Energy Efficiency of the IEEE 802.15.4 Standard in Dense Wireless Micro-Sensor Networks: Modeling and Improvement Perspectives

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by

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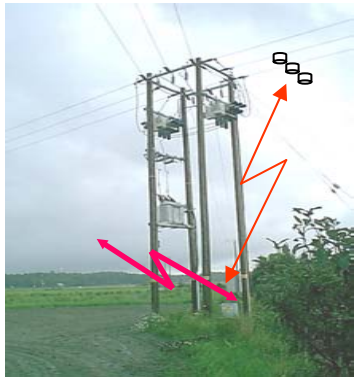
The Opportunity: Micro-power Wireless Sensor Networks

Industrial Plants and Power Line Monitoring (courtesy ABB)

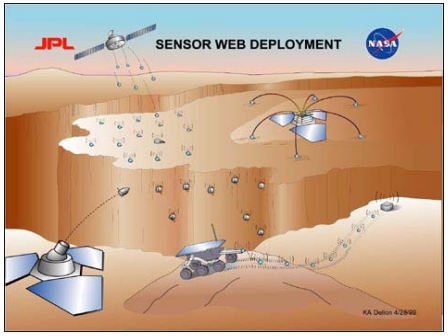


Operating Room of the Future (courtesy John Guttag)

Target Tracking & Detection (Courtesy of ARL)

Location Awareness (Courtesy of Mark Smith, HP)

NASA/JPL *sensorwebs*



Micro-Power Wireless Sensor Networks require power-aware radio

Constraints

Application Characteristics	Typical Values
Data Rate	bps to kbps
Spatial Density	0.1-20 nodes/m^3
Transmission Distance	10 – 100m
Extended Lifetime	5 years
Small Size	1 “AA” battery

An important milestone has been the release of the IEEE 802.15.4 standard

- Standard for the physical (PHY) and medium access control (MAC) layers of low data rate wireless personal area network (LDR-WPAN)
- Standard approved: 05/2003
- Task Group 4b created for extension
- Silicon is being released

Courtesy Chipcon

Is 802.15.4 appropriate for Micro-Power Wireless sensor networks?

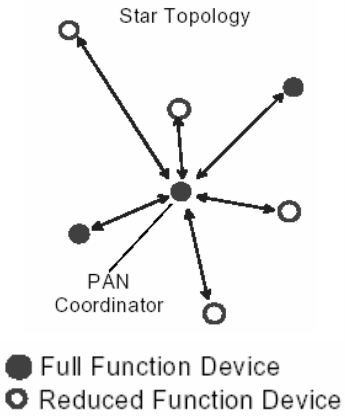
To answer that question, we have:

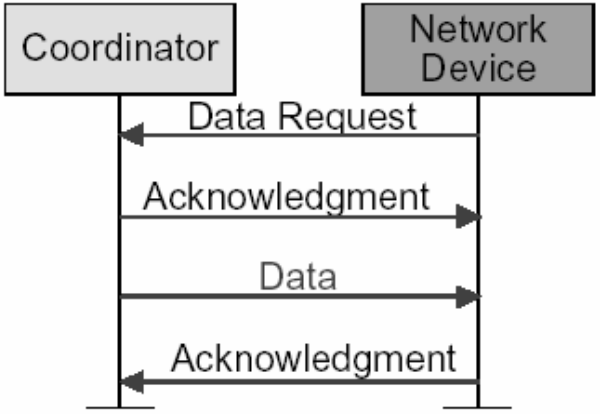
- **Characterized the performance and power consumption of a 802.15.4 PHY implementation**
- **Proposed and Energy-efficient activation policy and energy consumption model**
- **Evaluated the performance and power consumption at system level, considering the MAC**
- **Derived guidelines for further power reduction**

The IEEE 802.15.4 PHY

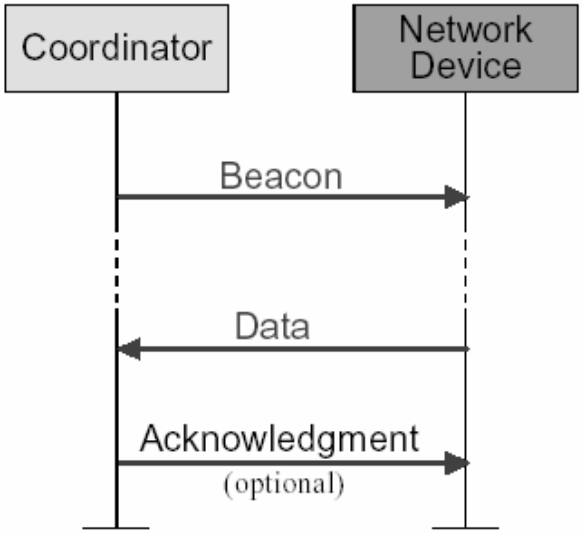
- 16 channels in 2450MHz band (world), 10 Channels in 915MHz band (US), 1 channel in 868MHz band (EU)
- Direct Sequence Spread Spectrum (DSSS) radio
- 2Mchip/s OQPSK modulation
- PHY data rate: 250kbps
- Transmit power up to 0 dBm

The IEEE 802.15.4 MAC





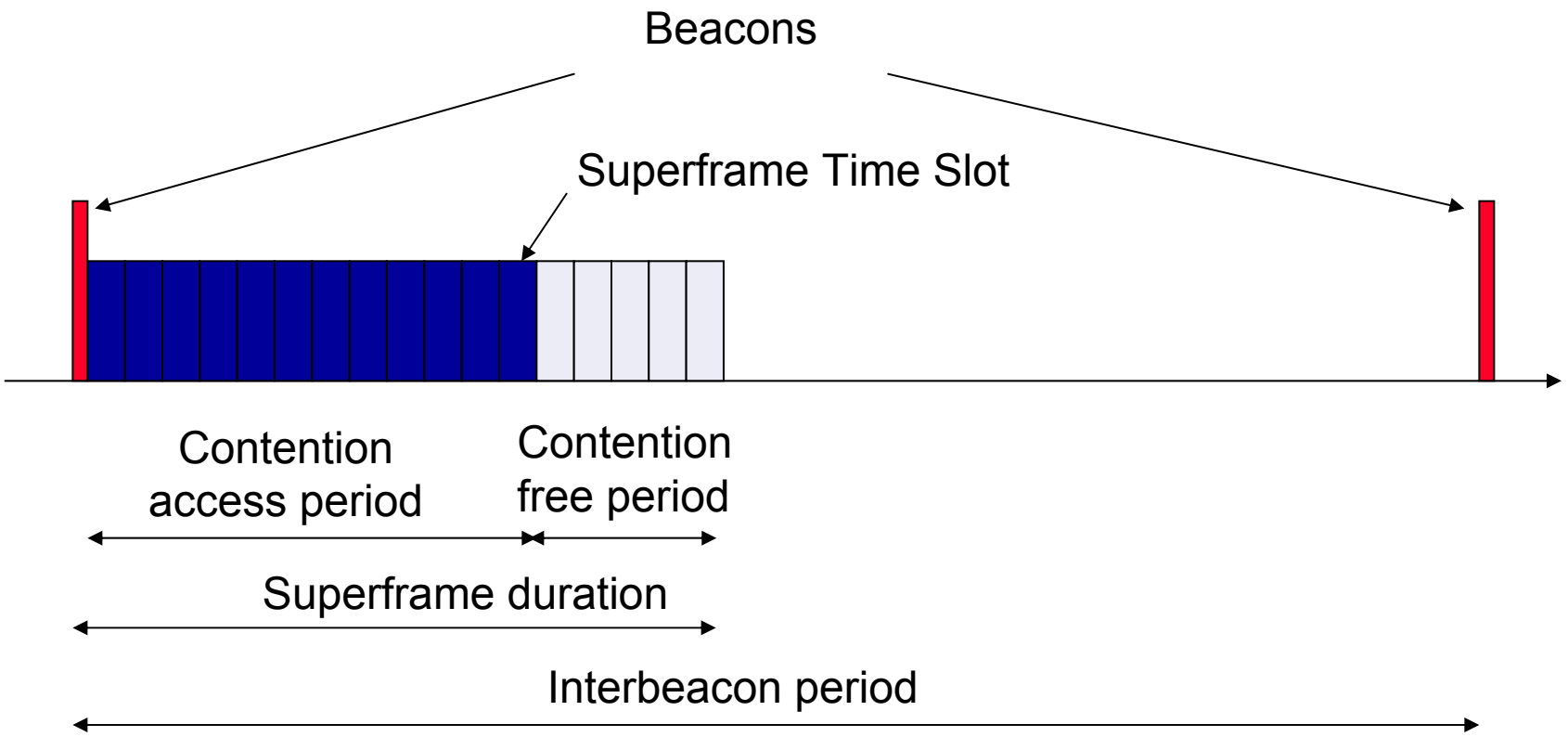
downlink



uplink

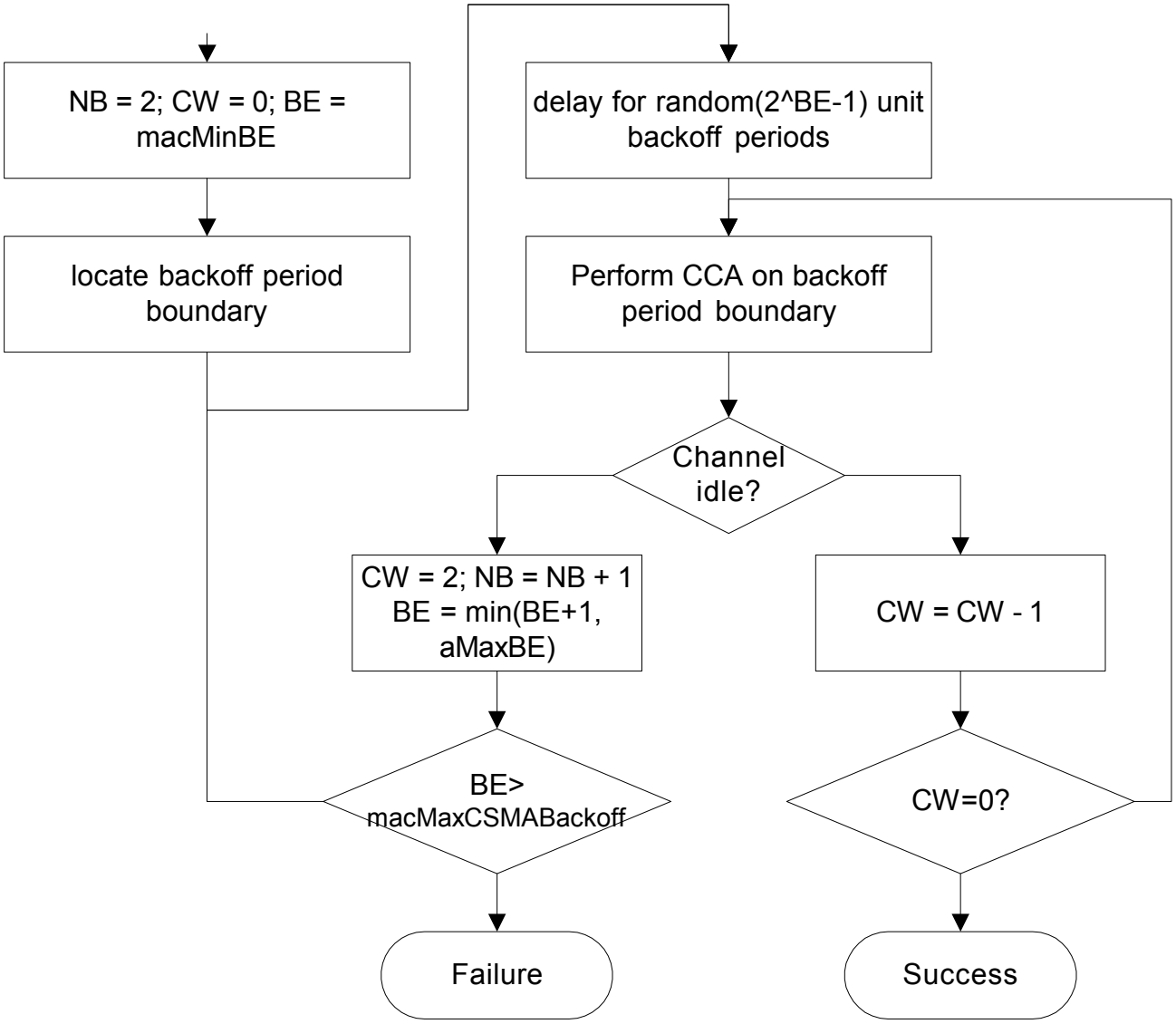
- **Beacon mode**
- **Indirect transmission at downlink**
- **Direct transmission at uplink**
- **Slotted CSMA/CA**
- **Most power efficient mode**
- ***Multi-hop not considered here***

The beacon mode introduces a superframe structure



We look at the contention access mode since it accommodates more nodes (dense network)

Slotted CSMA/CA is used to access the channel

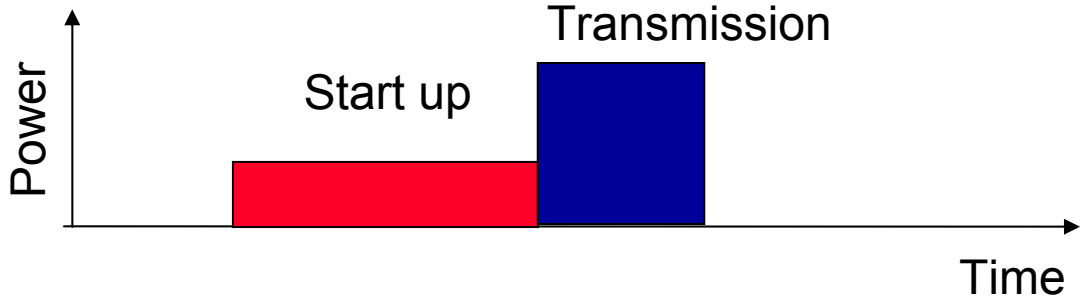


We have characterized a typical 802.15.4 chip: the Chipcon CC2420

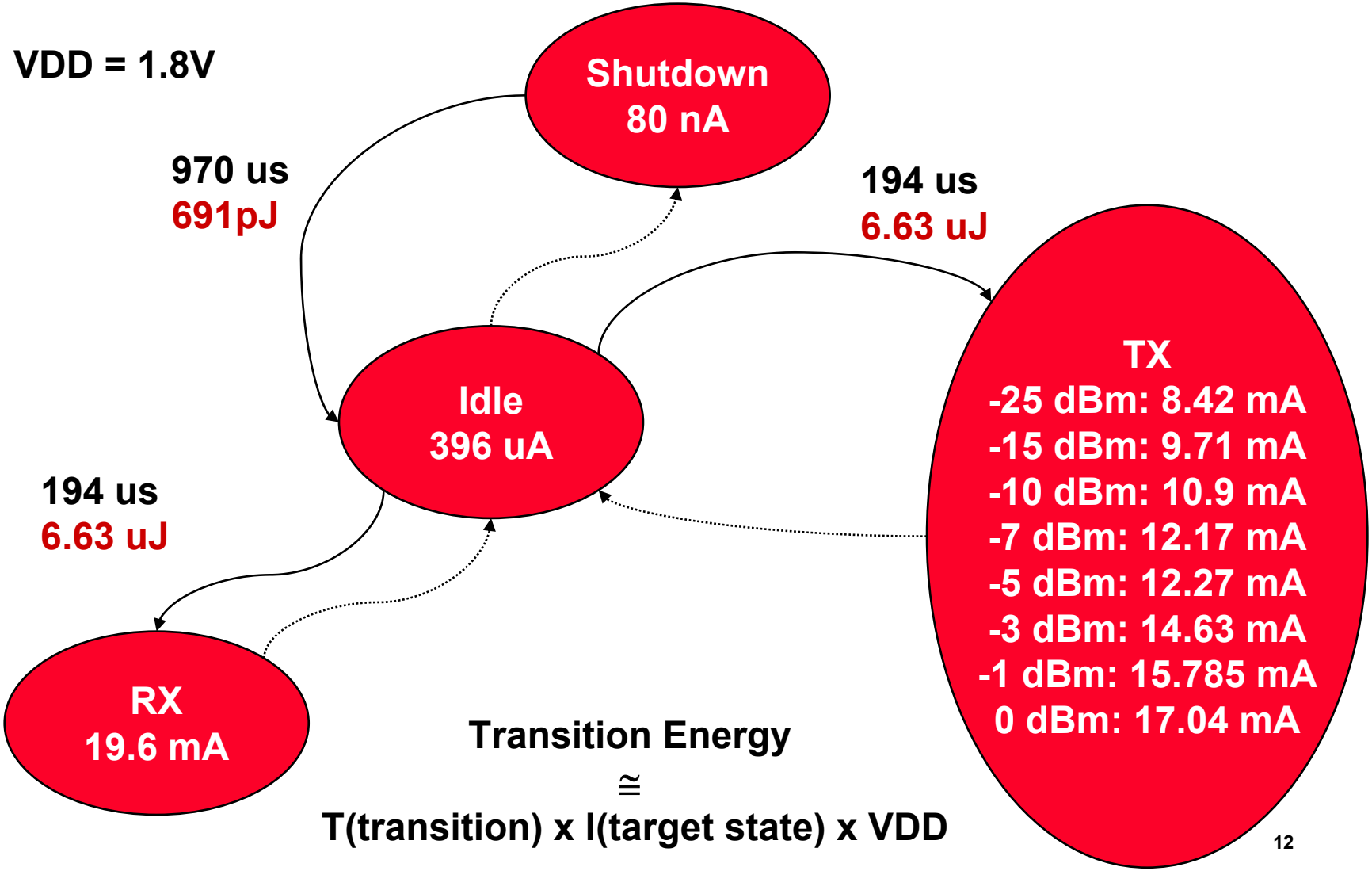
- Power measurements
- Characterization of the state transition time and energy
- Characterization of the link performance

Power characterization

- **4 main states to be characterized:**
  - **Shutdown: clock is off; radio is off**
  - **Idle: the clock is on; radio is off**
  - **Transmit: clock on; radio in transmit mode**
  - **Receive: clock on; radio in receive mode**
- **In sensor networks, the transition time and energy between the radio state is important!**



Results


VDD = 1.8V
Shutdown
80 nA
970 us
691pJ
194 us
6.63 uJ
Idle
396 uA
194 us
6.63 uJ
TX
-25 dBm: 8.42 mA
-15 dBm: 9.71 mA
-10 dBm: 10.9 mA
-7 dBm: 12.17 mA
-5 dBm: 12.27 mA
-3 dBm: 14.63 mA
-1 dBm: 15.785 mA
0 dBm: 17.04 mA
RX
19.6 mA
Transition Energy
≅
T(transition) x I(target state) x VDD

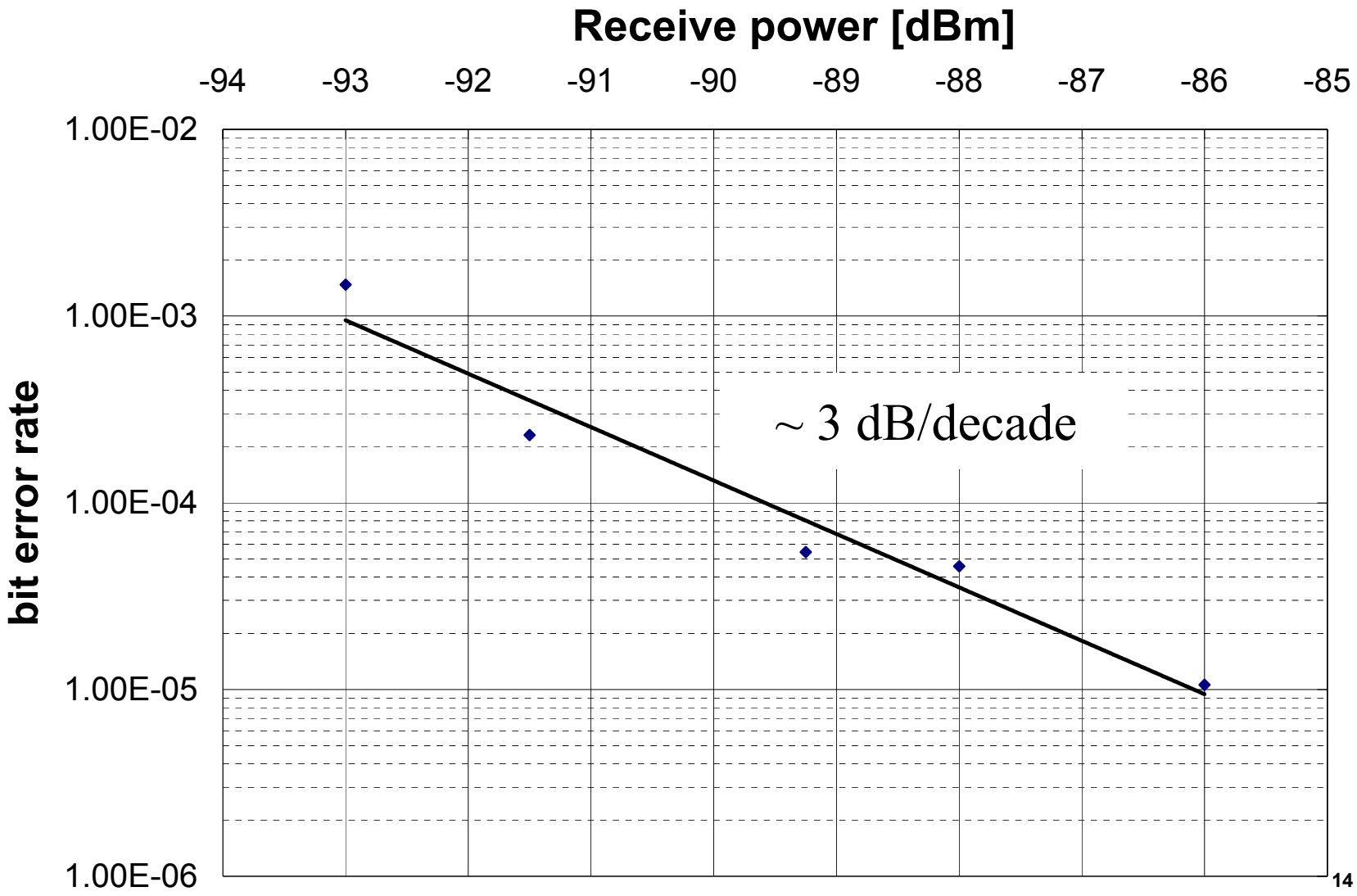
Link performance characterization

- **Link performance (i.e. packet error rate, PER) has a direct impact on the system power consumption**

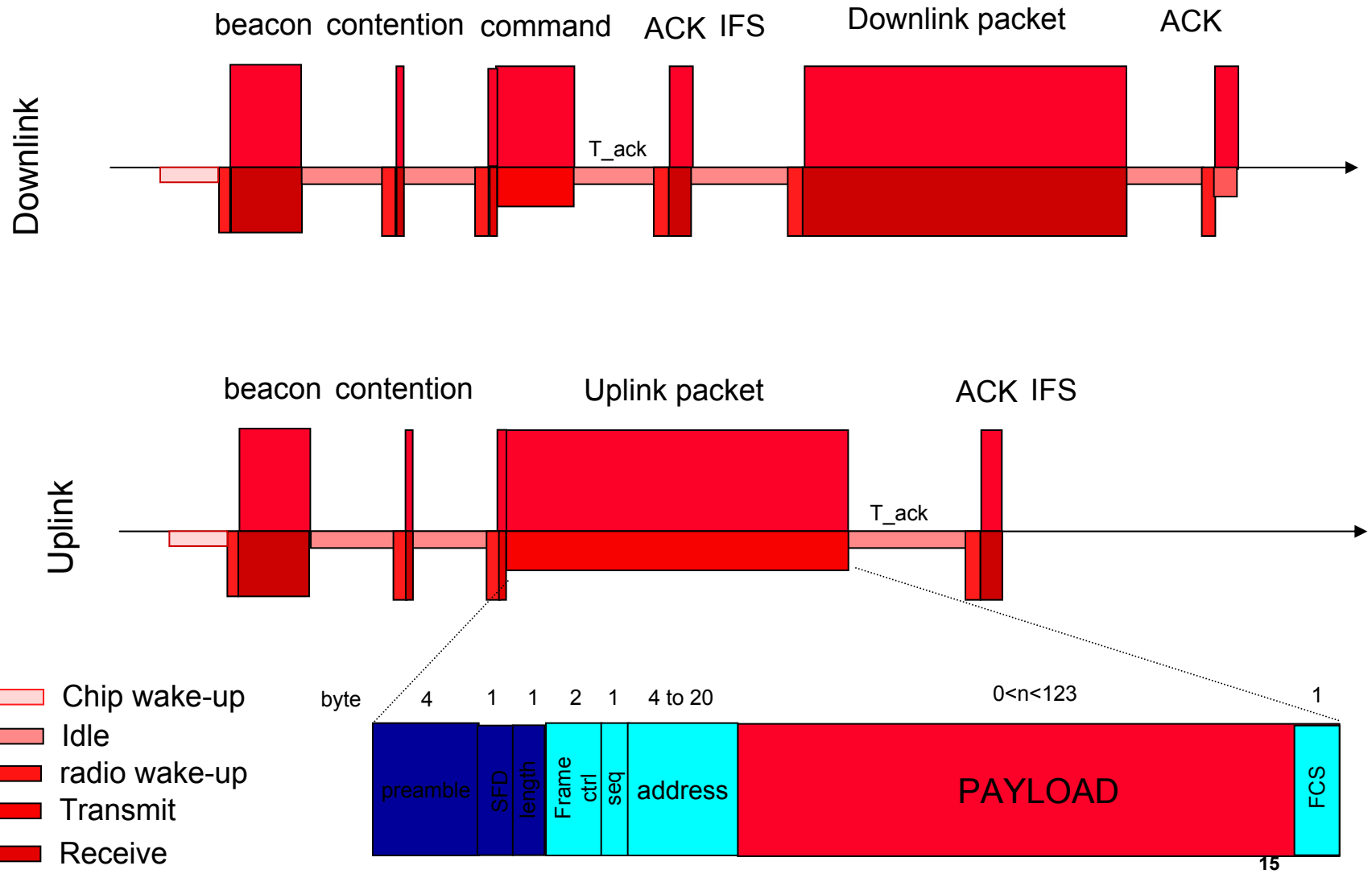
  Higher PER → more retransmission → more energy to transmit a bit reliably

- **We have to characterize the relation between the received power at the antenna and the bit error rate (BER)**

Results


Receive power [dBm]
-94
-93
-92
-91
-90
-89
-88
-87
-86
-85
bit error rate
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
~ 3 dB/decade

The ideal activation policy can be derived



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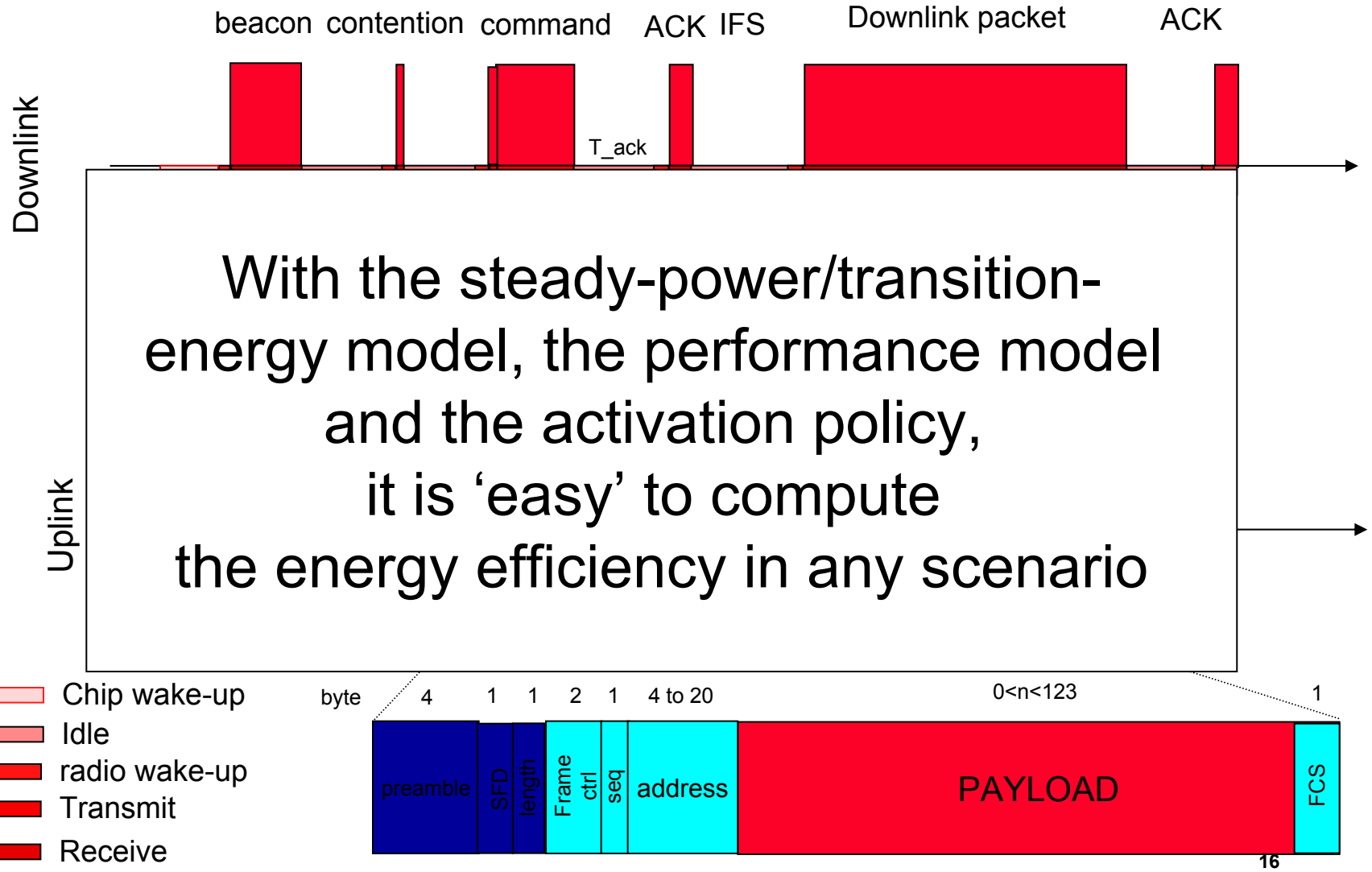
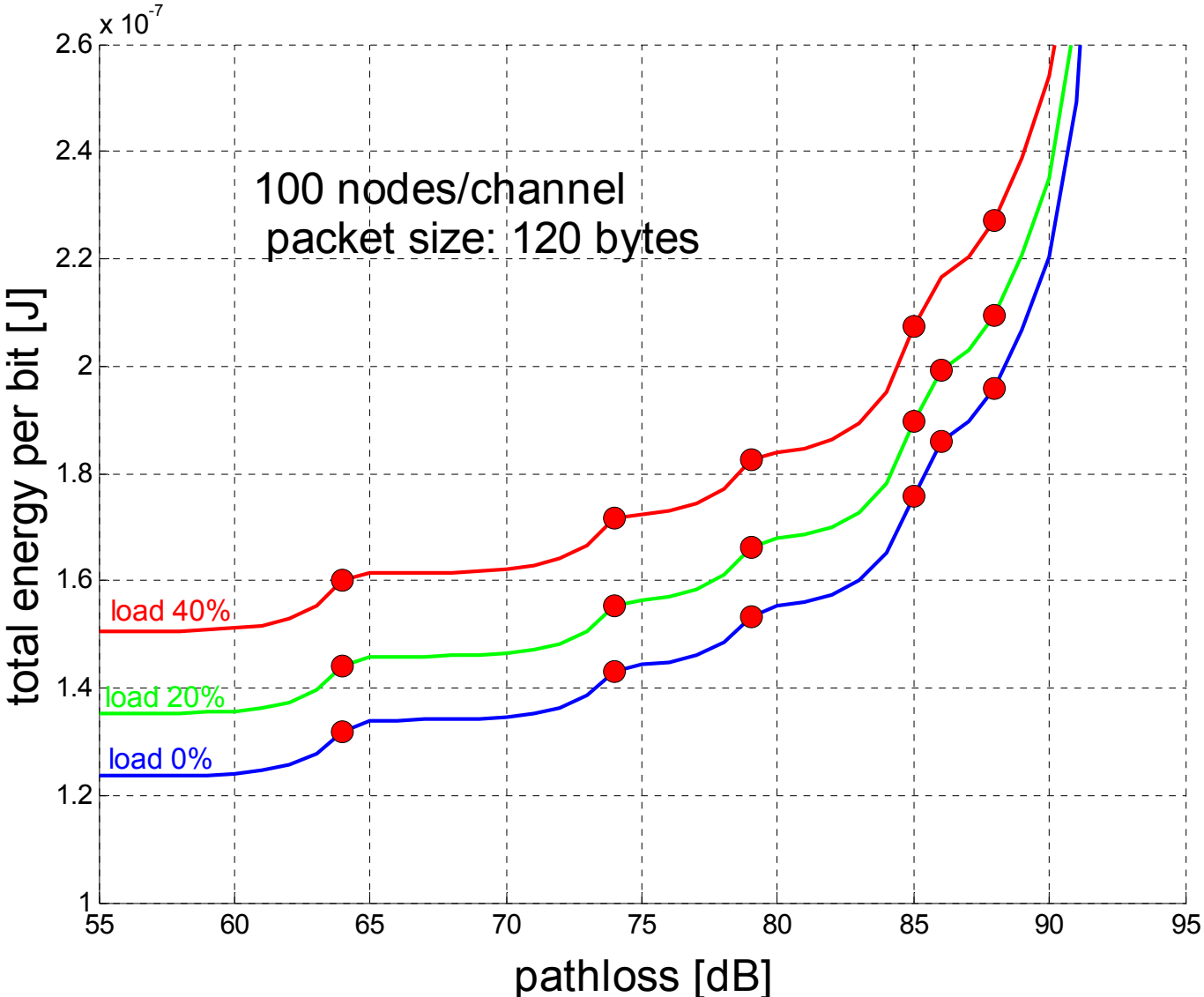


802.15.4-based Micro-Power Sensor Network: A Case Study

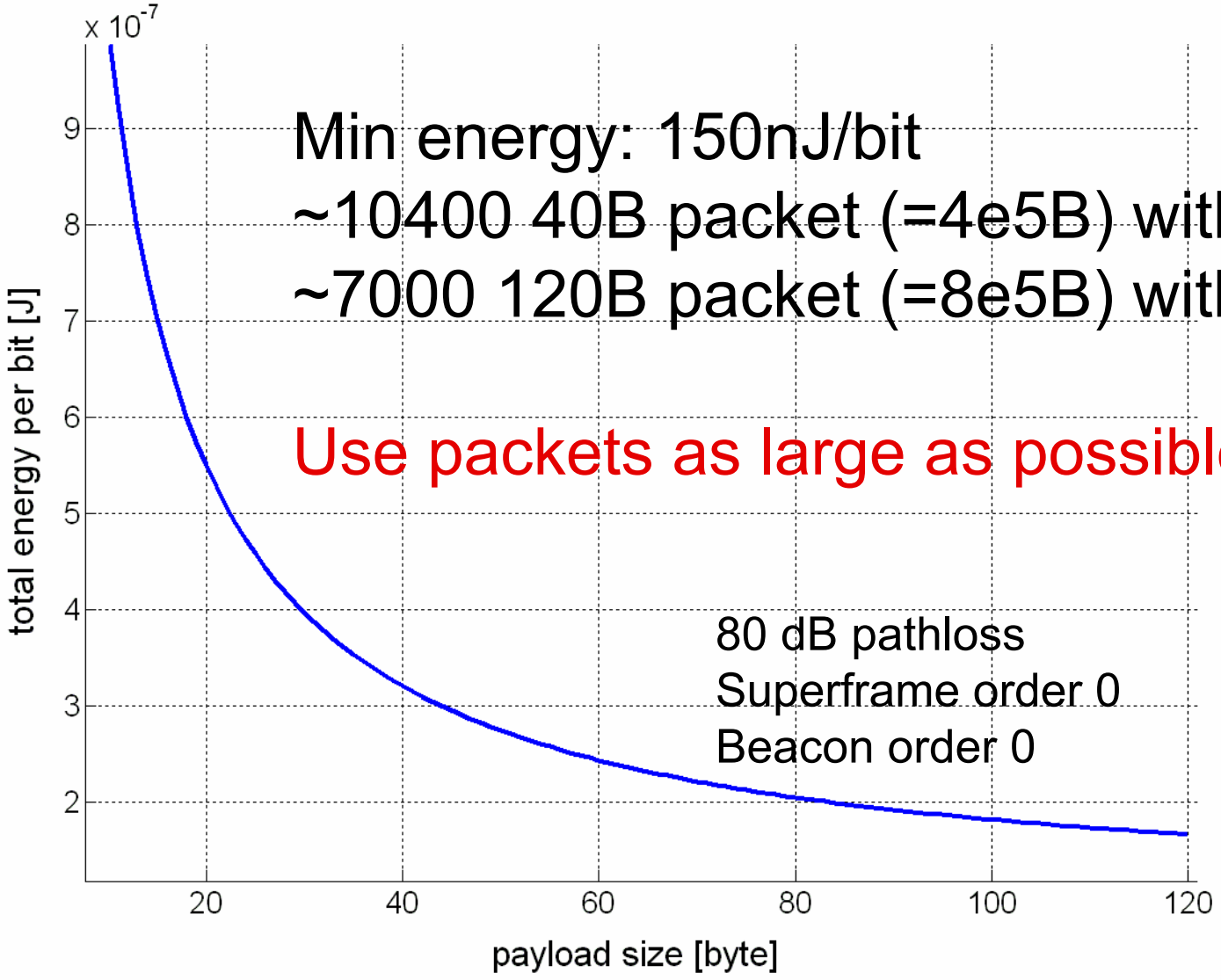
- Star network: 100 nodes per channel, 1 base station
- 1-hop node to base station
- Path loss between 55 and 90 dB
- 1 byte gathered per node every 8 ms
- 1 kbps per node, 100kbps per channel

What do we have to add to the activation policy to be 'micro-power'?

Transmit power scaling saves up to 40% energy per bit



Buffering is necessary to maximize the energy efficiency

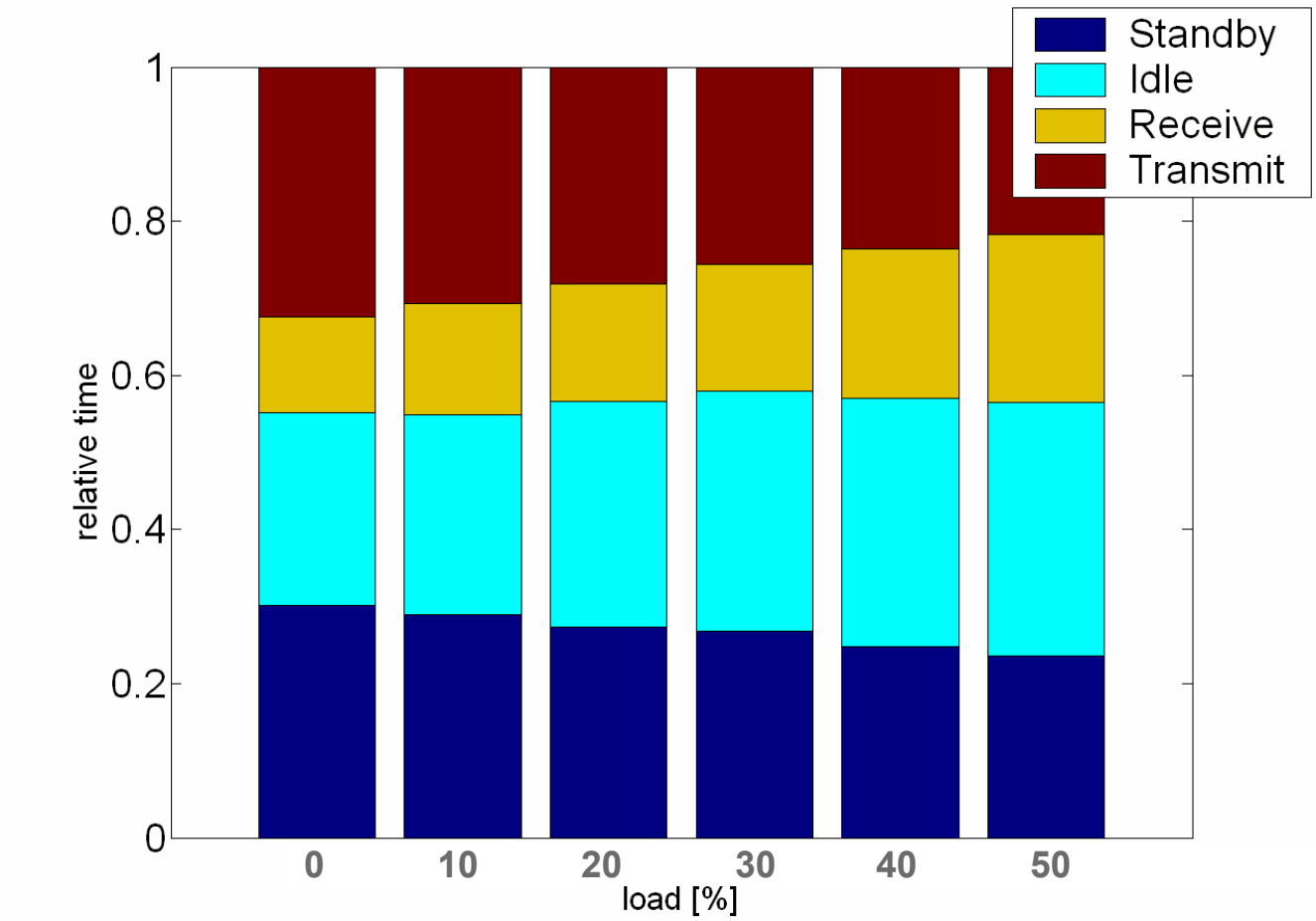


802.15.4-based Micro-Power Sensor Network: A Case Study

- Star network: 100 nodes per channel, 1 base station
- 1-hop node to base station
- Path loss between 55 and 90 dB
- 1 byte gathered per node every 8 ms
- 1 kbps per node, 100kbps per channel
- 120 bytes per packet
- 1 packet every 960ms
- Beacon order 6
- Load 42%

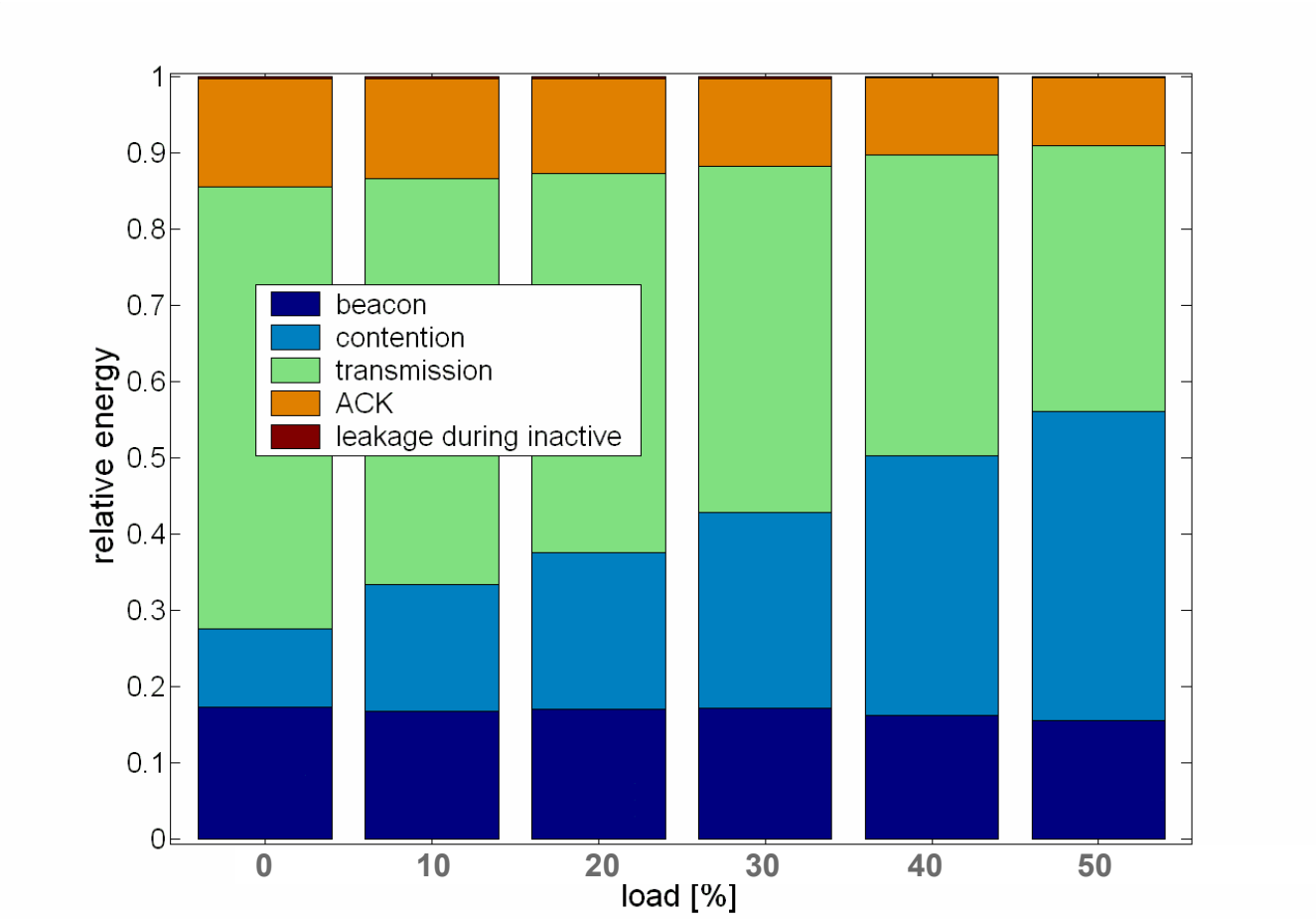
211μW

Where does the power go?



When load is high, the node spends more time in RX than in TX mode!

The contention procedure overhead dominates at high load



The overhead of the contention procedure (N x transceiver switch-on for CCA + idle) is dominant at high loads

Conclusions

- IEEE 802.15.4 is a reasonable standard for Micro-Power Sensor Radio
- Using the largest packet size (buffering) always improves the energy efficiency
- Transmit power scaling saves up to 40% energy
- In highly loaded networks, the transceiver is more often in receive mode than in transmit mode!
- The overhead of the contention procedure, which multiplies the number of radio turn-ons, is dominant at high load

Guidelines for Micro-Power:

- Larger packet support, more buffering
- Receiver power optimization
- Scalable receiver with low power/low performance for CCA, regular power/performance for full reception
- Lower idle power
- Further reduced shutdown-idle transition time