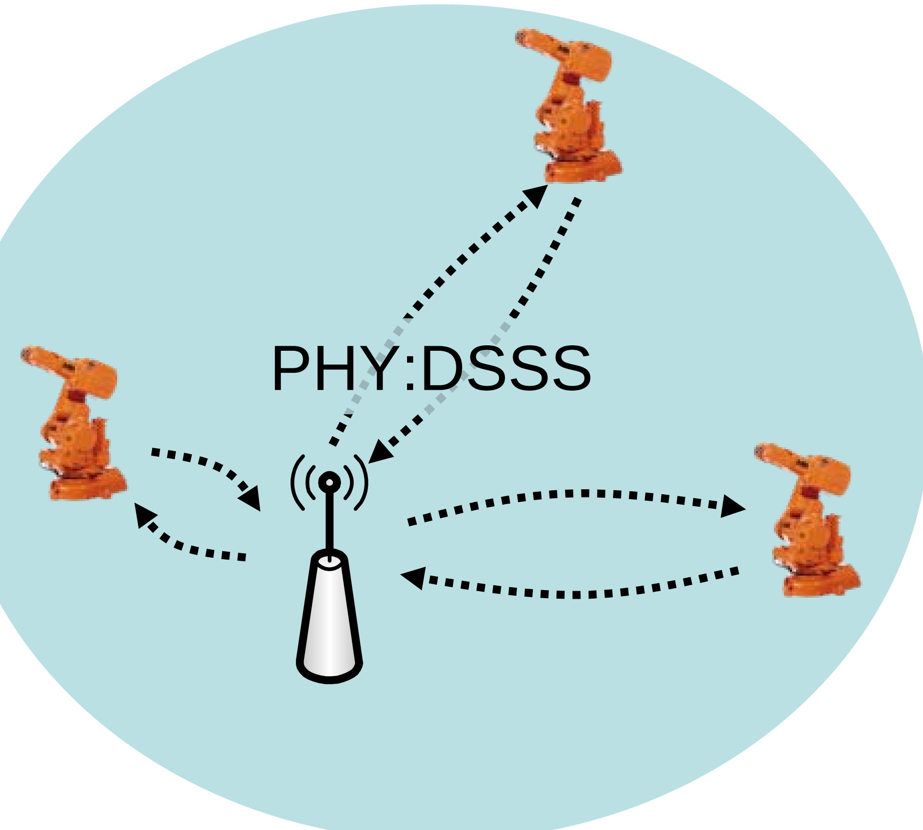
Solution Heuristics



DSSS with low data rate for high robustness

Observation: Centralized, last-hop wireless scheme is preferred

Centralized: Economical & Simple



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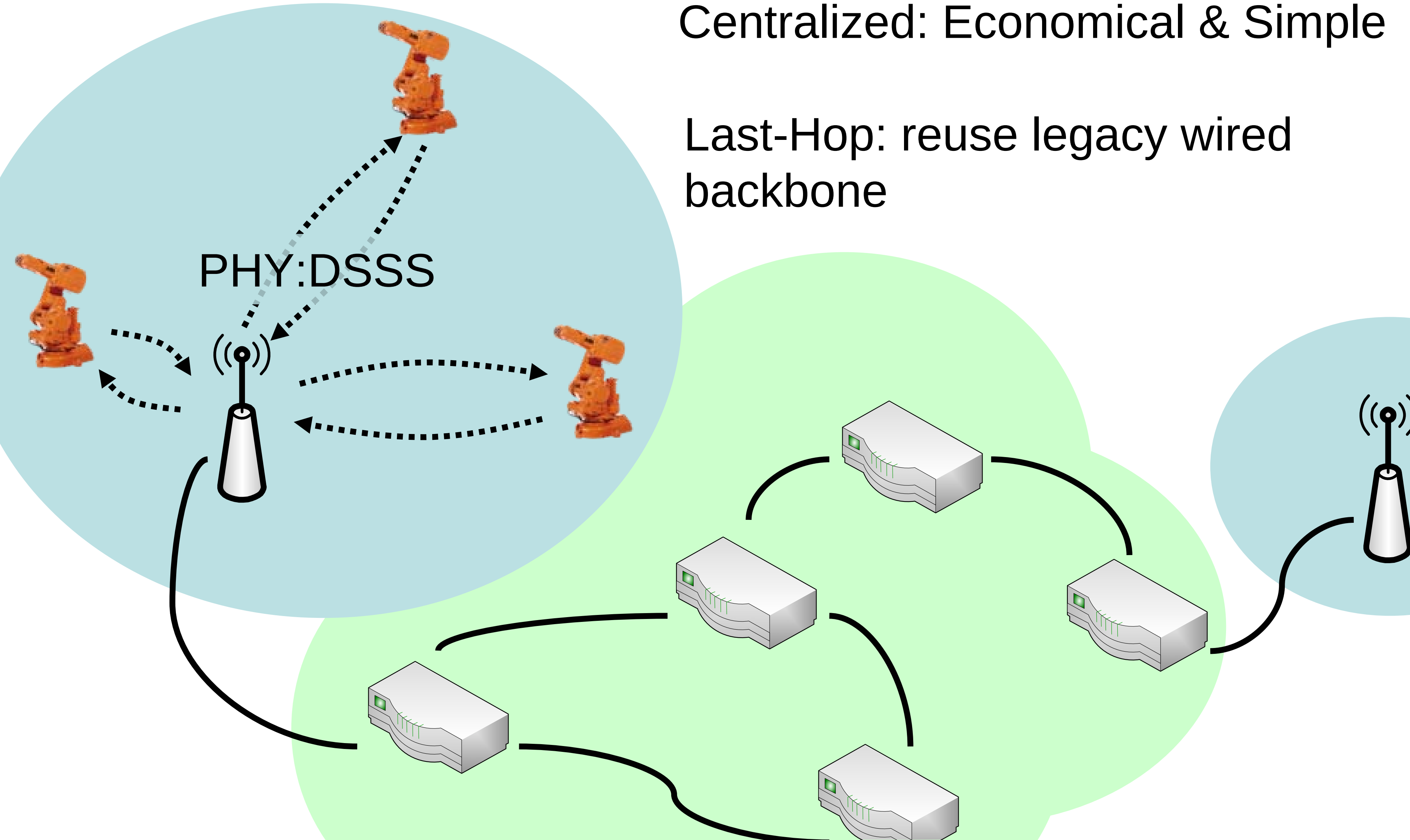
Centralized: Economical & Simple

Last-Hop: reuse legacy wired backbone



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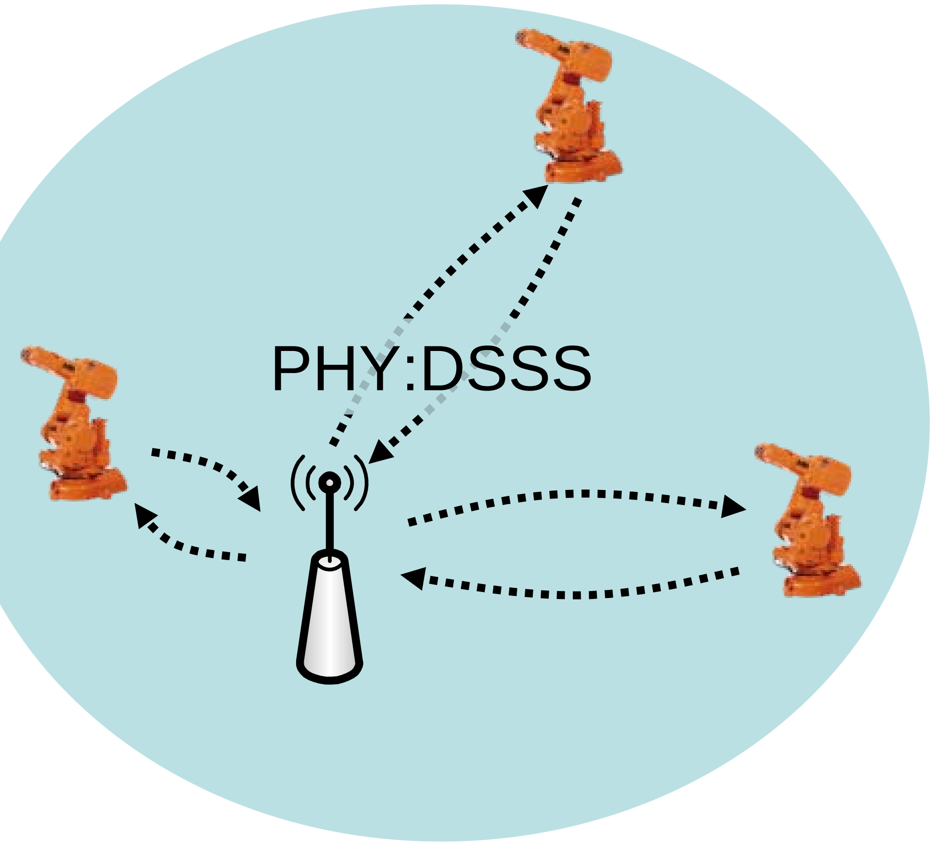
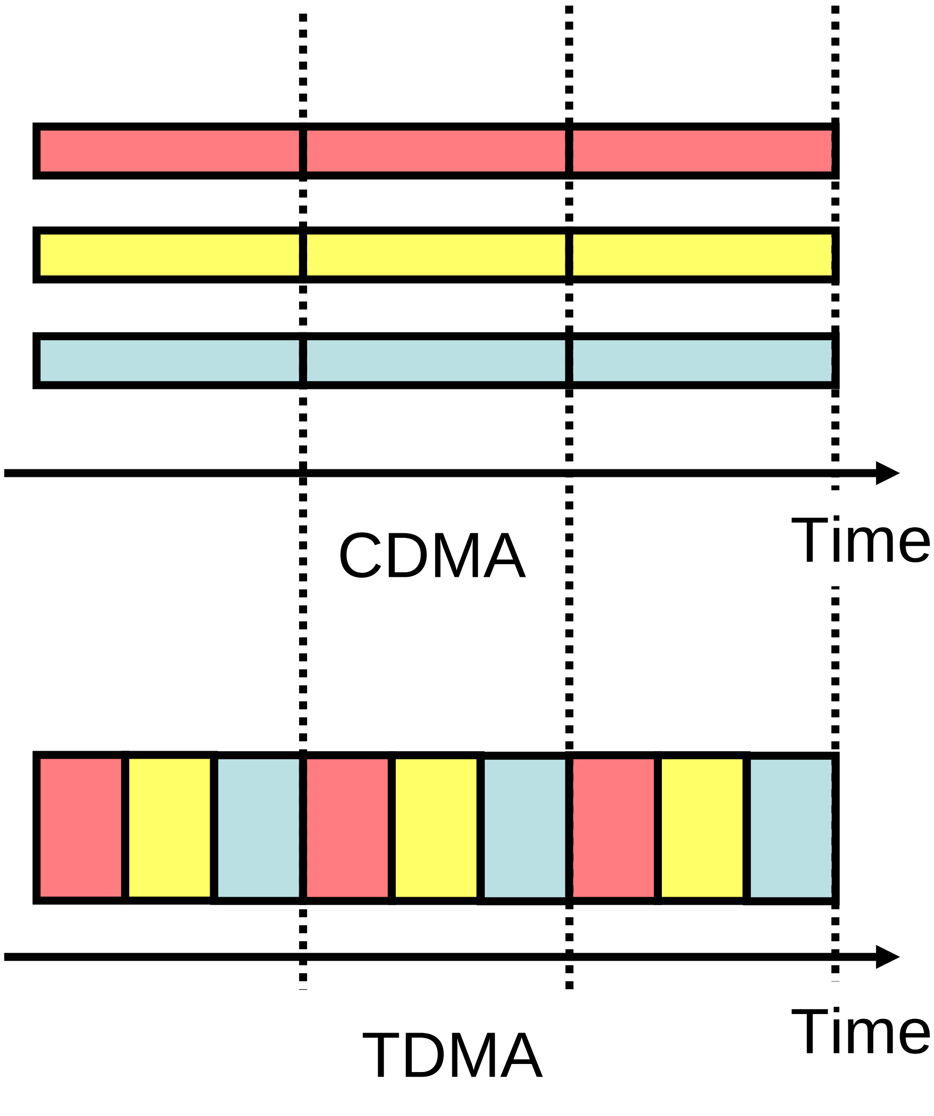


DSSS with low data rate for high robustness

Centralized WLAN paradigm

Observation: CDMA is better than TDMA (e.g., IEEE 802.11 PCF).



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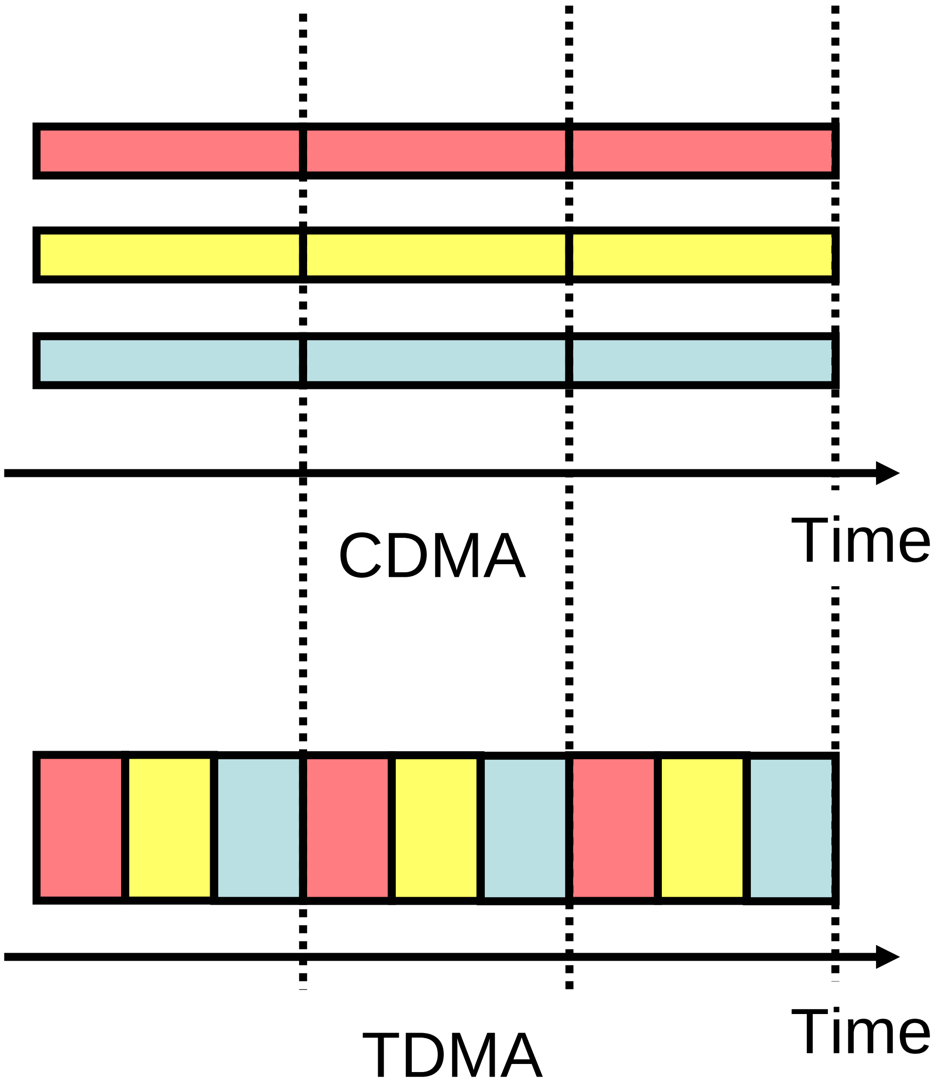
Smaller overhead under adverse channel conditions



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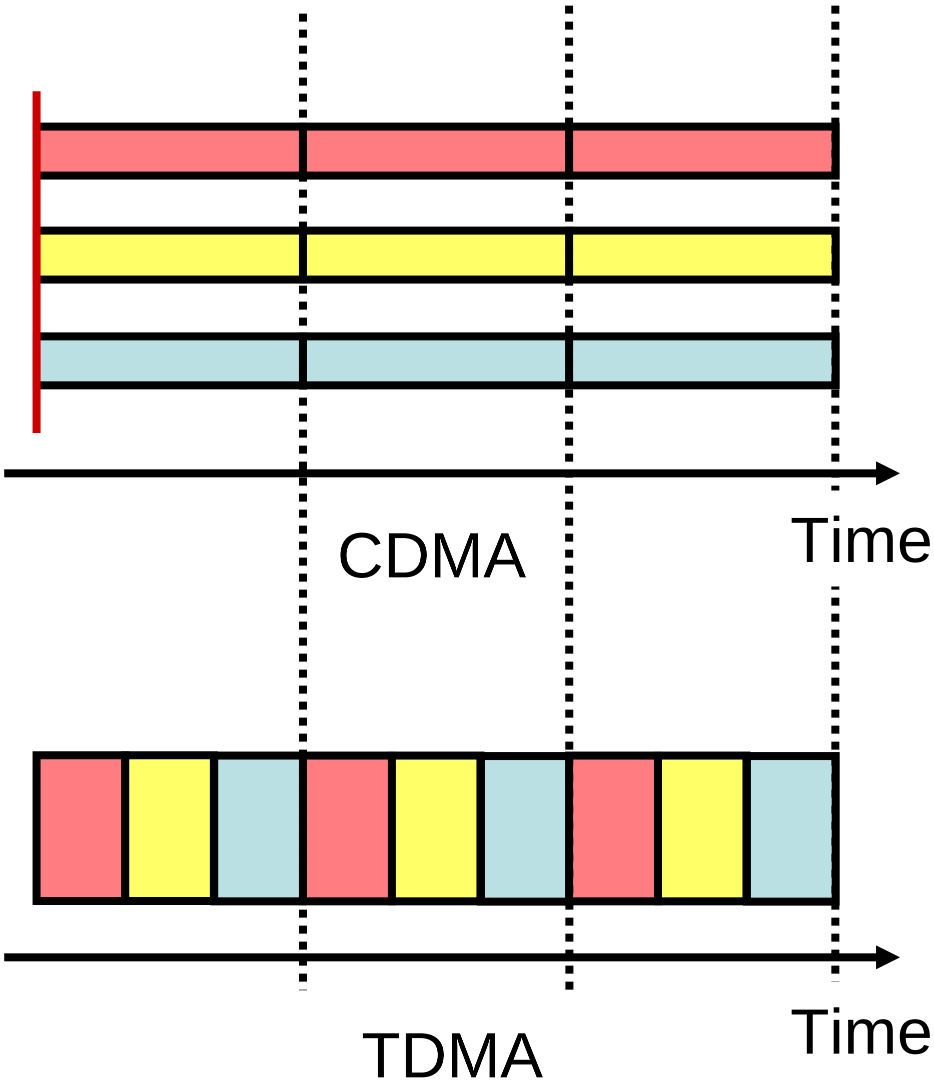

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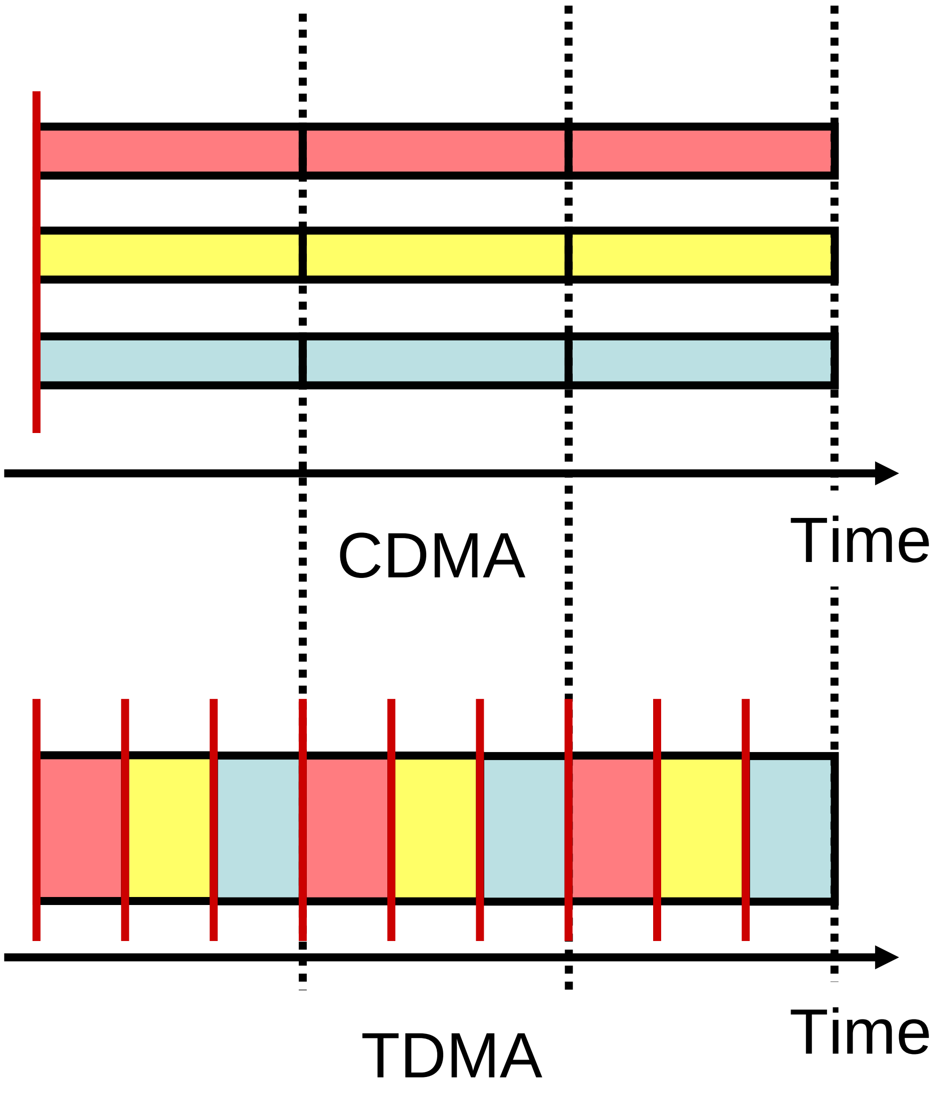

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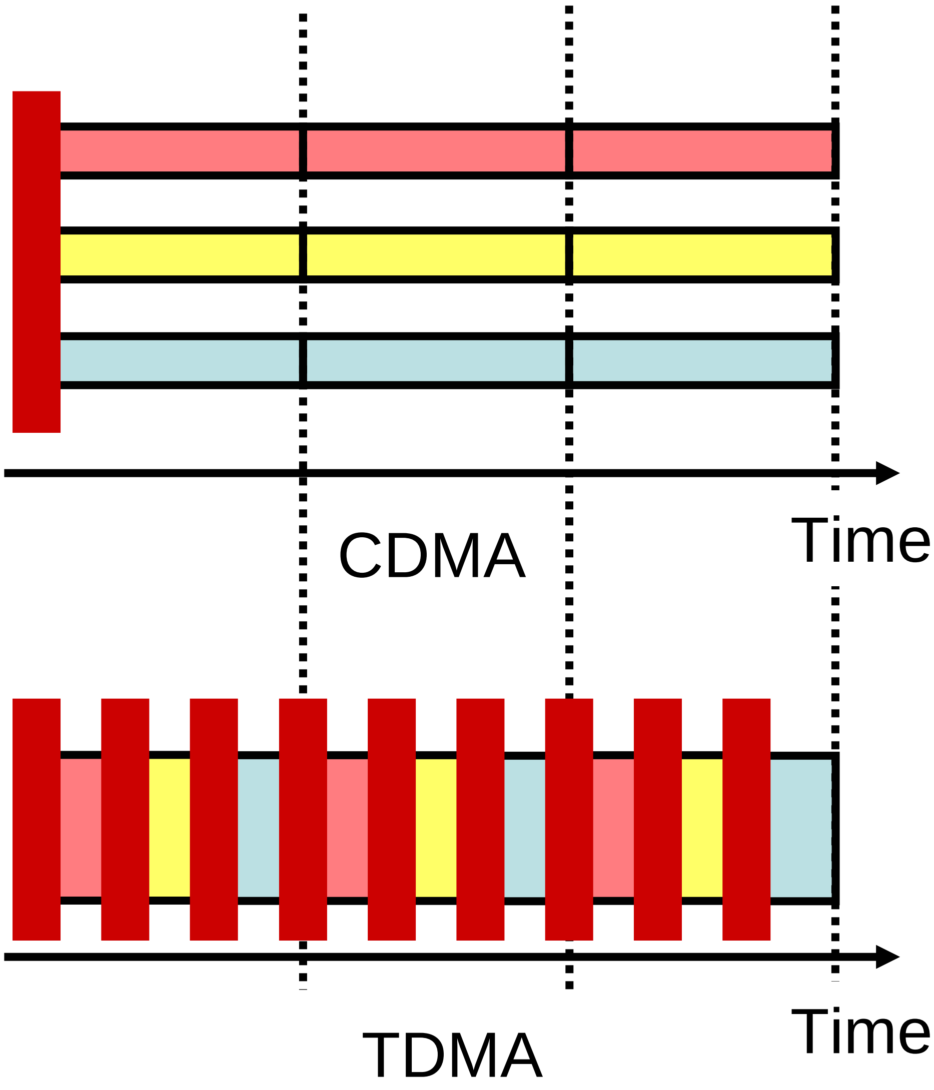

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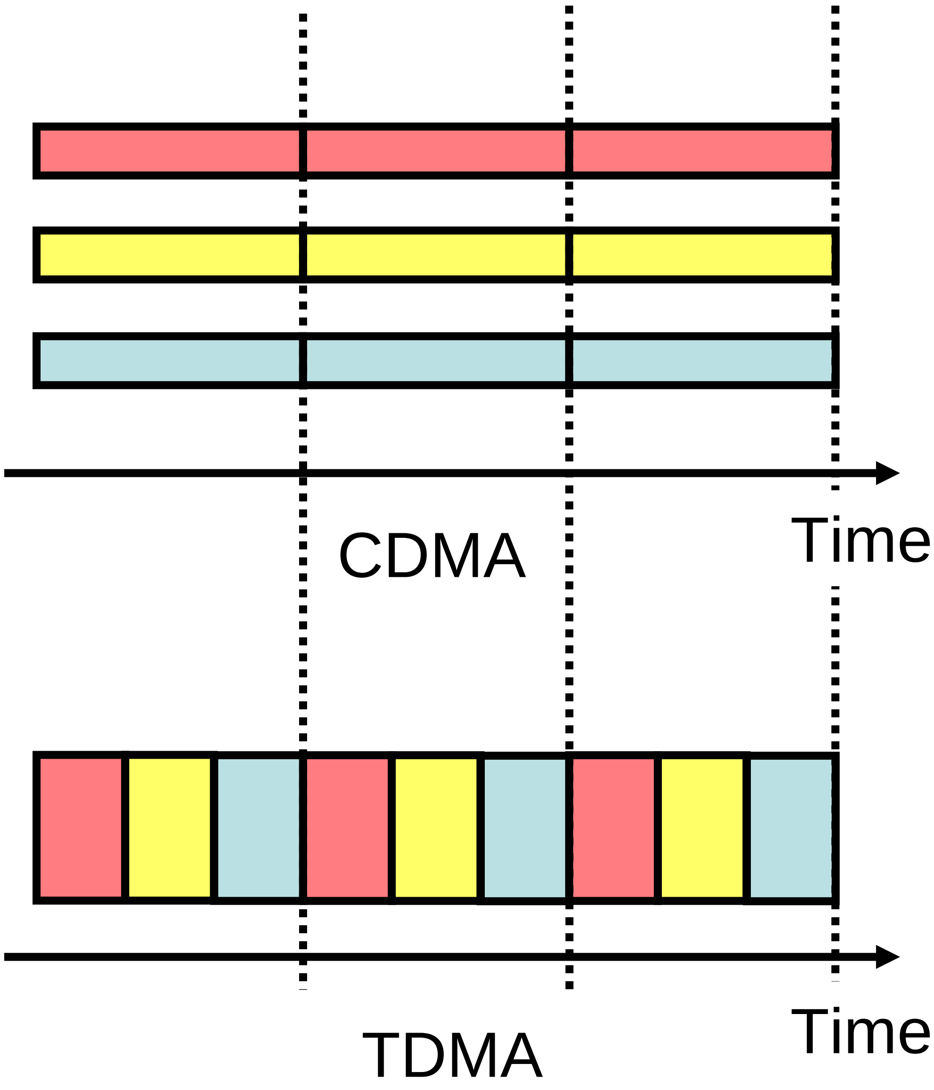

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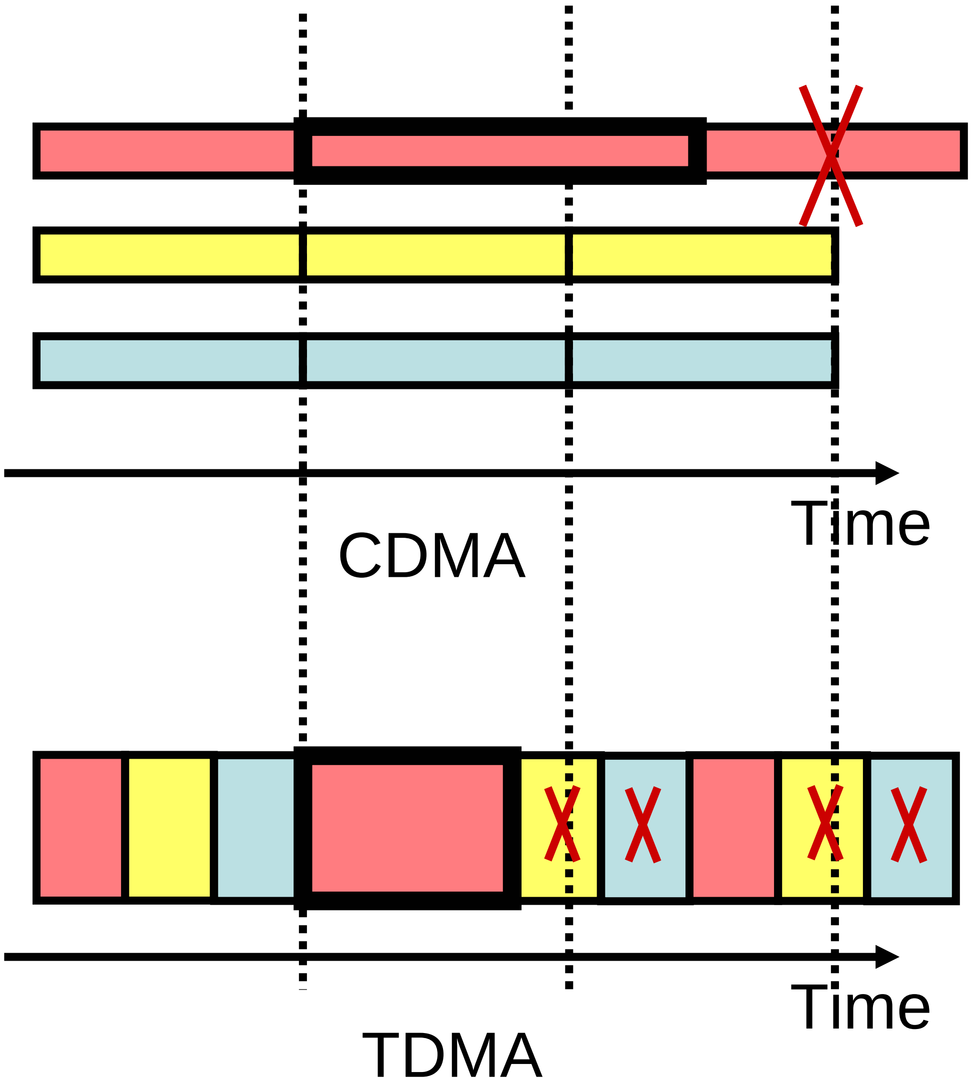
Better overrun isolation



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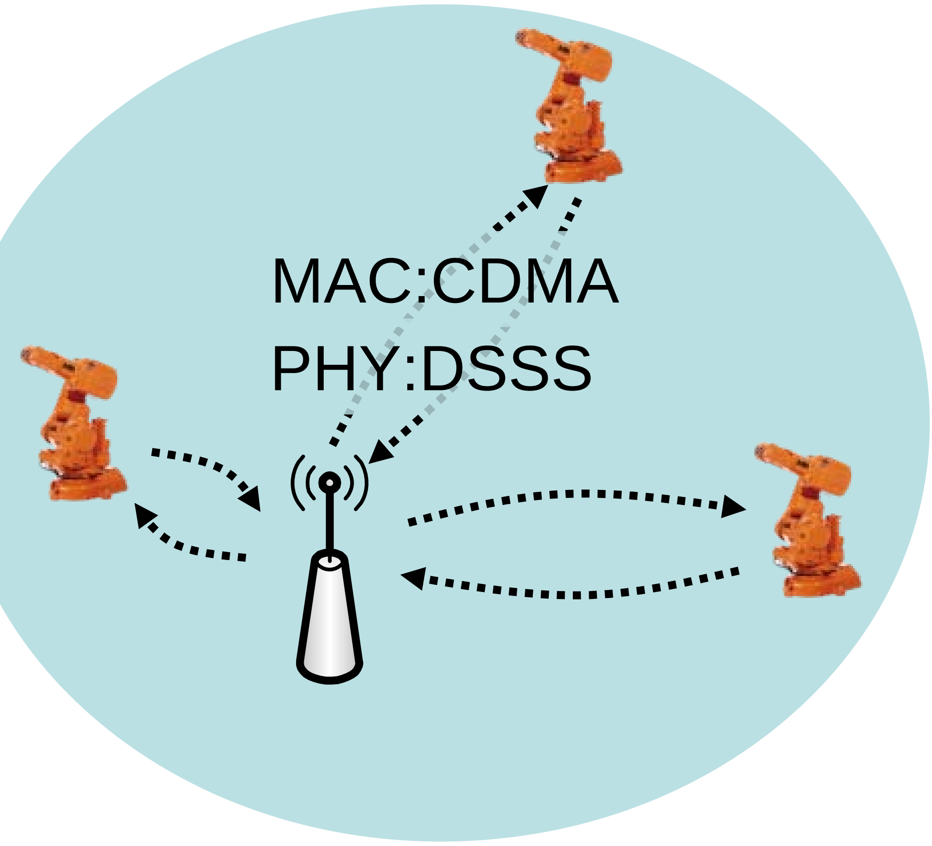
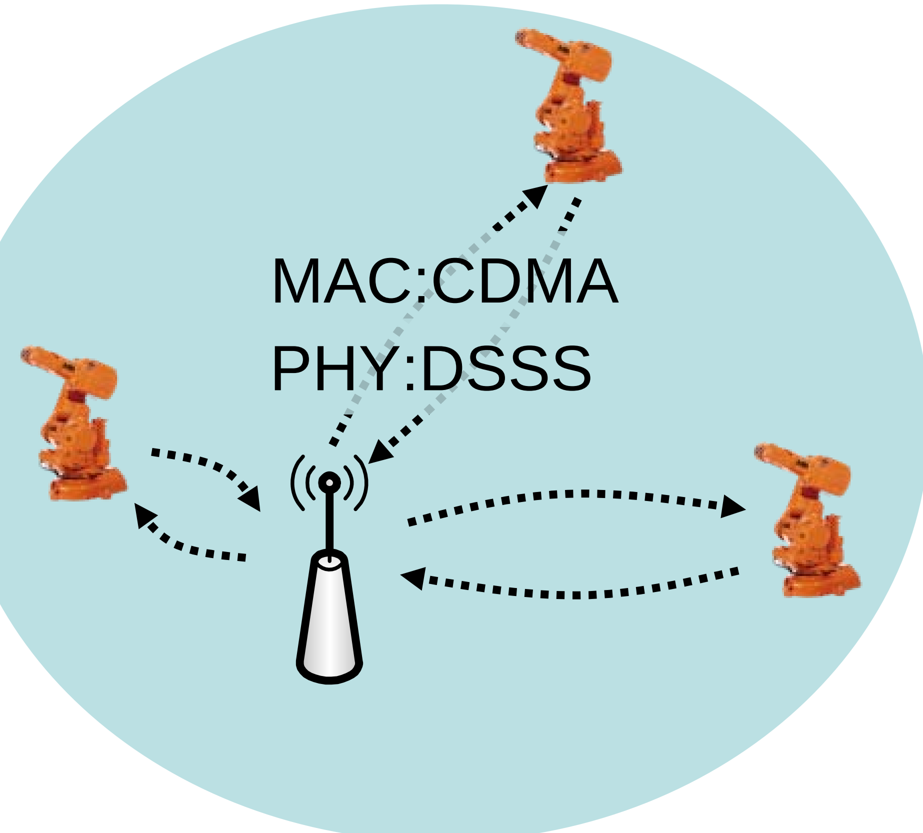


Centralized WLAN paradigm

DSSS with low data rate for high robustness

CDMA instead of TDMA

Solution Heuristics → Choose DSSS-CDMA cell phone network paradigm!



DSSS with low data rate for high robustness

Centralized WLAN paradigm

CDMA instead of TDMA

Simulation and Comparisons

Wireless medium model complies with typical settings for industrial environments [Rappaport02]:

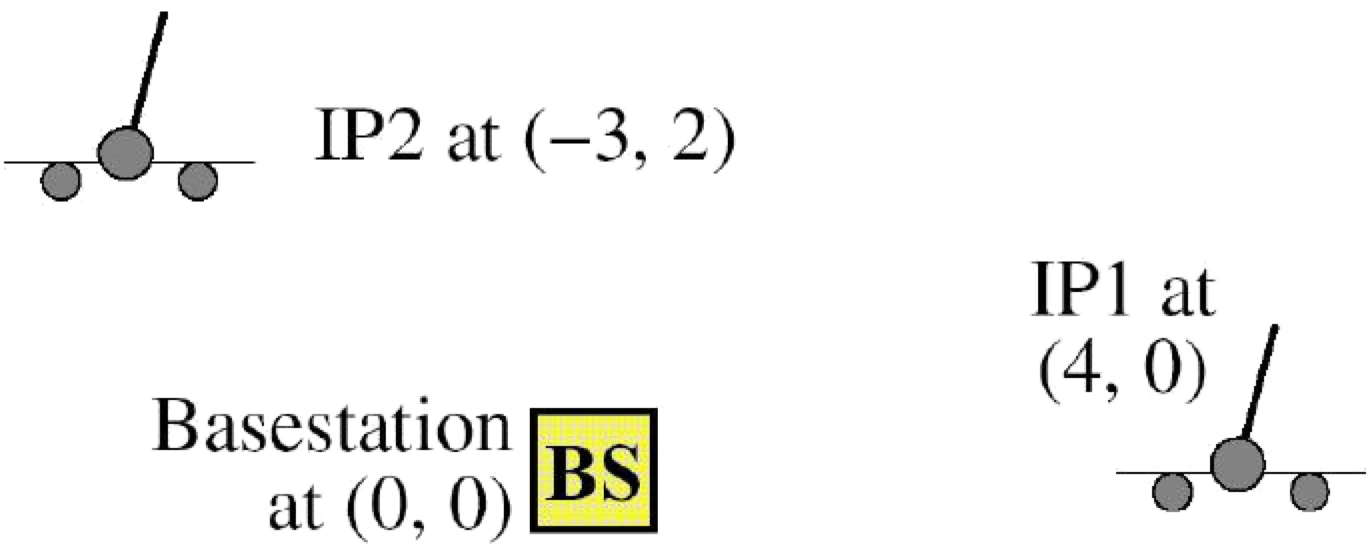
Table 1. Wireless Medium Model

Large-scale path loss model	Log-normal shadowing model with $\beta = 4 \sim 6, \sigma = 6.8\text{dB}$ *
Small-scale fading model	Rayleigh
Multipath max excess delay	90.909nsec
Additive White Gaussian Noise†	Spectral density $= -174$dBm/Hz

$*$ β is the path loss exponent, σ is the log-normal standard deviation.

† Typically refers to thermal noise.

A simulated demo showing DSSS-CDMA tolerates RF jamming, while IEEE 802.11b cannot



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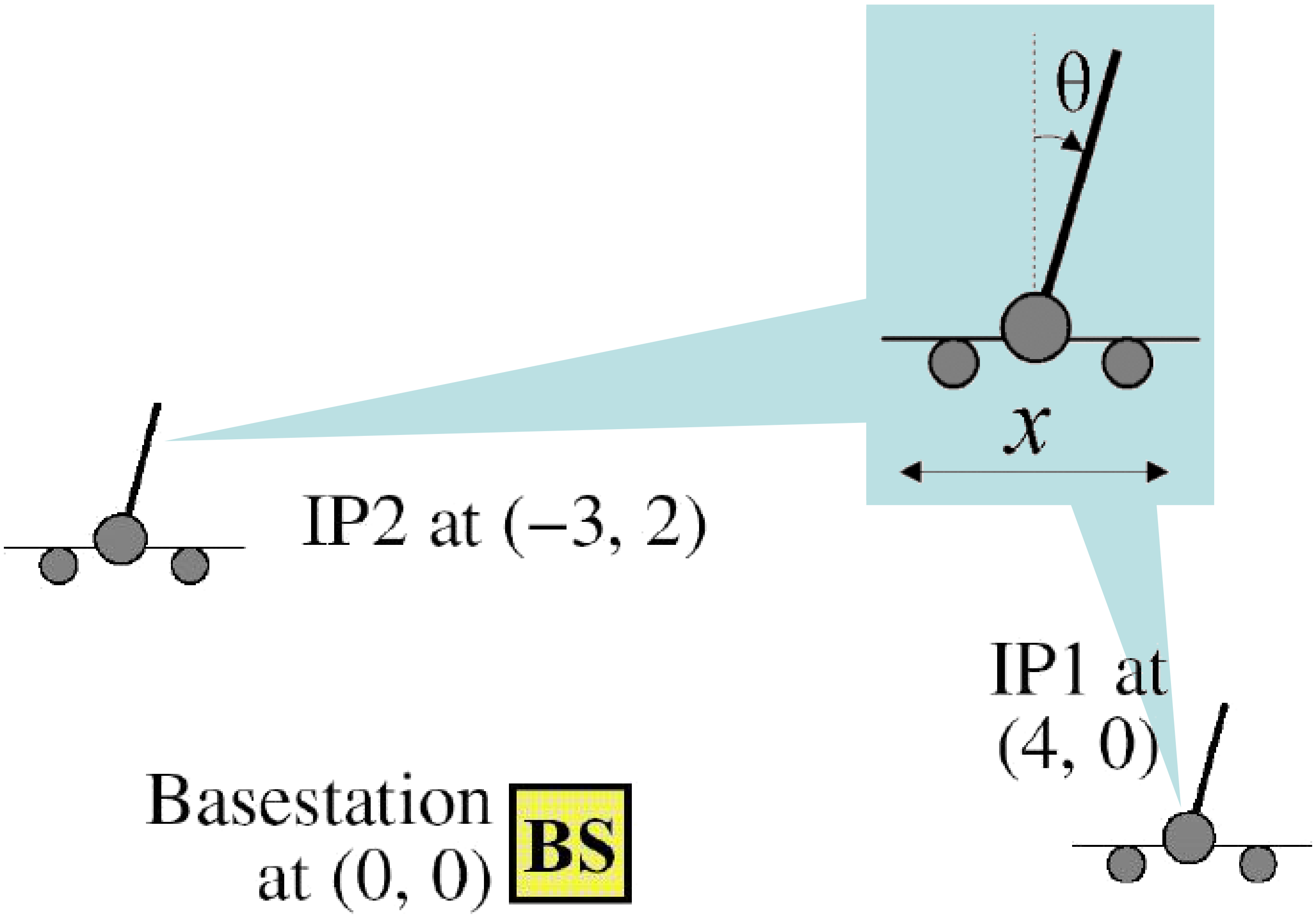

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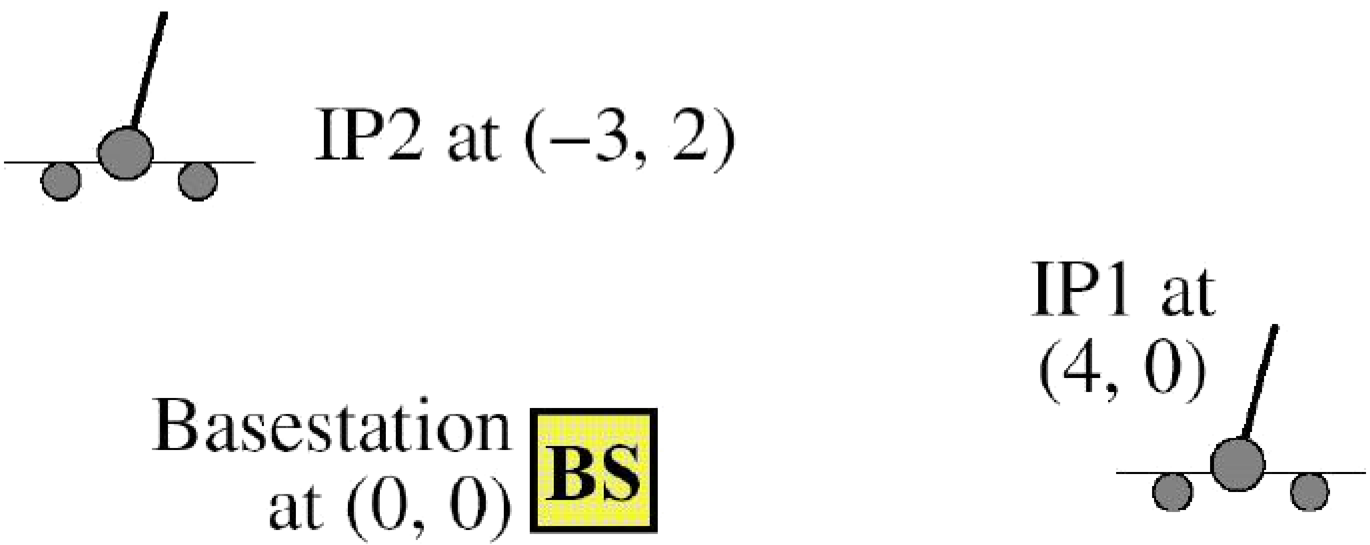
Typical industrial environment wireless medium model



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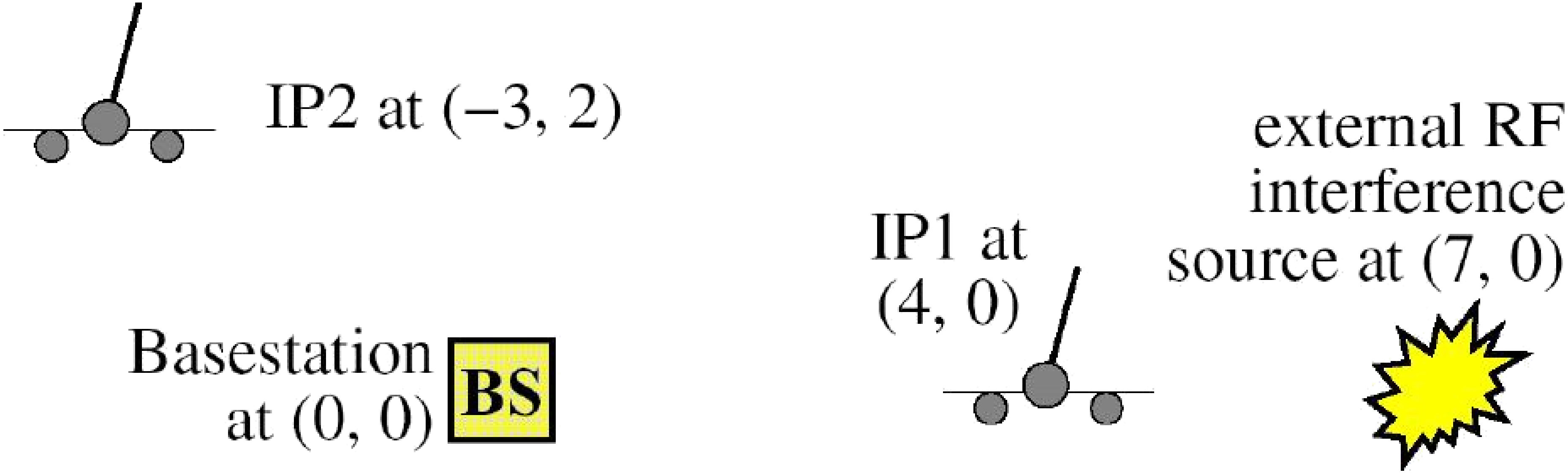

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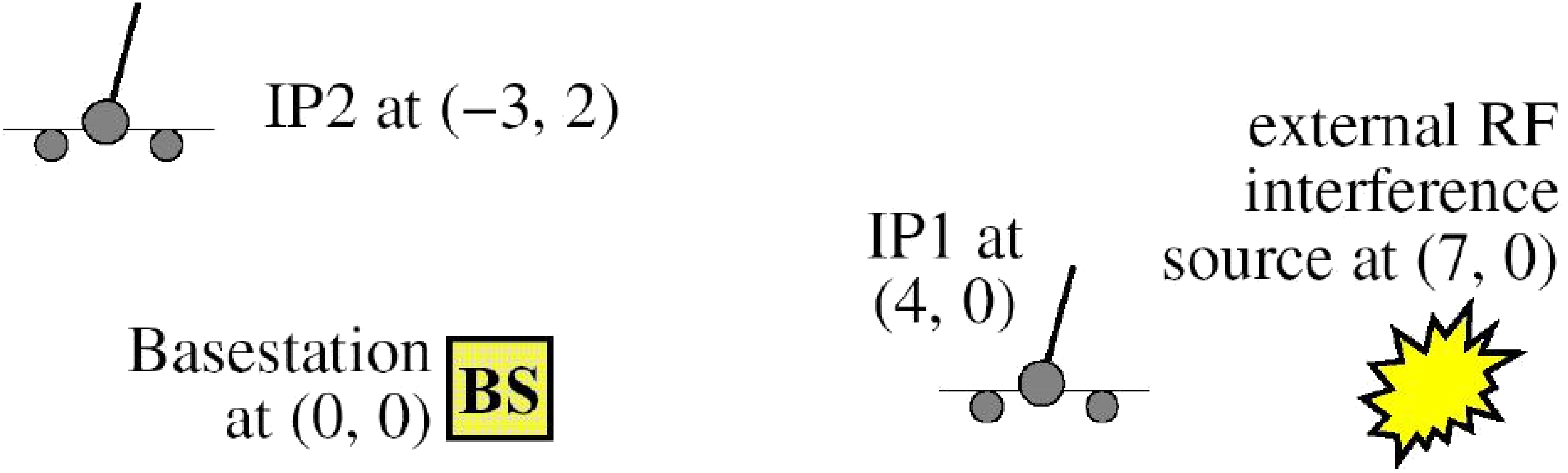
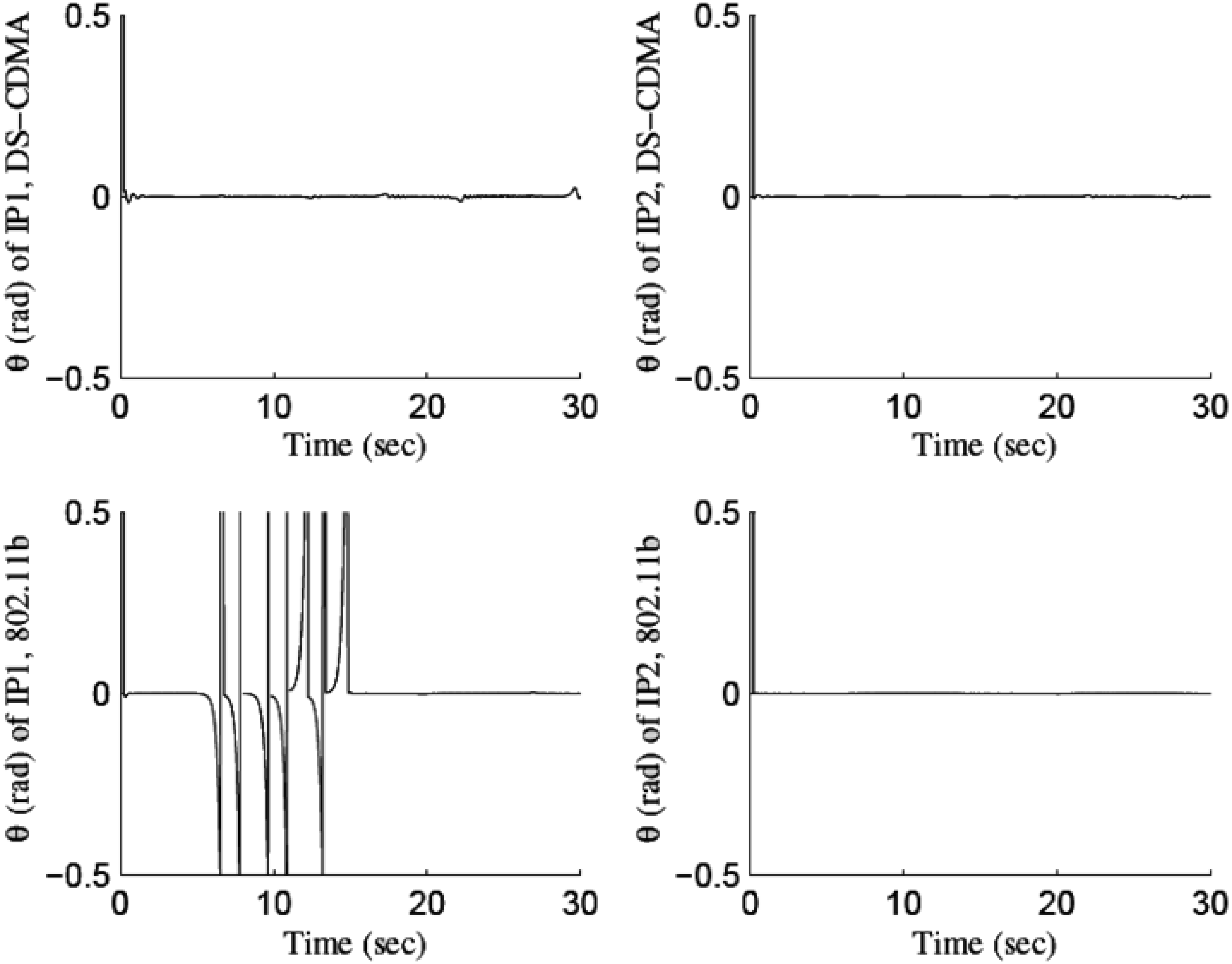
Comparison:

- DSSS-CDMA: lowest data rate
- IEEE 802.11b: keep retransmitting



A simulated demo showing DSSS-CDMA tolerates RF jamming, while IEEE 802.11b cannot



A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b

Monte-Carlo simulation setup

- 20m x 20m room, base station at the center
- ***n*** (***n*** = 1, …, 100) remote stations, random layout
- 200 trails for each ***n***
- Typical industrial environment wireless medium model

Robustness Method:

- DSSS-CDMA: lowest data rate
- IEEE 802.11a/b: keep retransmitting

A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b

802.11:

- Use the most robust mode:
  - 802.11b (DSSS): 1, 2, 5.5, 11Mbps
  - 802.11a (OFDM): 6, 9, 12, 18, 24, 36, 48, 54Mbps
- Under adverse channel conditions, 802.11 keeps retransmitting (PCF).

DSSS-CDMA

- Deploy as slow data rate as (i.e., as large processing gain *g* as) the application allows (proposition 1).
- Keep transmitting even under adverse channel conditions.

Simulation and Comparisons

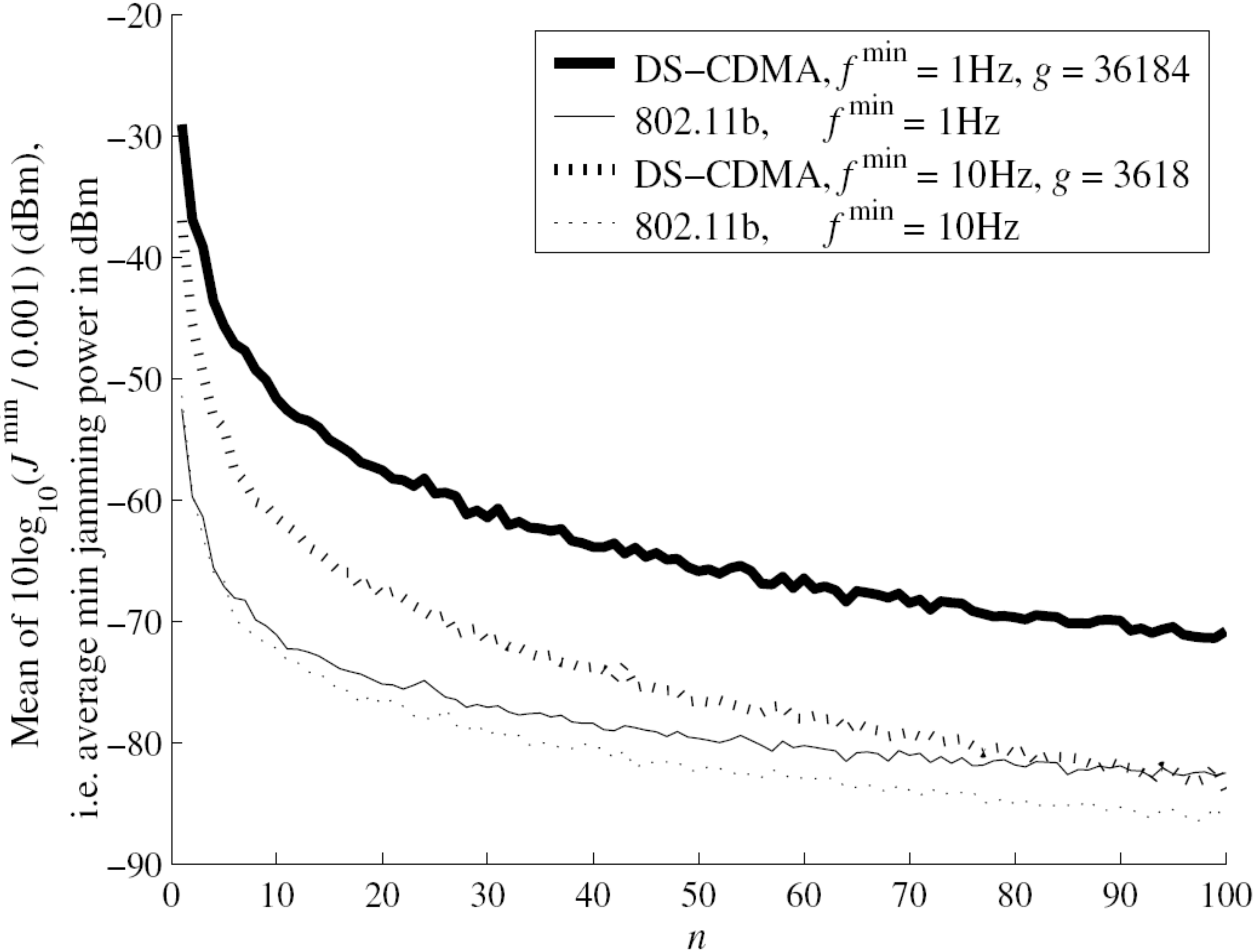
Table 2. Physical Layer Settings for Comparisons

	Max trans power*	RF band†
DSSS-CDMA vs. IEEE 802.11b comparison	1watt	2.425 ∼ 2.449GHz
DSSS-CDMA vs. IEEE 802.11a comparison	800mw	5.735 ∼ 5.795GHz

∗ According to FCC regulation.

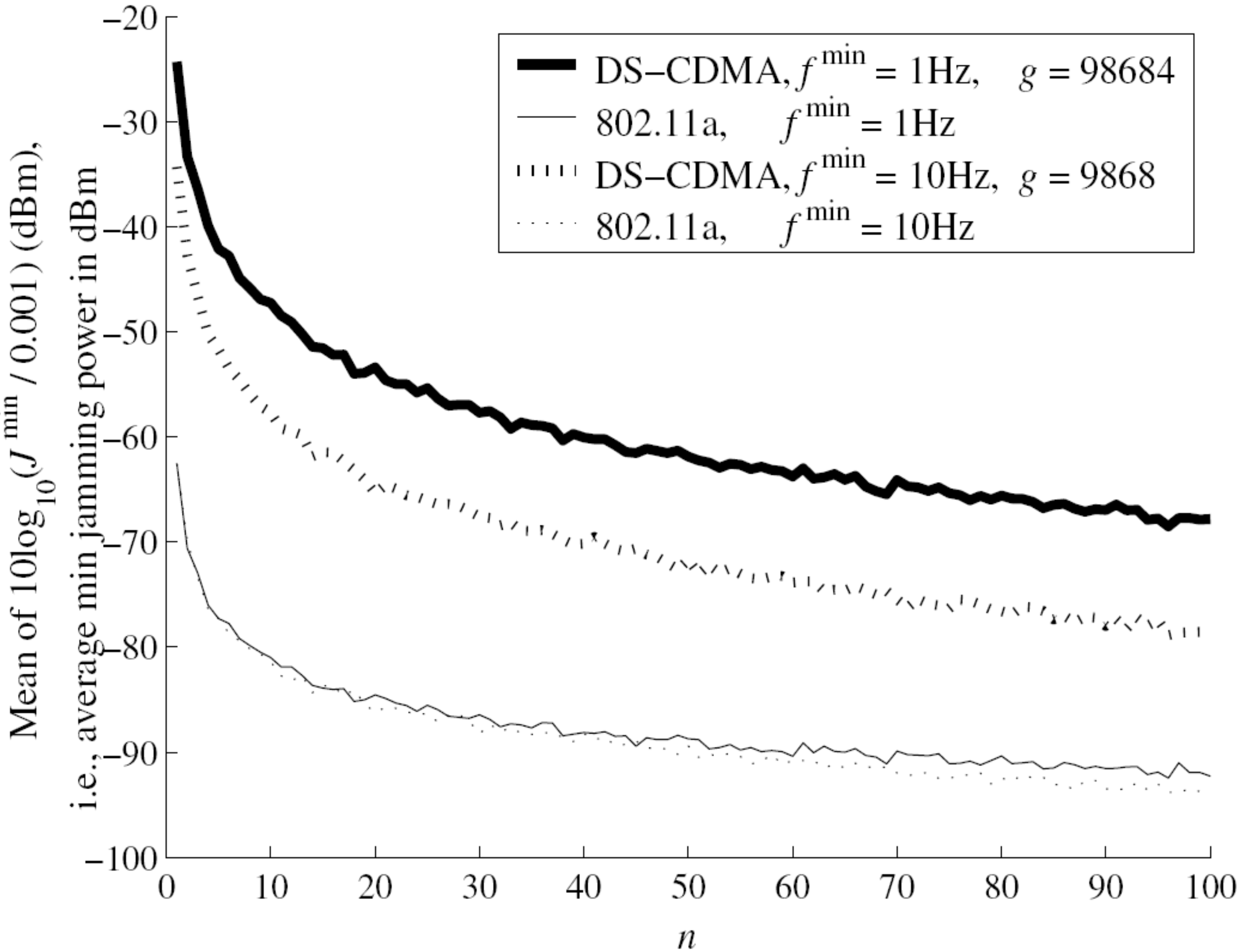
† According to IEEE 802.11 specification. Note RF bandwidth also decides baseband bandwidth (i.e. chip rate for DSSS and bit rate for OFDM).

A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b



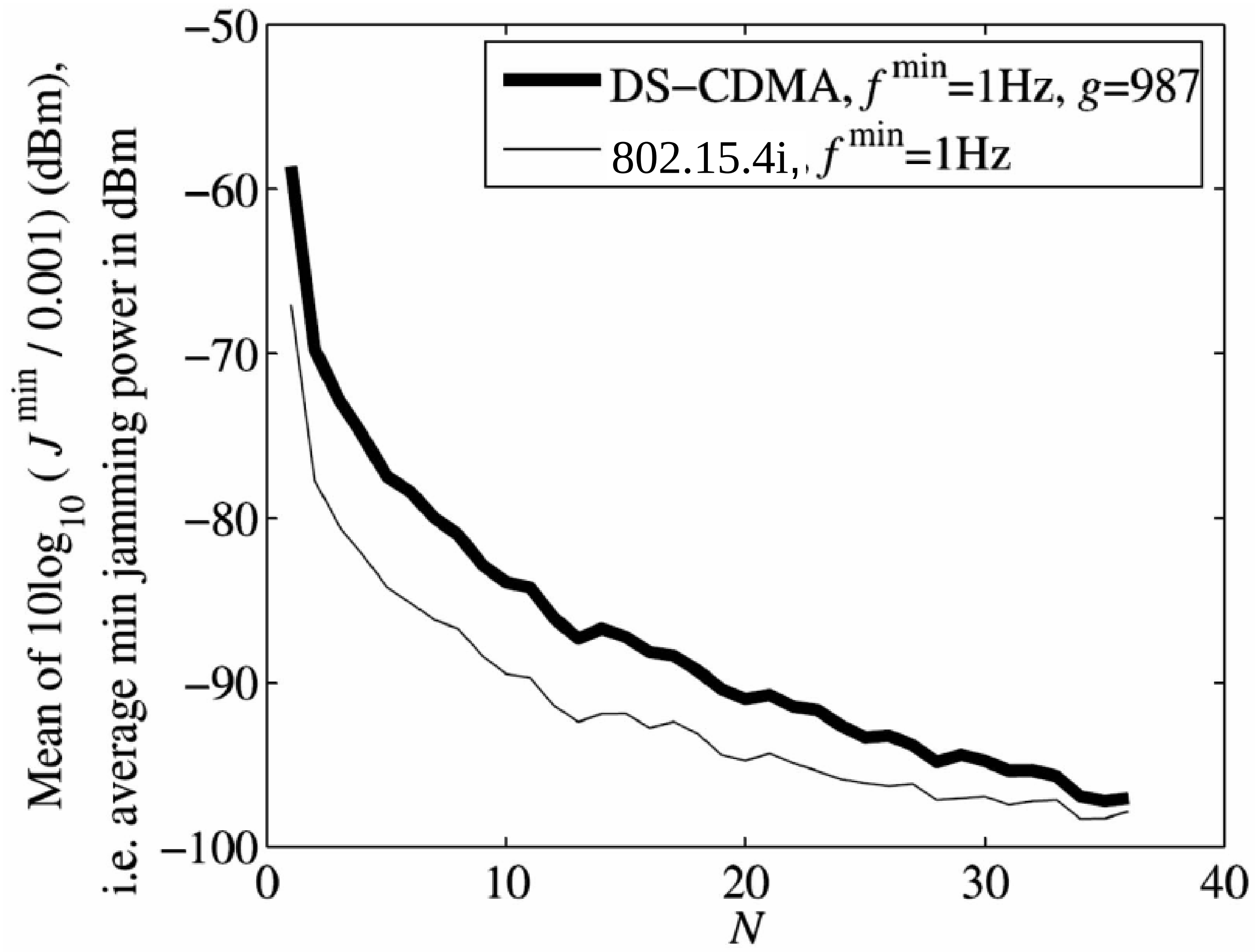
(a) Comparison with IEEE 802.11b

A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b

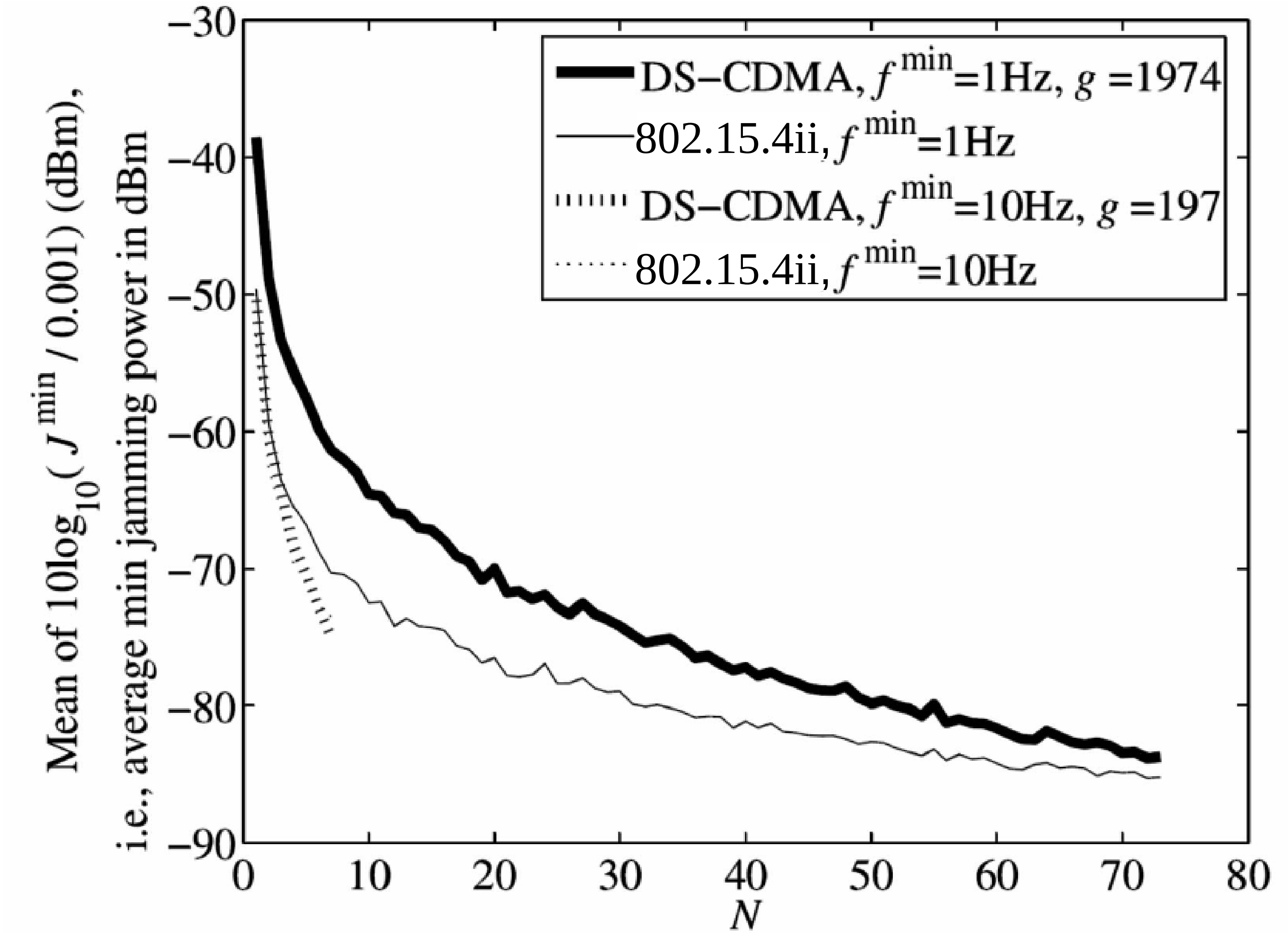


(b) Comparison with IEEE 802.11a

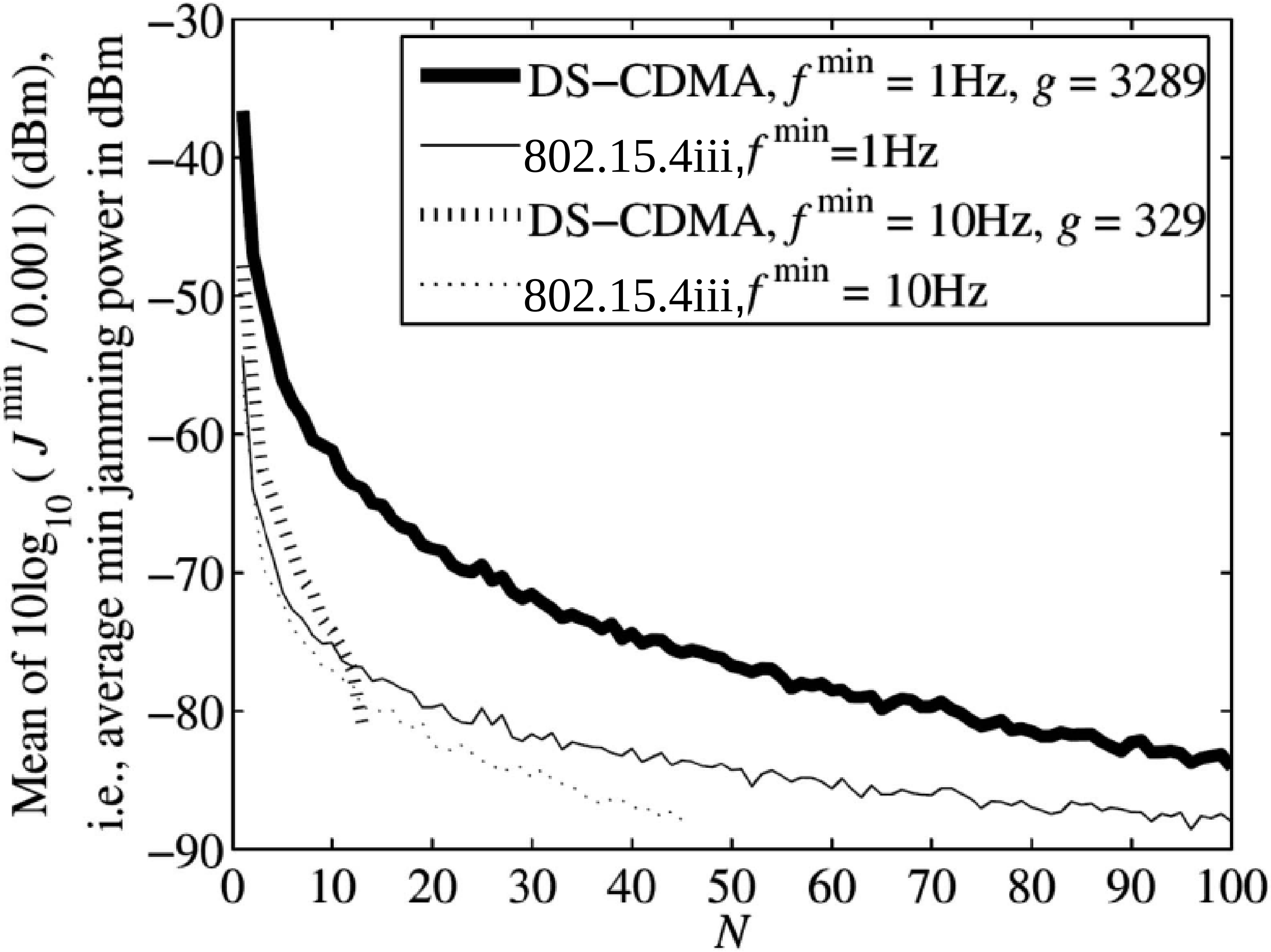
Monte Carlo comparison with IEEE 802.15.4



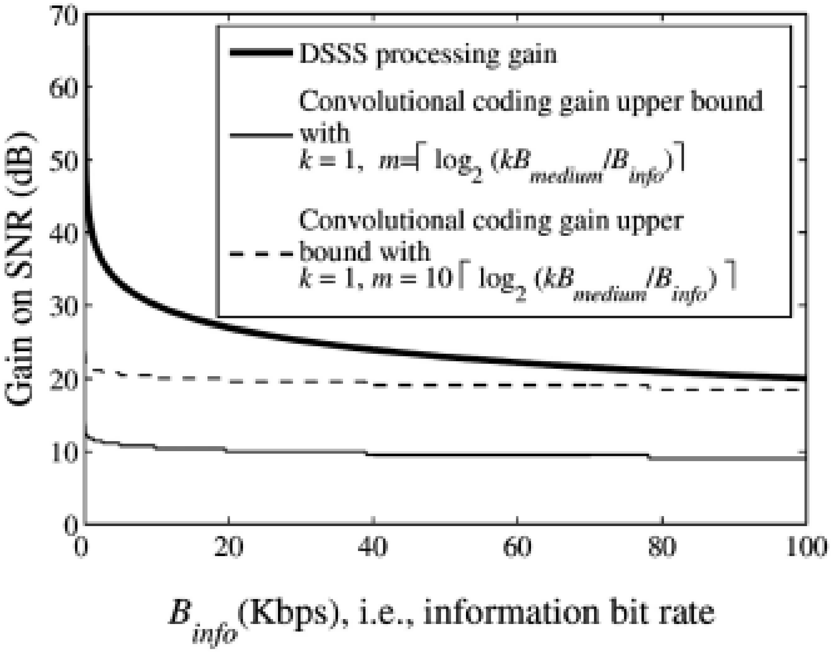
Monte Carlo comparison with IEEE 802.15.4

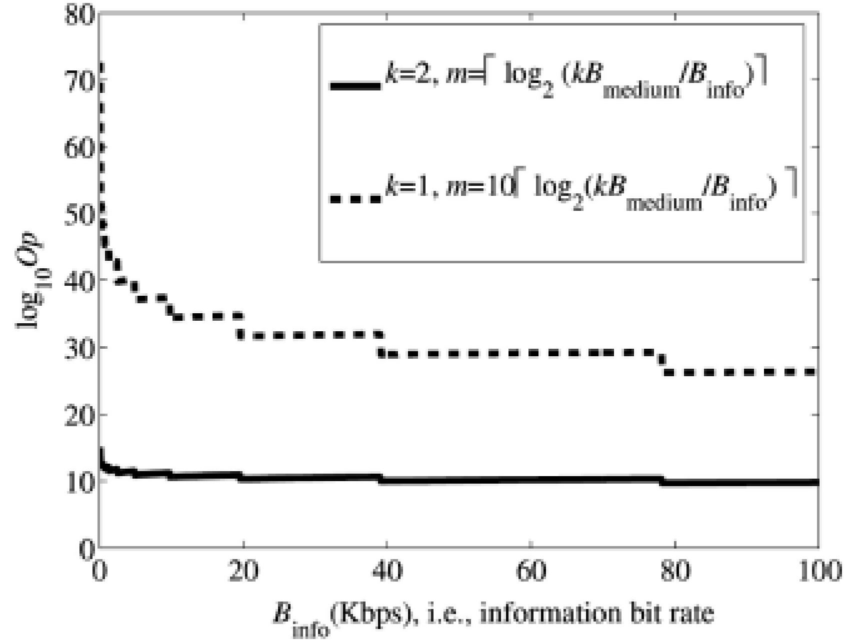


Monte Carlo comparison with IEEE 802.15.4



Feasibility of Convolutional Coding





k input bits, ***m*** shift registers

Conclusion

“DSSS-CDMA Cell Phone Paradigm + Slowest Data Rate” is more robust than “IEEE 802.11 + Retransmission”.

Conclusion

“DSSS-CDMA Cell Phone Paradigm + Slowest Data Rate” is more robust than “IEEE 802.11 + Retransmission”.

For real-time wireless LAN, change philosophy from pursuing throughput/delay to pursuing reliability/robustness.

Thank You!


CPS
Middleware
Real-Time Switch
Real-Time Wireless LAN
Real-Time Localization

Publications

Journal Publications:

1. **[TMC] Qixin Wang**, Rong Zheng, Ajay Tirumala, Xue Liu, and Lui Sha, “Lightning: A Hard Real-Time, Fast, and Lightweight Low-End Wireless Sensor Election Protocol for Acoustic Event Localization”, (accepted for publication) in IEEE Transactions on Mobile Computing.
2. **[TMC07] Qixin Wang**, Xue Liu, Weiqun Chen, Marco Caccamo, and Lui Sha, “Building Robust Wireless LAN for Industrial Control with the DSSS-CDMA Cell Phone Network Paradigm”, in IEEE Transactions on Mobile Computing, vol 6, number 6, June, 2007.
3. **[TOSN06]** Xue Liu, **Qixin Wang**, Wenbo He, Marco Caccamo, and Lui Sha, "Optimal Real-Time Sampling Rate Assignment for Wireless Sensor Networks", in ACM Transactions on Sensor Networks, vol 2, issue 2, May, 2006.

Conference, Workshop and Other Publications:

4. **[RTAS08] Qixin Wang**, Sathish Gopalakrishnan, Xue Liu, and Lui Sha, "A Switch Design for Real-Time Industrial Networks", (full paper accepted for publication) in Proceedings of the 14th IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS 2008), 2008.
5. **[RTSS07] Qixin Wang**, Xue Liu, Jennifer Hou, and Lui Sha, "GD-Aggregate: A WAN Virtual Topology Building Tool for Hard Real-Time and Embedded Applications", in Proceedings of the 28th IEEE Real-Time Systems Symposium (RTSS 2007), pp. 379-388, Tucson, Arizona, Dec. 3-6, 2007.
6. **[HCMDSS07a]** Mu Sun, **Qixin Wang**, and Lui Sha, “Building Safe and Reliable MD PnP Systems”, in Joint Workshop on High Confidence Medical Devices, Software, and Systems (HCMDSS) and Medical Devices Plug-and-Play (MD PnP), June, 2007.
7. **[HCMDSS07b]** Jennifer C. Hou, **Qixin Wang**, et. al., “PAS: A Wireless-enabled, Sensor-integrated Personal Assistance System for Independent and Assisted Living”, in Joint Workshop on High Confidence Medical Devices, Software, and Systems (HCMDSS) and Medical Devices Plug-and-Play (MD PnP), June, 2007.
8. **[ICSMC06] Qixin Wang**, Wook Shin, Xue Liu, et. al., “I-Living: An Open System Architecture for Assisted Living”, (invited paper) in Proc. of IEEE International Conference on Systems, Man, and Cybernetics 2006.
9. **[RTSS05] Qixin Wang**, Xue Liu, Weiqun Chen, Wenbo He, and Marco Caccamo, "Building Robust Wireless LAN for Industrial Control with DSSS-CDMA Cellphone Network Paradigm", in Proc. of the 26th IEEE International Real-Time Systems Symposium (RTSS 2005), Miami, USA, December, 2005. (Power Point)(Poster-Sized Power Point)
10. **[ICAS05]** Xue Liu, Rong Zheng, Jin Heo, **Qixin Wang**, and Lui Sha, "Timing Control for Web Server Systems Using Internal State Information", in Proc. of Joint International Conference on Autonomic and Autonomous Systems and International Conference on Networking and Services (ICAS-ICNS 2005), 2005.
11. **[RTSS04] Qixin Wang**, Rong Zheng, Ajay Tirumala, Xue Liu, and Lui Sha, "Lightning: A Fast and Lightweight Acoustic Localization Protocol Using Low-End Wireless Micro-Sensors", in Proc. of the 25th IEEE International Real-Time Systems Symposium (RTSS 2004), Lisbon, Portugal, December, 2004. (Power Point) (Demo Video)
12. **[RTSS03]** Xue Liu, **Qixin Wang**, Lui Sha and Wenbo He, "Optimal QoS Sampling Frequency Assignment for Real-Time Wireless Sensor Networks", in Proc. of the 24th IEEE International Real-Time Systems Symposium (RTSS 2003), Cancun, Mexico, December, 2003.
13. **[IPSN03] Qixin Wang**, Wei-Peng Chen, Rong Zheng, Kihwal Lee, and Lui Sha, "Acoustic Target Tracking Using Tiny Wireless Sensor Devices", in Proc. of the 2nd International Workshop on Information Processing in Sensor Networks (IPSN'03), Lecture Notes in Computer Science 2634, Springer, 2003.