Lecture 5:
Energy for Networked autonomous devices

Igor Neri
July 15, 2014

NiPS Summer School 2014
ICT-Energy: Energy management at micro and nanoscales for future ICT

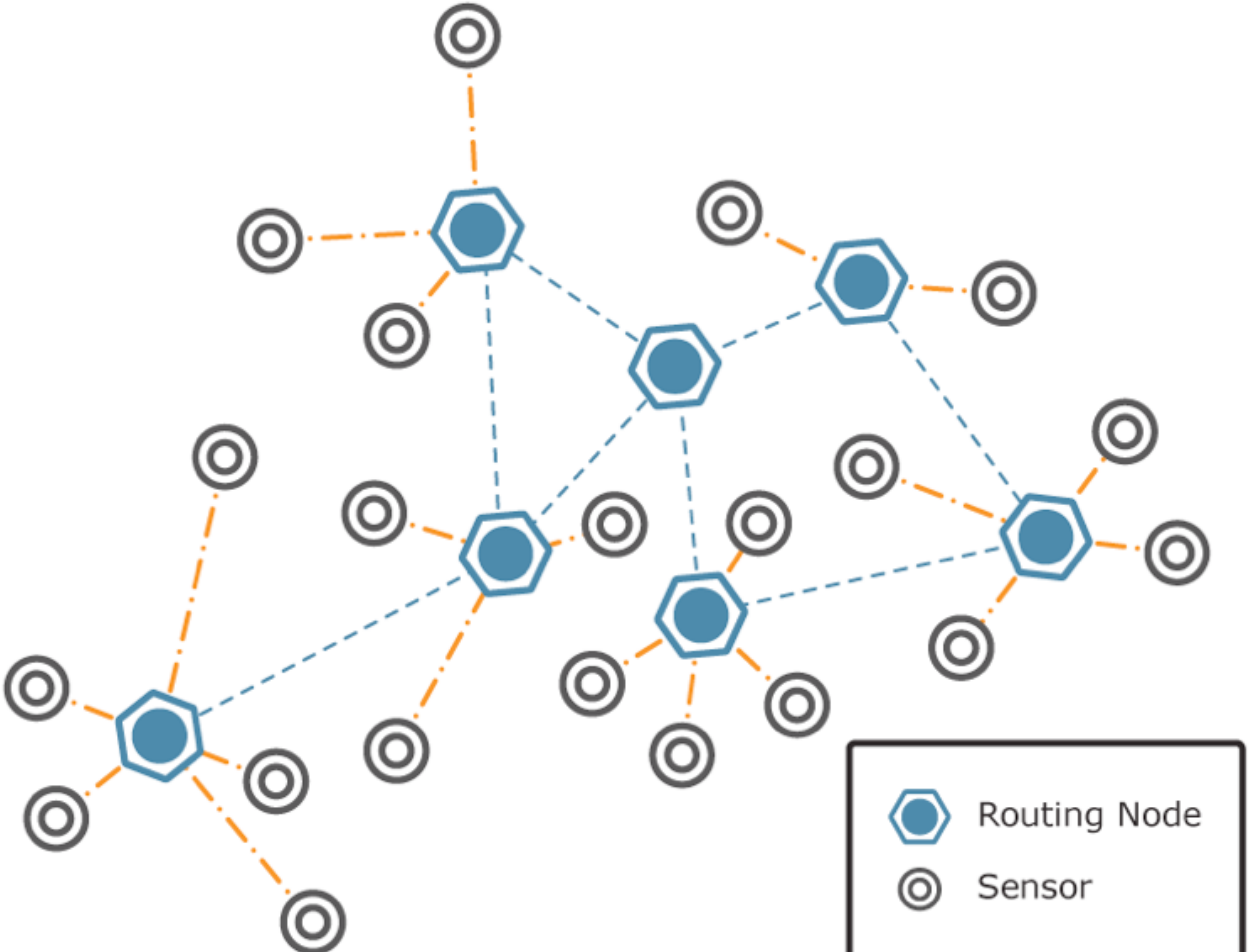
Motivation

- Critical in **battery-operated** devices.
- Critical in terms of **cost** (computer centers).
- Critical since energy is converted into **heat**.

Energy-aware design, sometimes called energy-efficient design, is the design of a system to meet a given performance constraint with the minimum energy consumption.

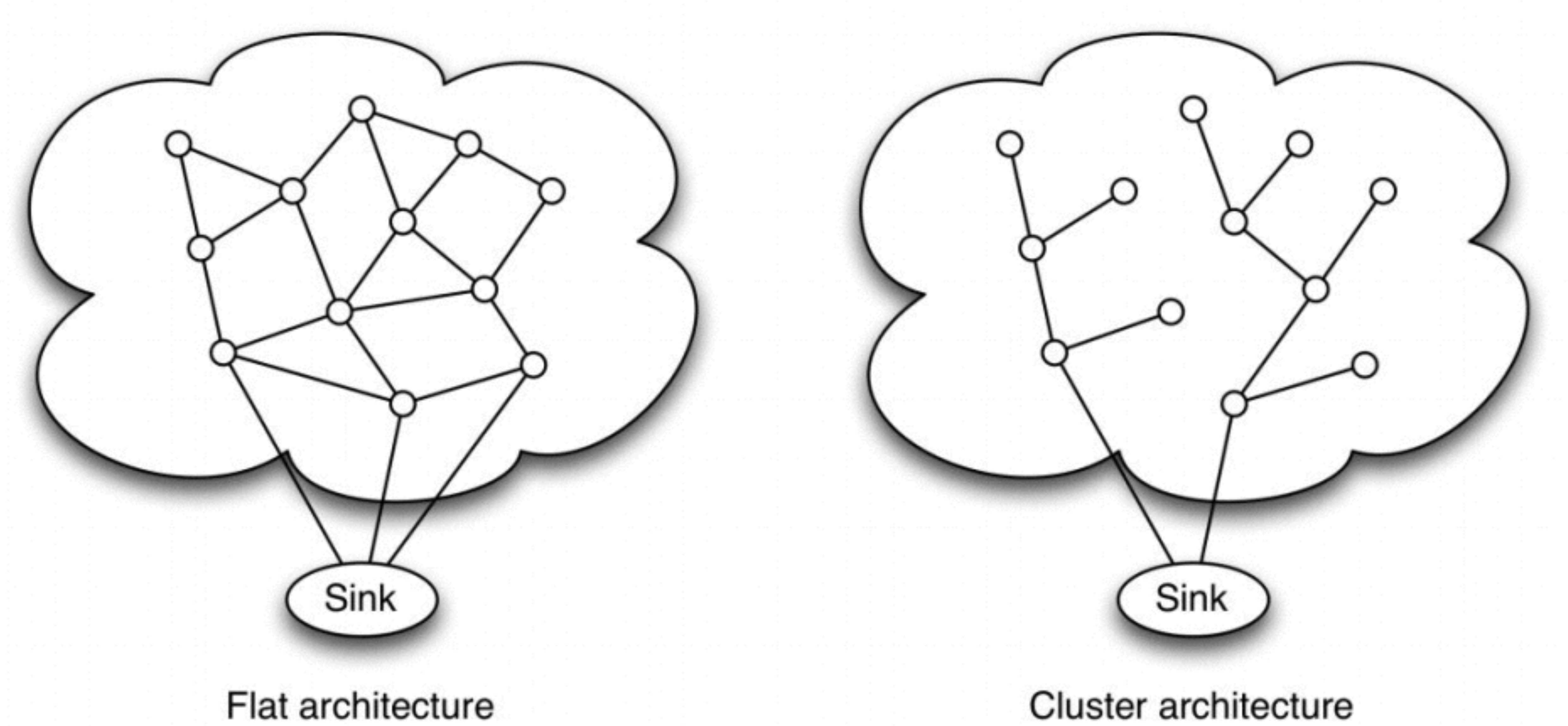
How

- Algorithm: scheduling, power-down strategies
- Data management: memory-aware software optimization, routing protocol
- Architecture: instruction set selection, dynamic voltage and frequency scaling
- Virtualization: power saving of corporate data centers
- Circuit: device sizing, exploiting of transistor stacking to reduce leakage power



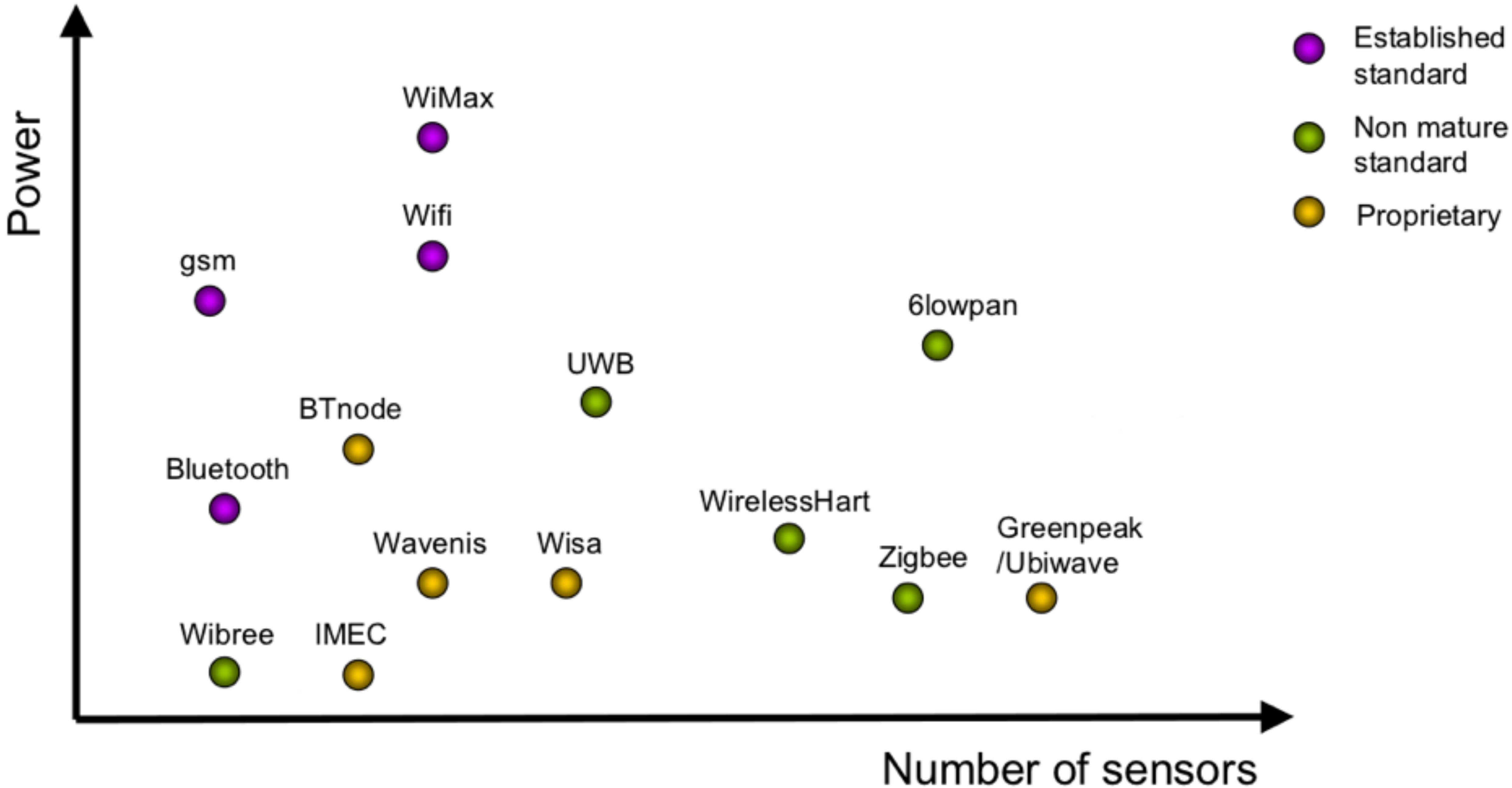
Where: Wireless Sensor Network

WSN



Where: Wireless Sensor Network Topology

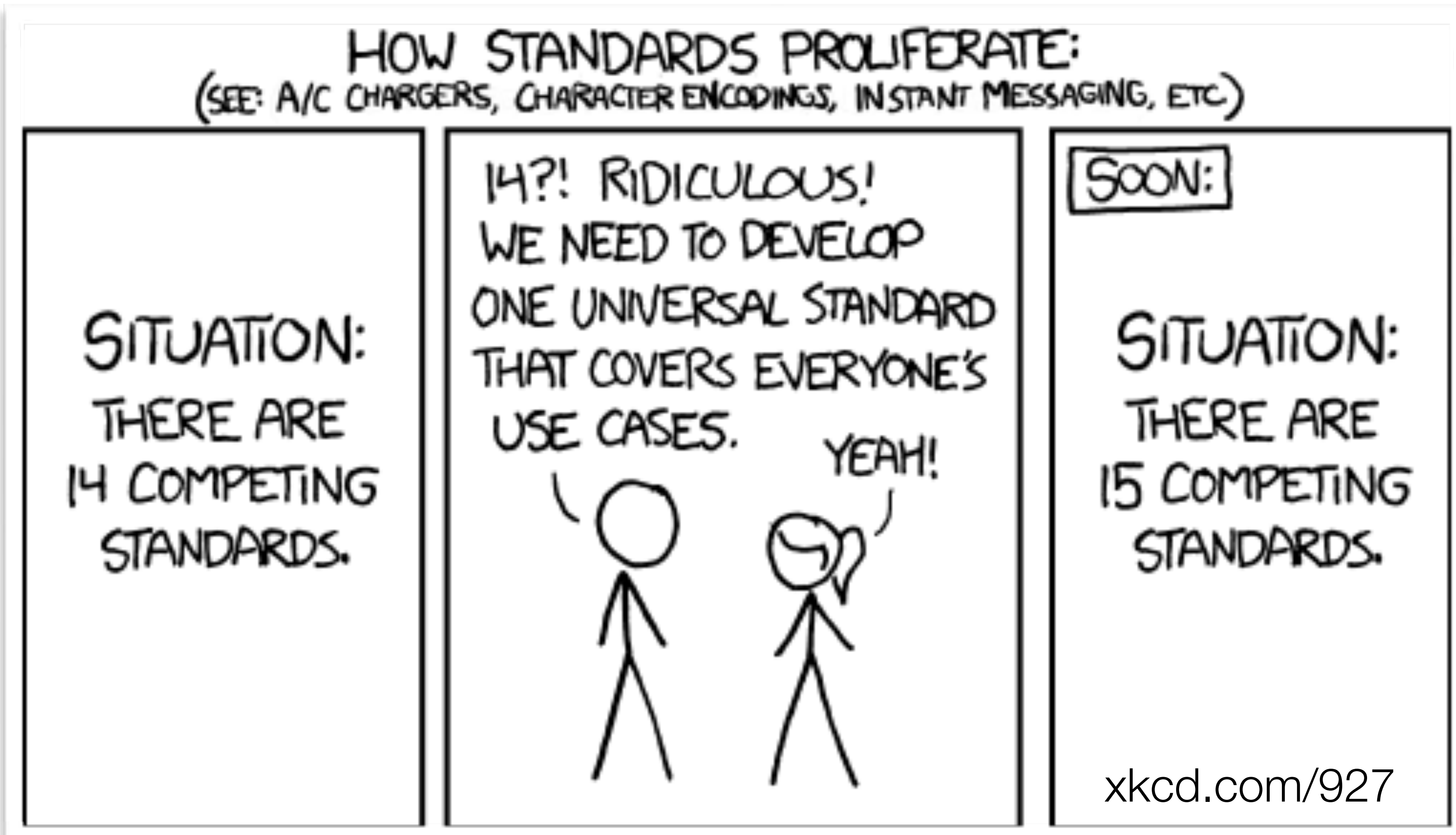
WSN



Network

Standard?

Power



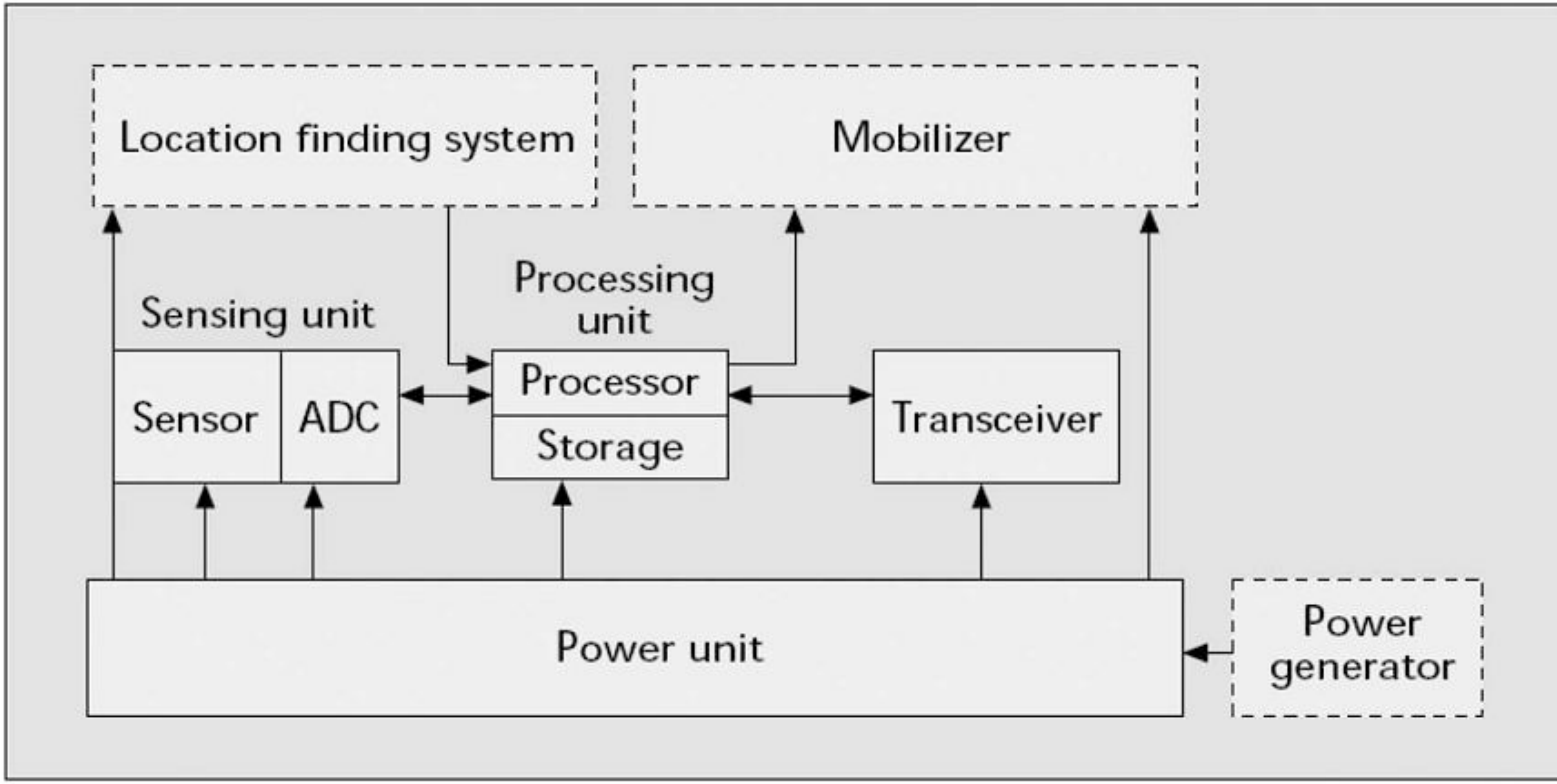
Established standard

Non mature standard

Proprietary

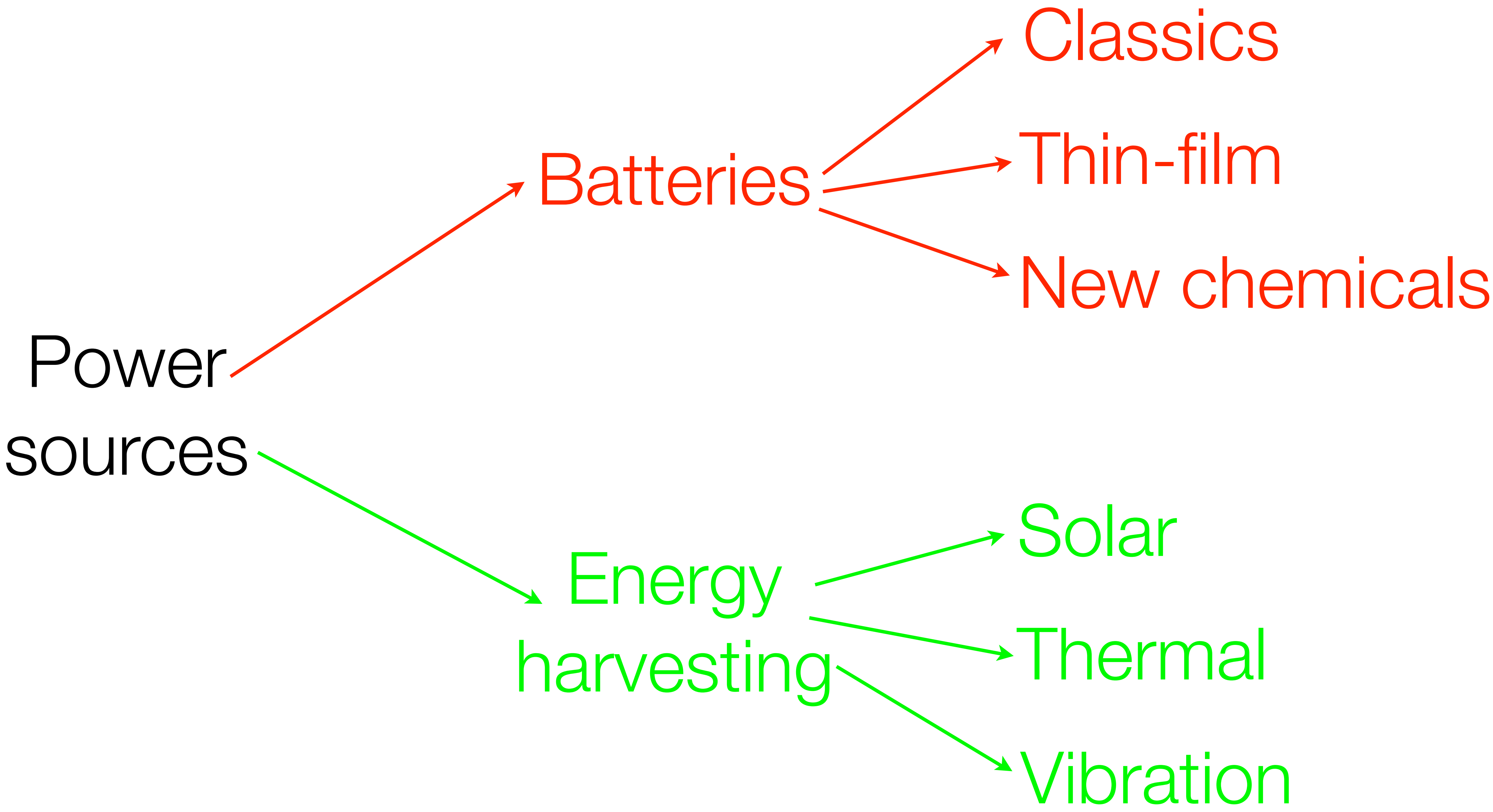
Number of sensors

Network | Standard?



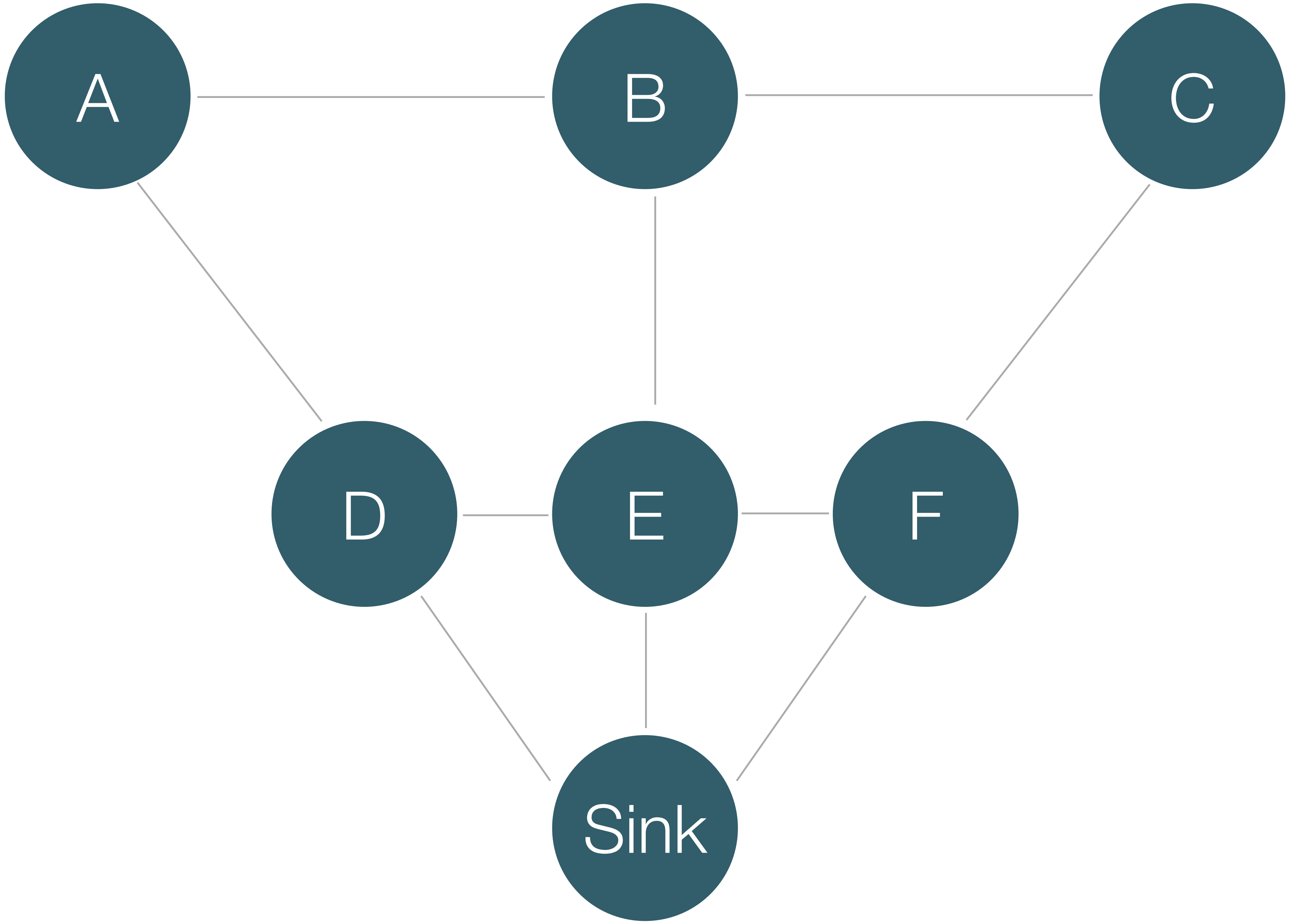
Where: Sensor Node

Hardware

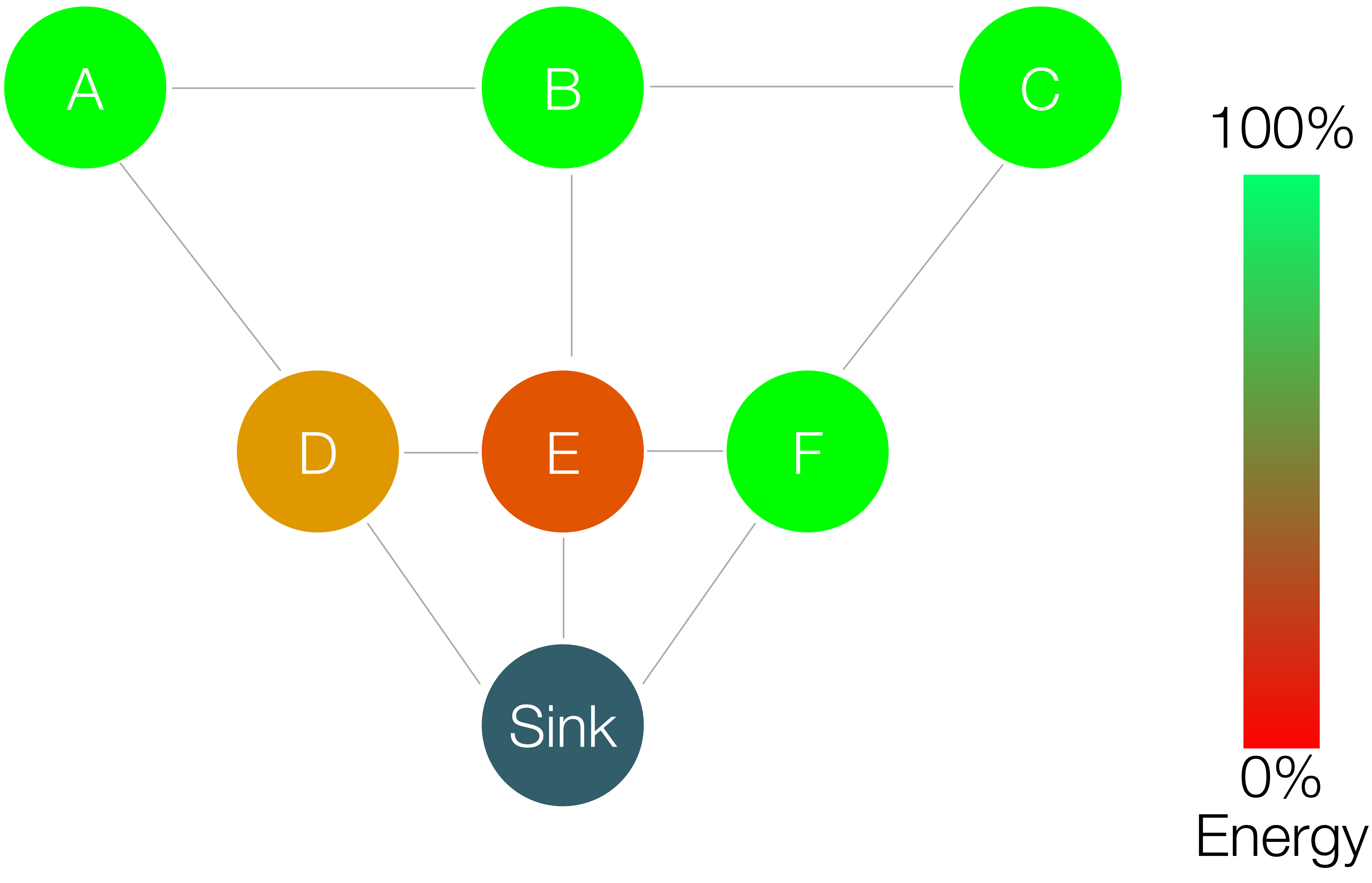


Where: Sensor Node | Power Source

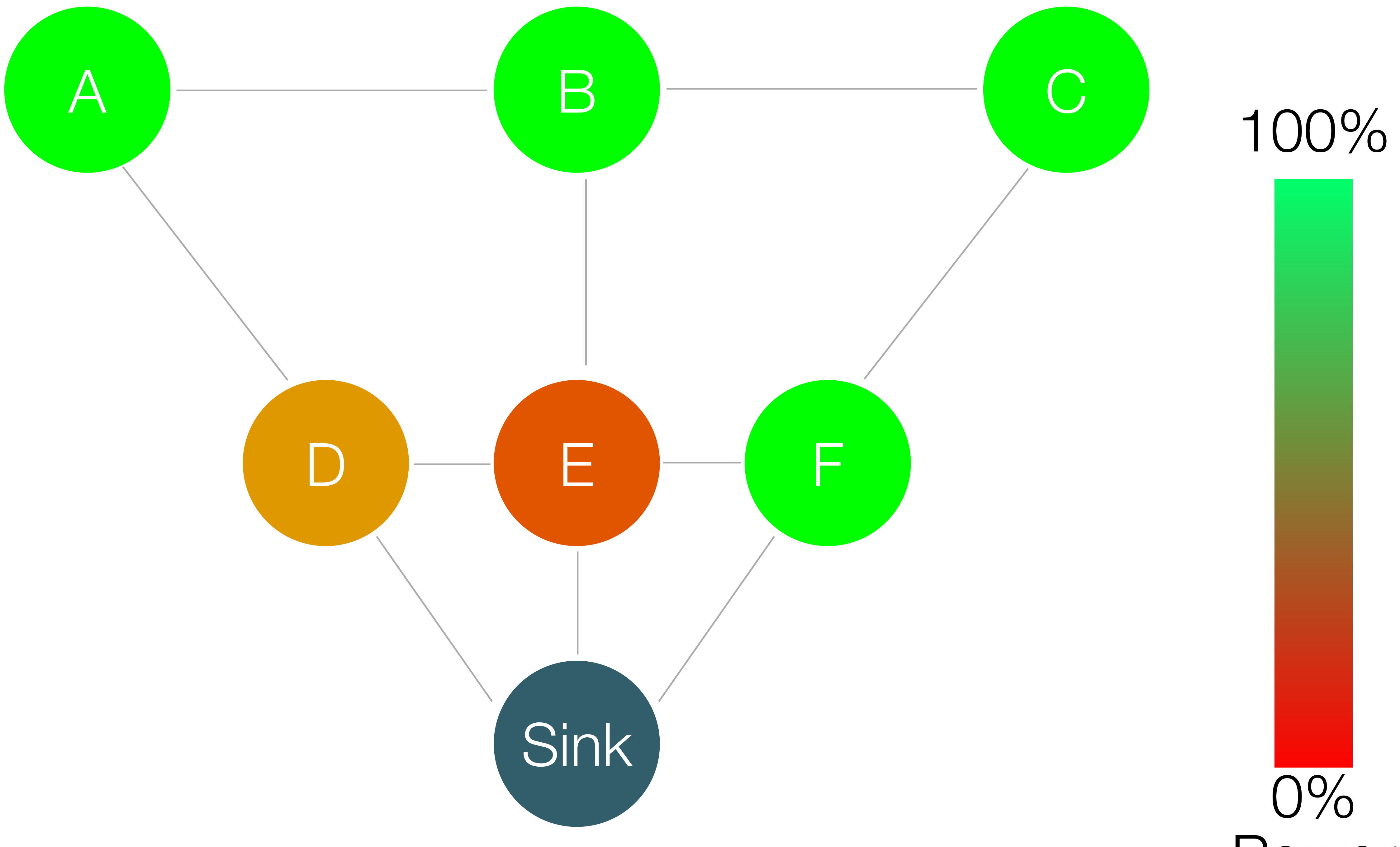
“Infinite” energy: shortest path



Battery operated: prolong network lifetime



EH operated: optimize routing based on power rather then energy



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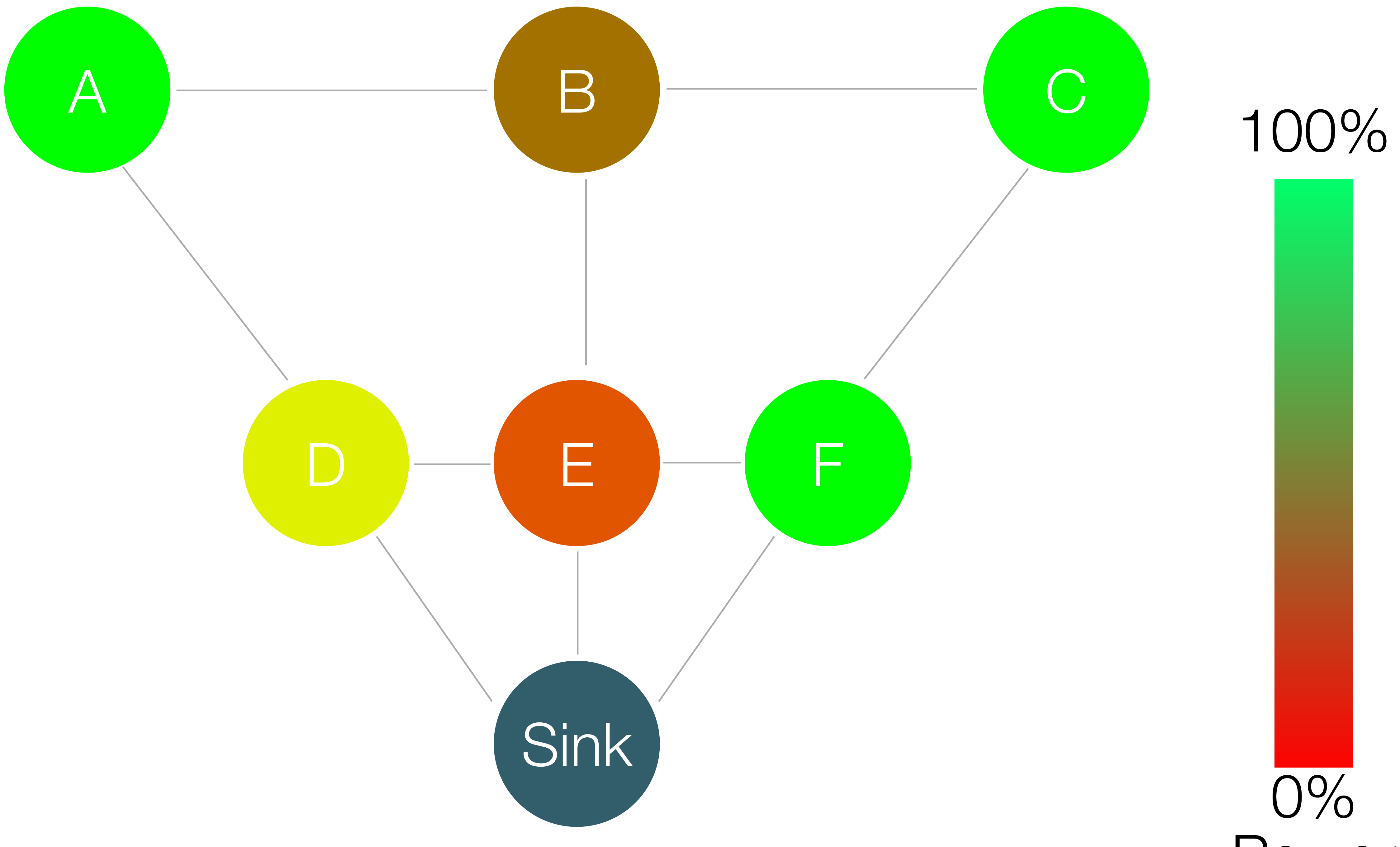
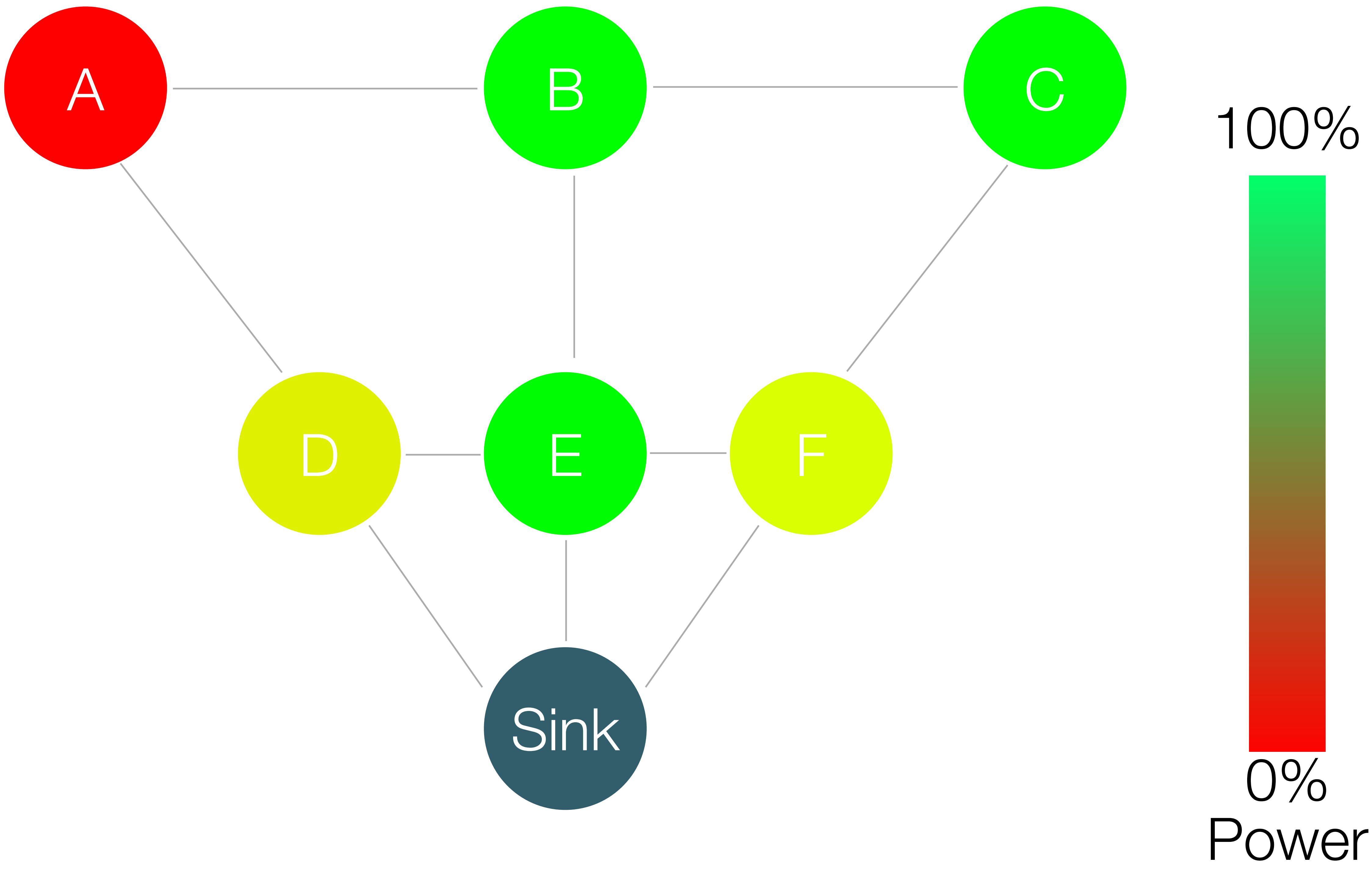
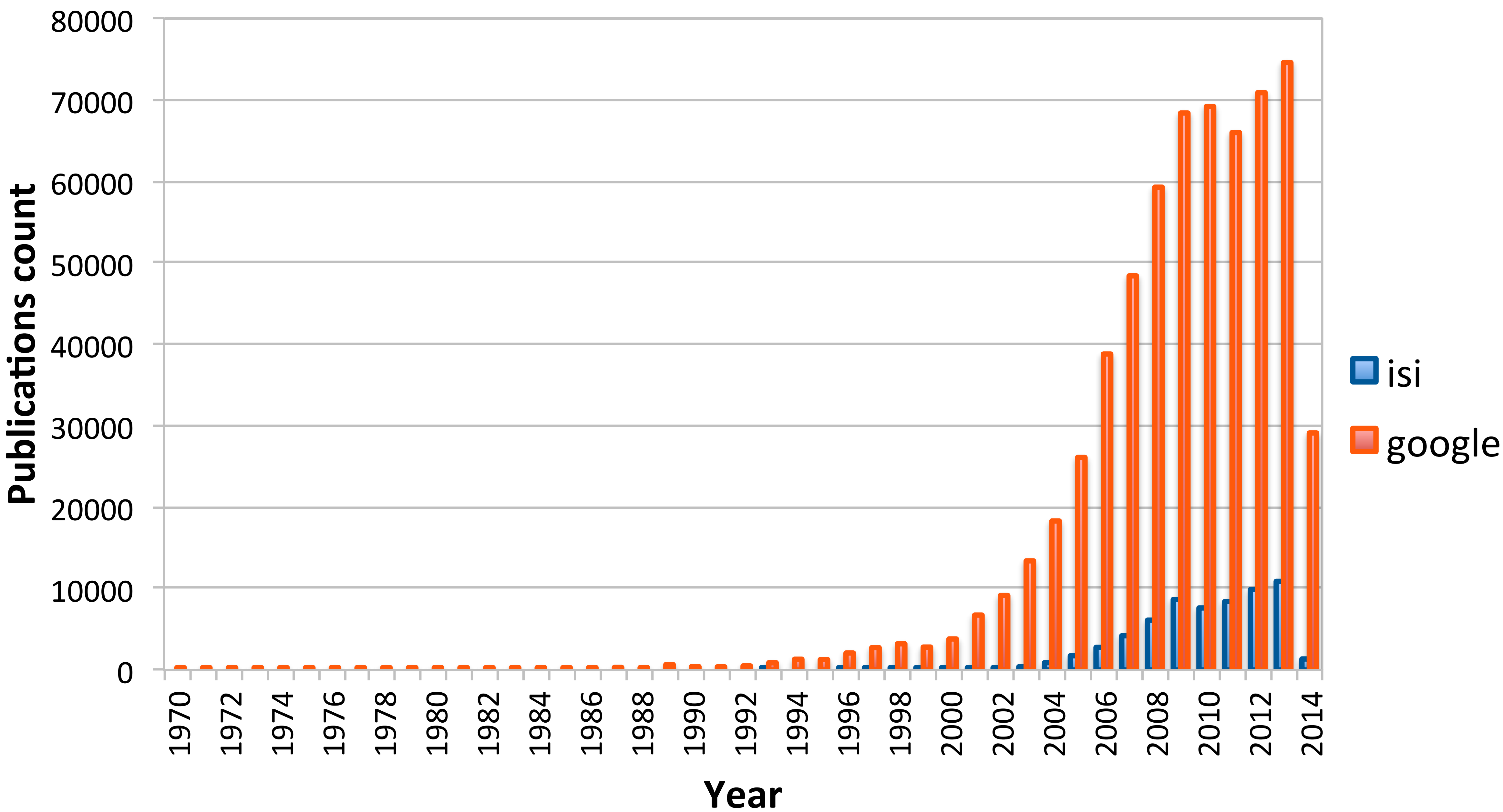
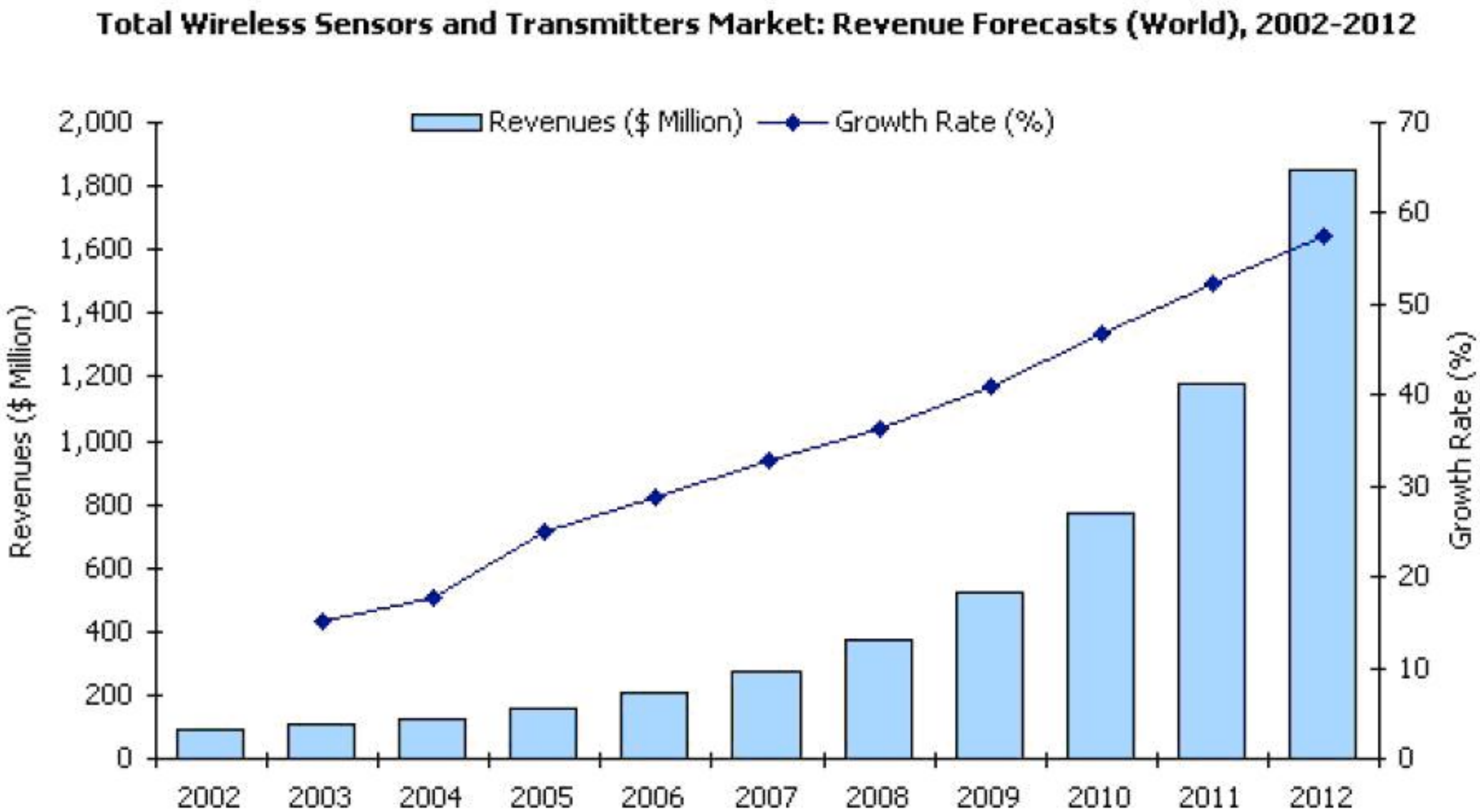


EH operated: optimize routing based on power rather then energy





Why? | scientific interest



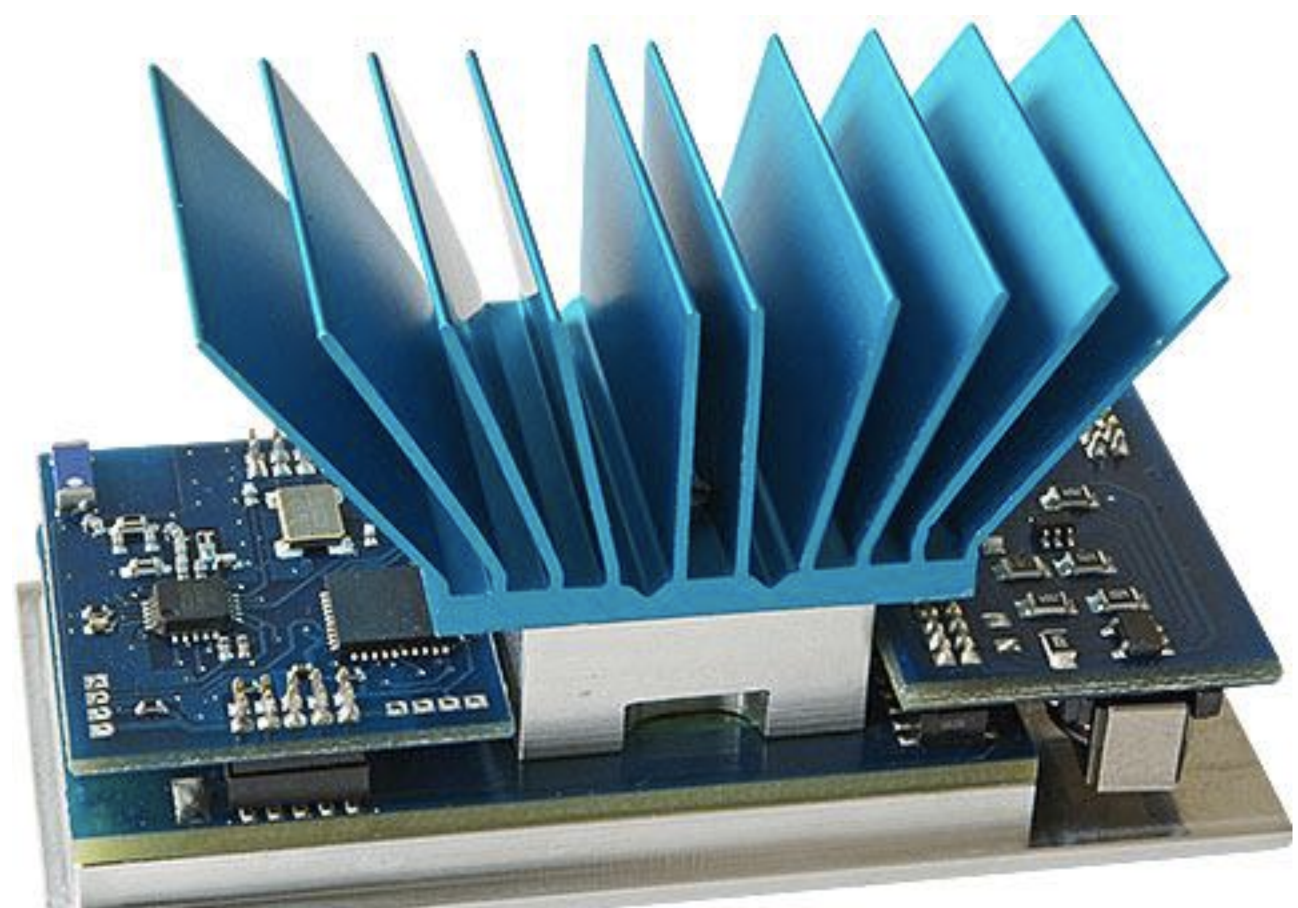
Frost & Sullivan

Why? | investors interest

So?

- Energy saving in WSN
- Energy consumption measurement
- Energy consumption modelling
- Energy awareness: application example

ENERGY SAVING IN WSN



micropelt TE-Power PLUS

Wireless Power Management

Dynamic Power Management in Wireless Sensor Networks

Amit Sinha

Anantha Chandrakasan
Massachusetts Institute of Technology

Power-aware methodology uses an embedded microoperating system to reduce node energy consumption by exploiting both sleep state and active power management.

designed, additional energy savings can be attained by using dynamic power management (DMP) where the sensor node is shut down if no events occur.[3] Such event-driven power consumption is critical to maximum battery life. In addition, the node should have a graceful energy-quality scalability so that the mission lifetime can be extended if the application demands, at

Dynamic Power Management

power-aware methodology

Power down mechanism

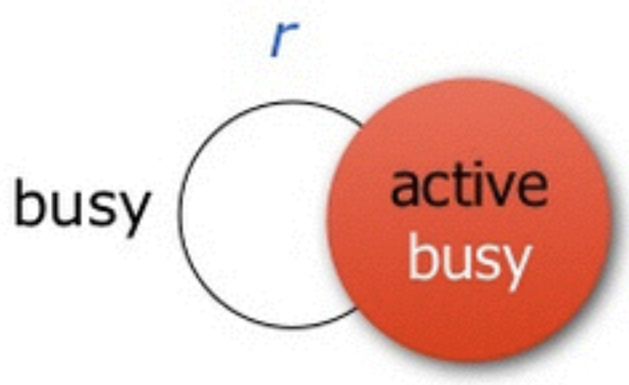
A system in idle state can be transitioned to **low power modes**

The goal is to develop transition schedules in order to minimise **energy consumption**

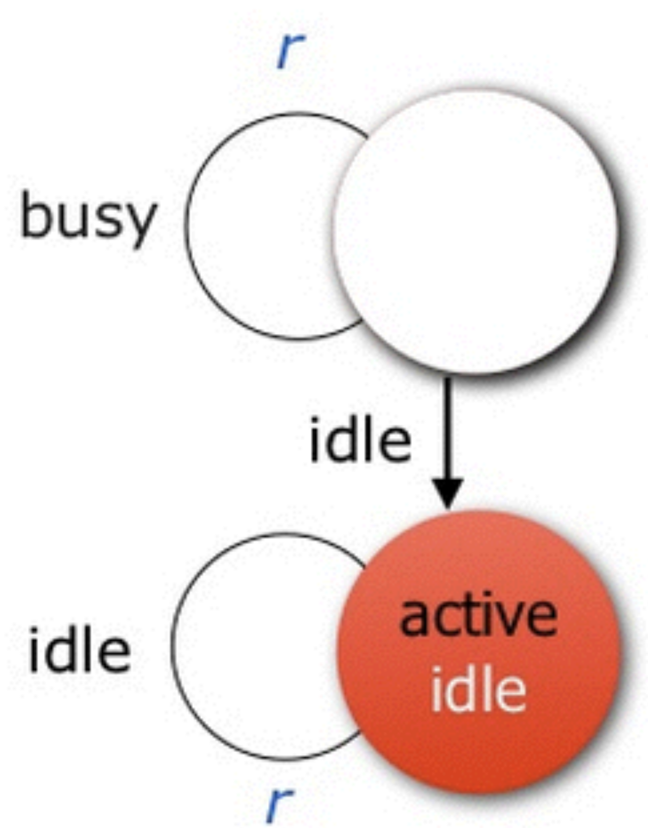
Power down mechanism:

- Two states system: **ON** - **OFF**

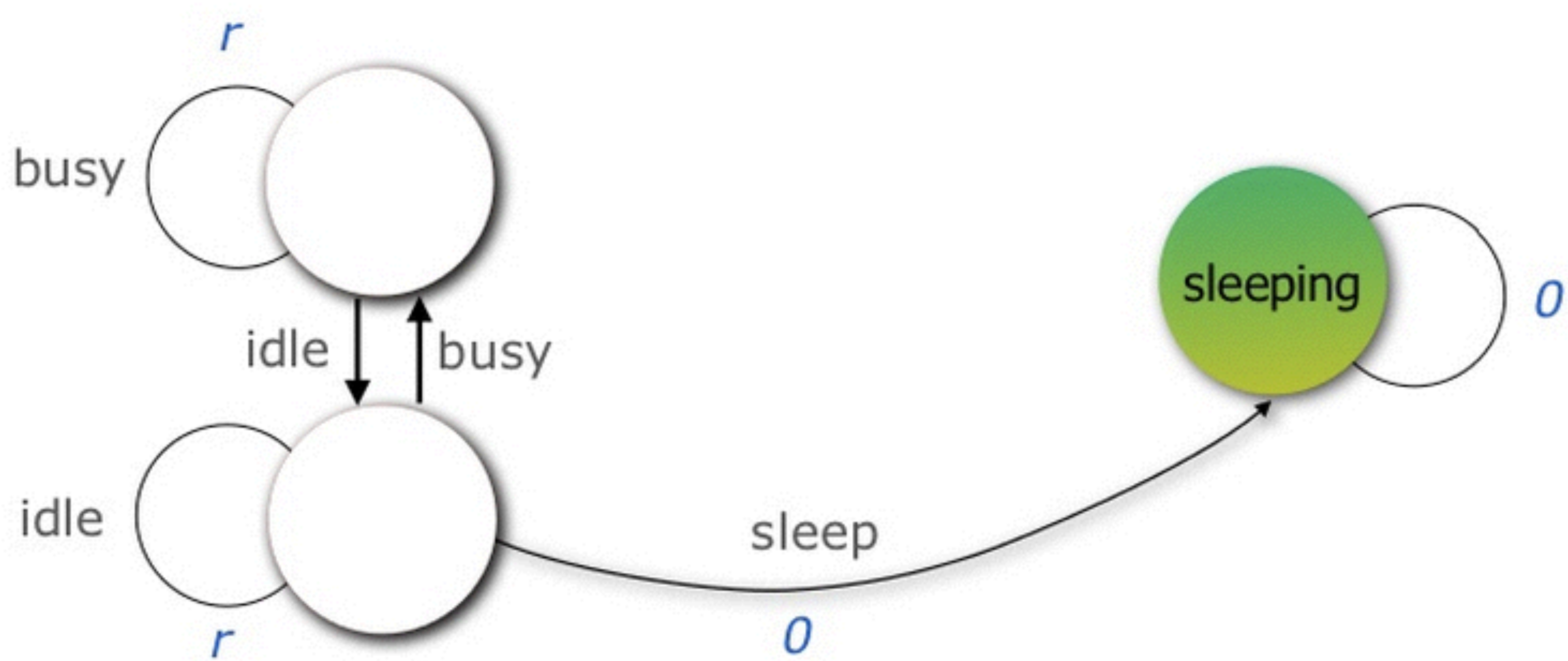
Power down mechanism: two states system



Power down mechanism: two states system

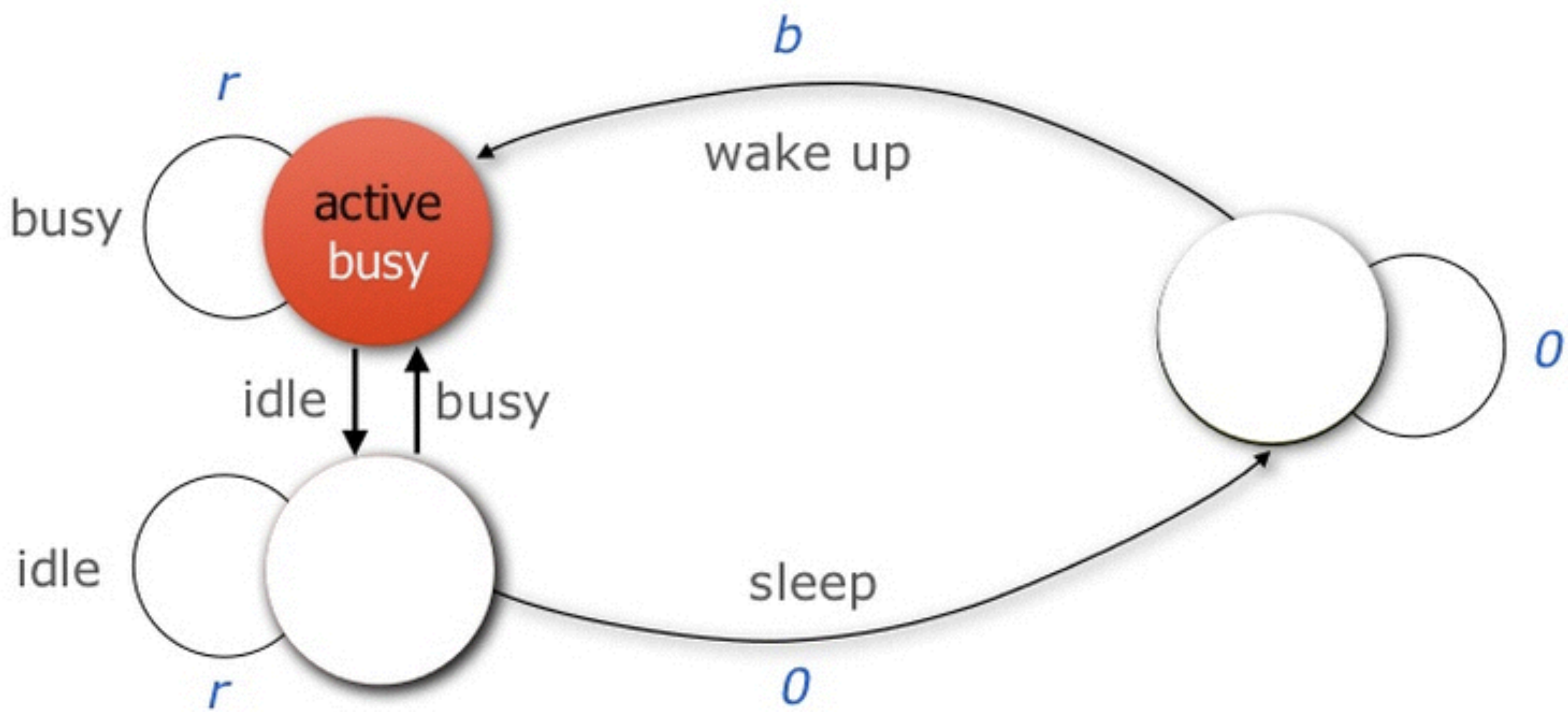


Power down mechanism: two states system

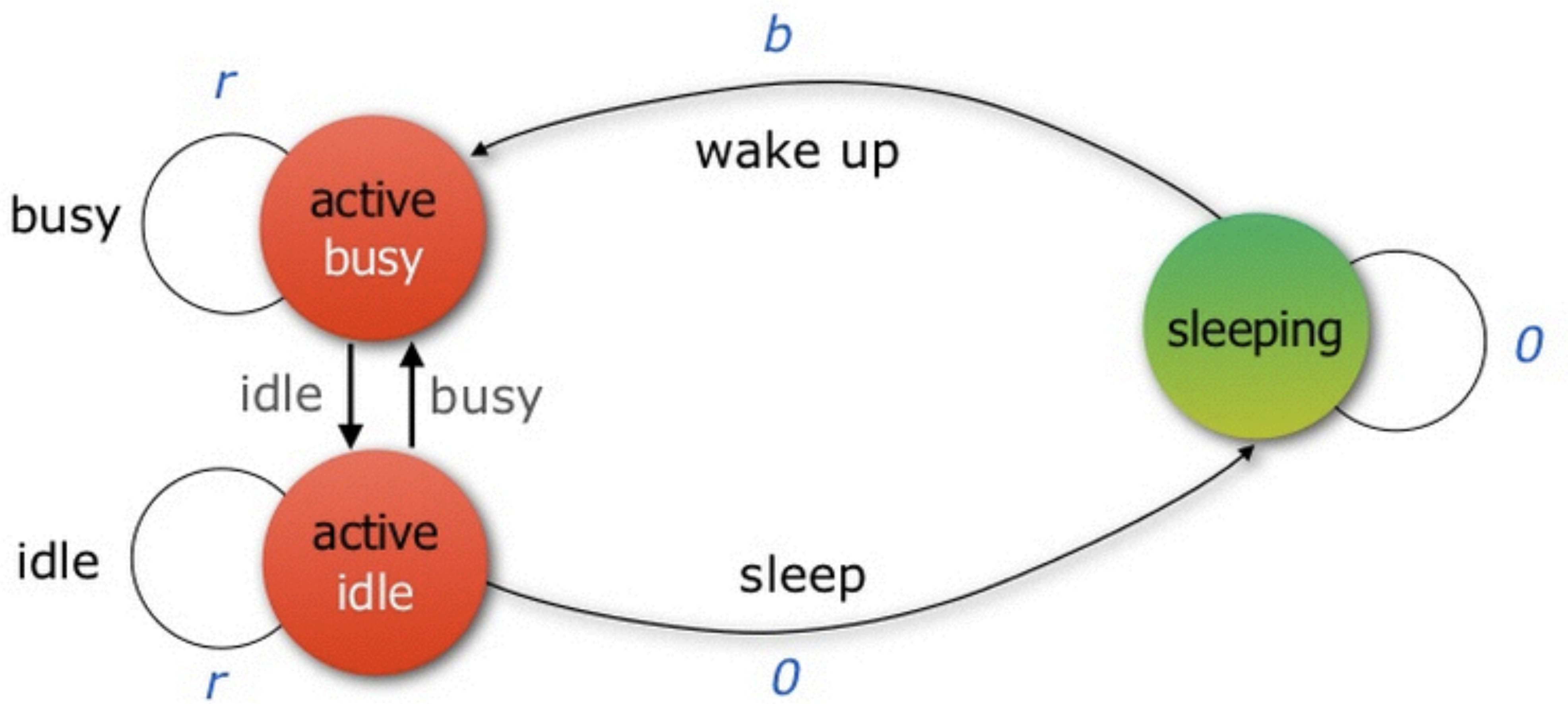


Cees Witteveen, Energy-Efficient Algorithms

Power down mechanism: two states system



Power down mechanism: two states system



Problem: determine when to transition to the sleep state in order to minimize energy consumption.

Power down mechanism

A system in idle state can be transitioned to **low power modes**

The goal is to develop transition schedules in order to minimise **energy consumption**

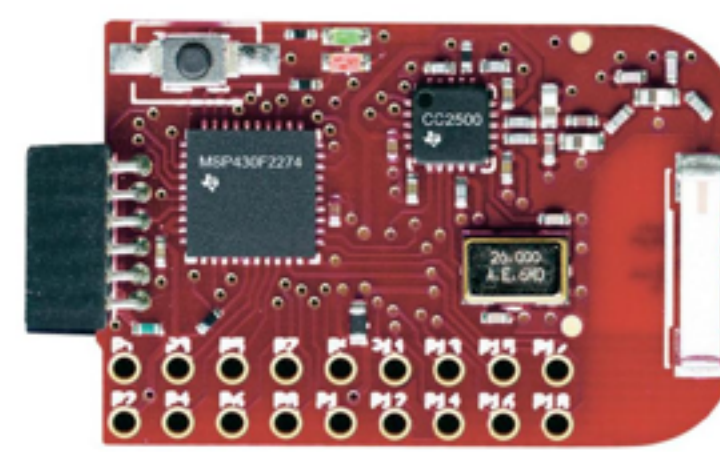
Power down mechanism:

- Two states system

- Multiple states system

Power down mechanism: msp430

- **Active Mode** (AM) - Everything is turned on, except perhaps for some peripherals
- **LPM0** - CPU and MCLK are shutoff
- **LPM1** - CPU and MCLK are off, DCO and DC generator are disabled if the DCO is not used for SMCLK
- **LPM2** - CPU, MCLK, SMCLK and DCO are disabled, while DC generator is still enabled
- **LPM3** - CPU, MCLK, SMCLK, DCO and DC generator are disabled
- **LPM4** - CPU and all clocks disabled



Power down mechanism: msp430

- **Active Mode** (AM) - Everything is turned on, except perhap
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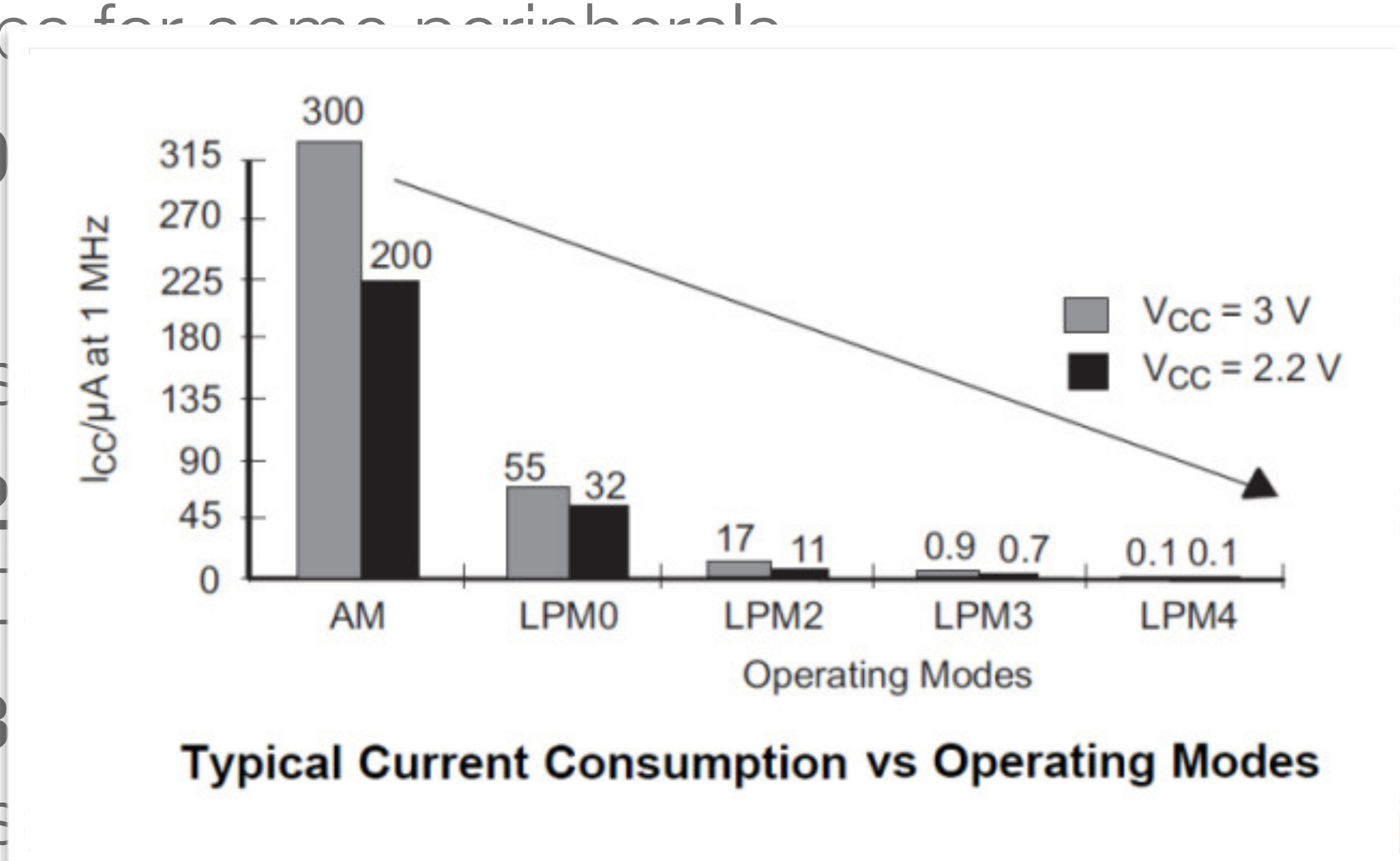
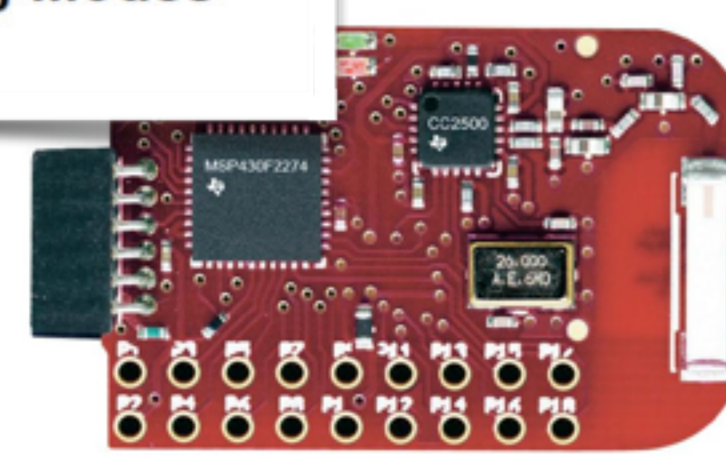
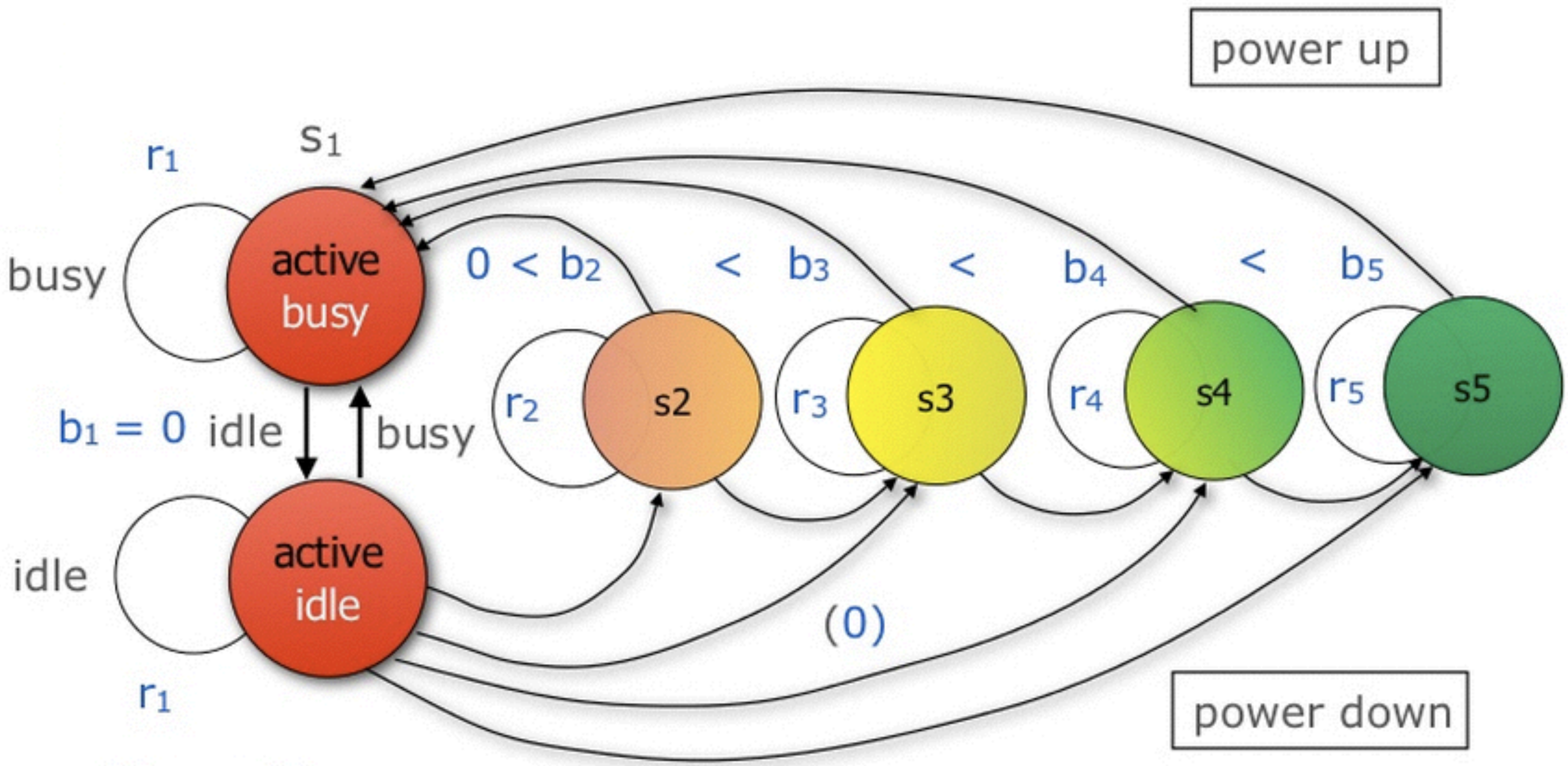


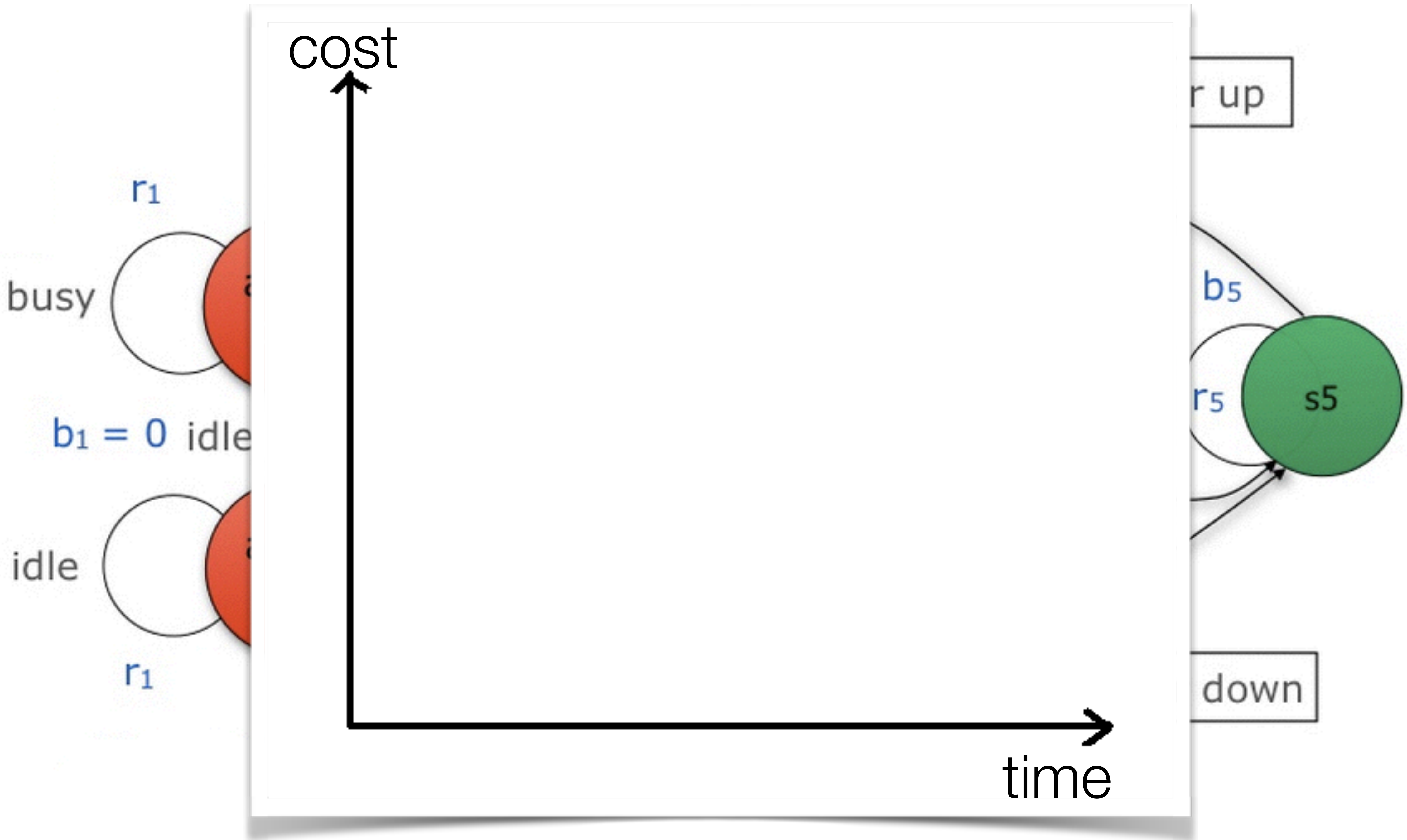
Typical Current Consumption vs Operating Modes



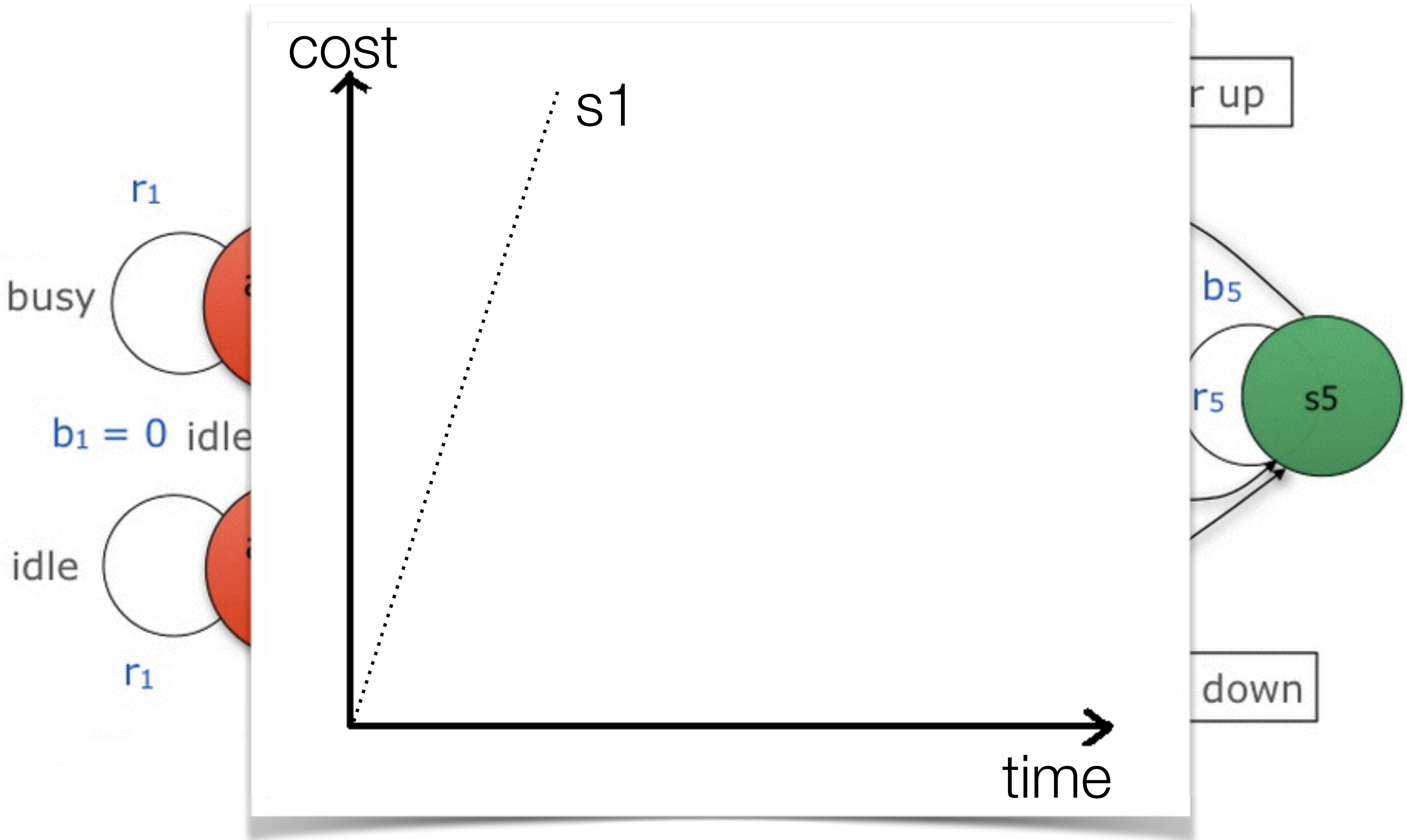
Power down mechanism: multiple states system



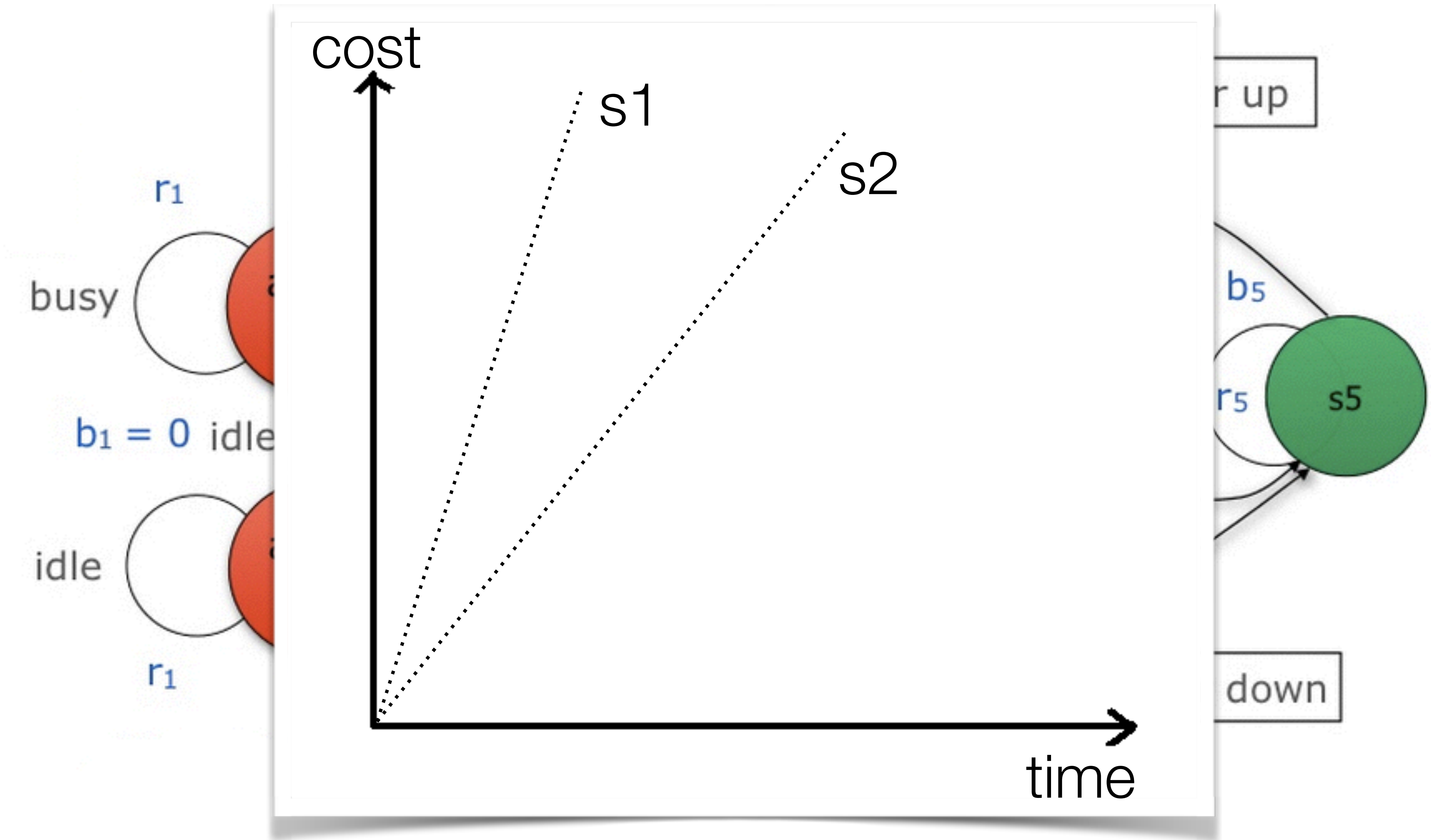
Power down mechanism: multiple states system



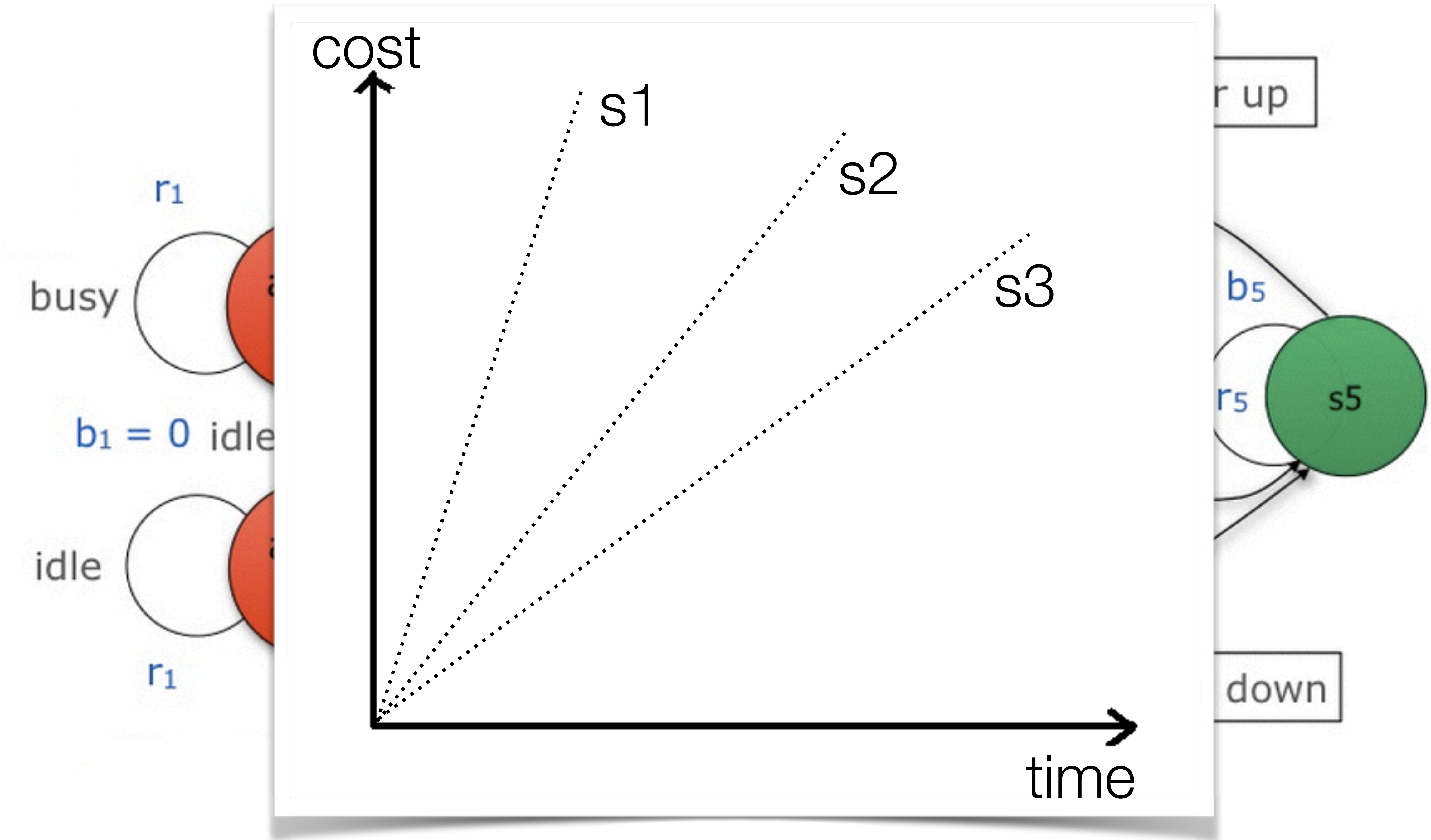
Power down mechanism: multiple states system



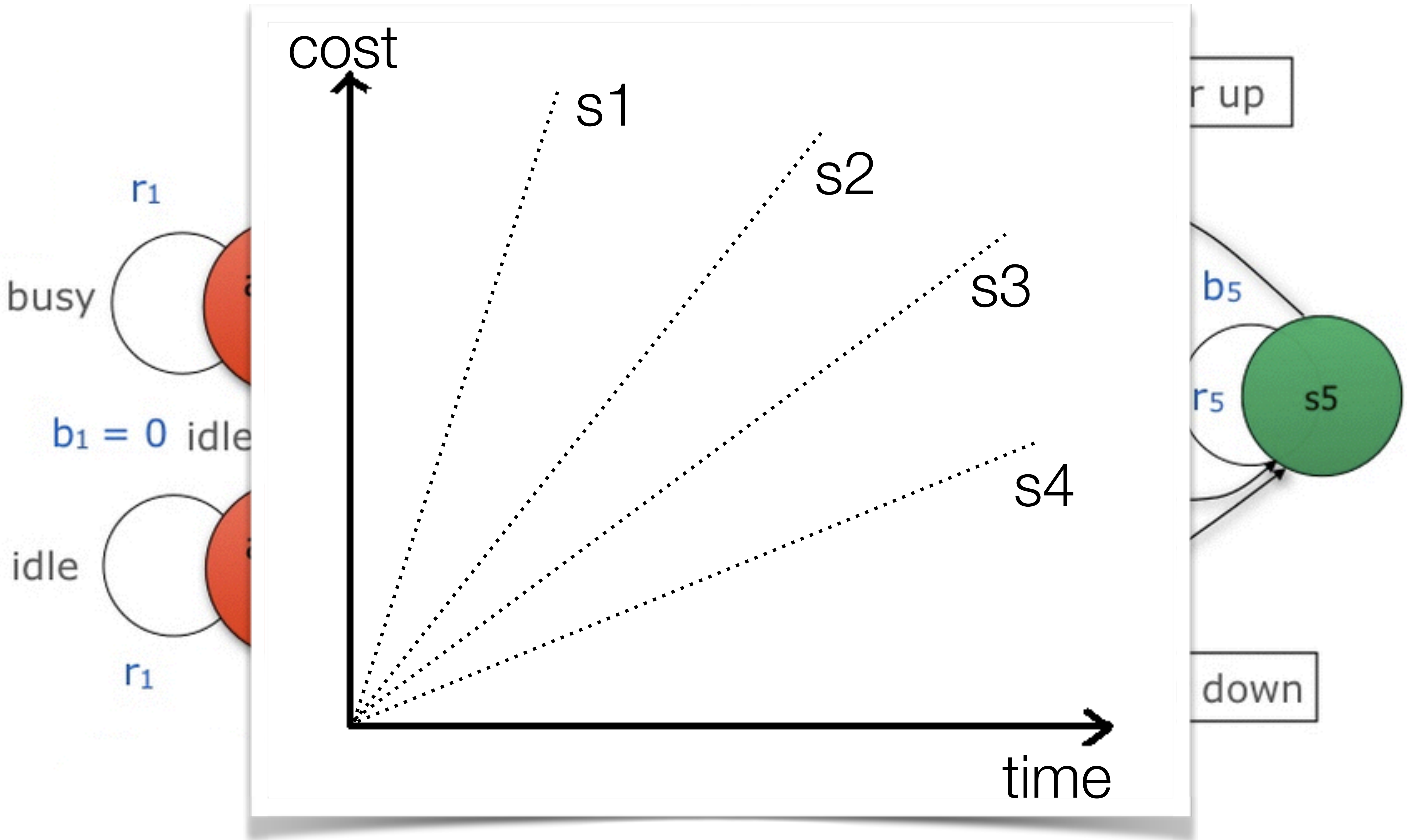
Power down mechanism: multiple states system



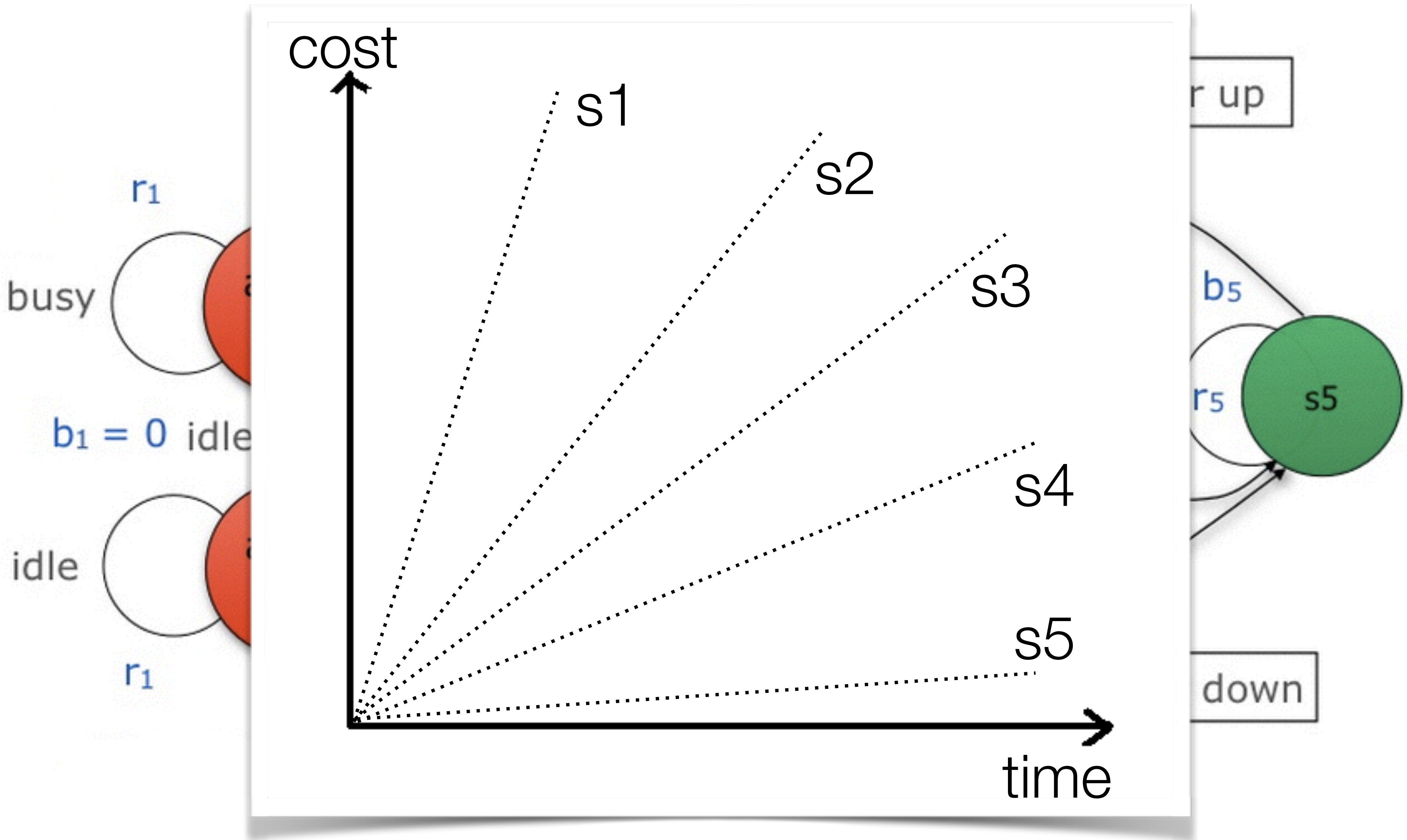
Power down mechanism: multiple states system



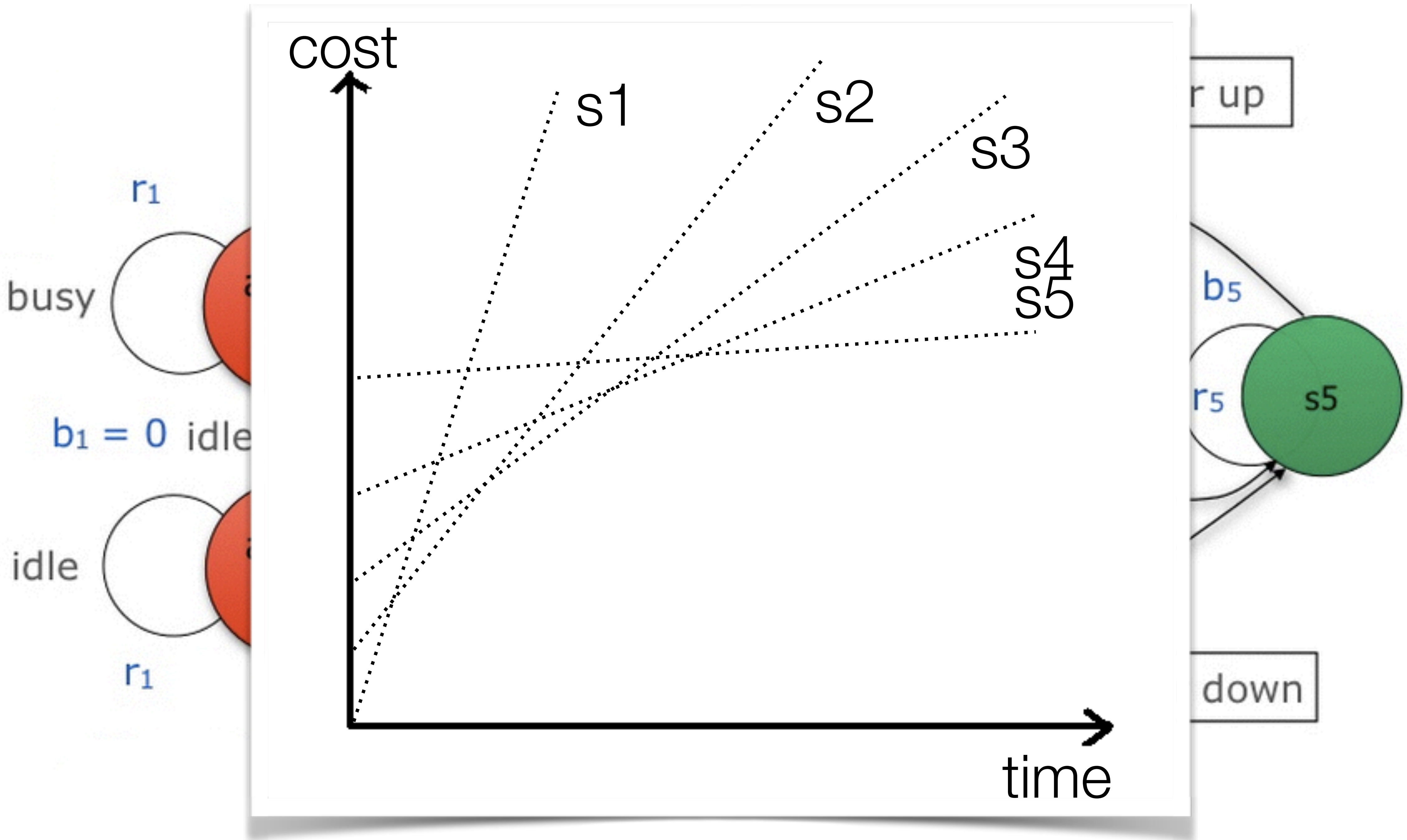
Power down mechanism: multiple states system



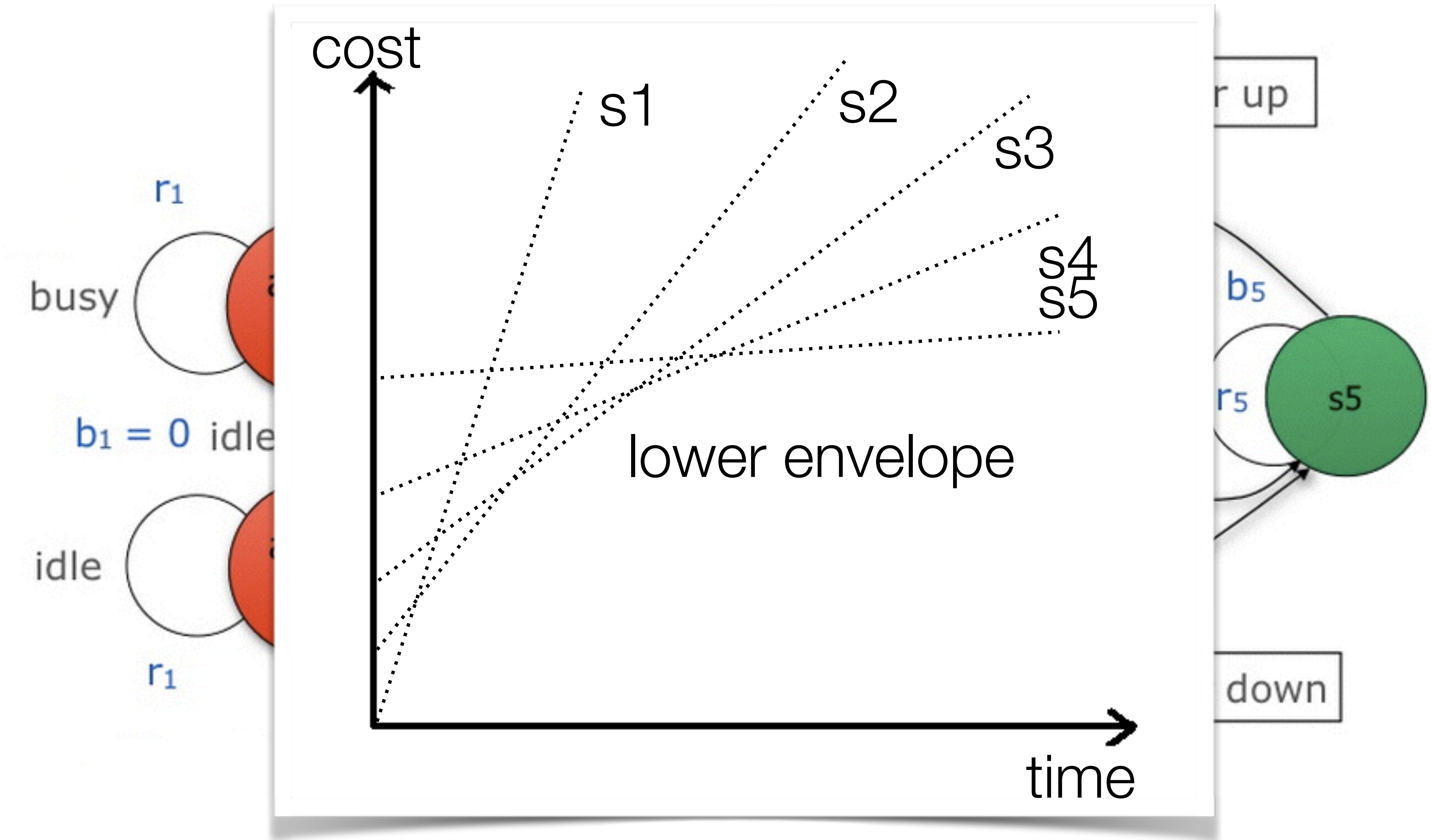
Power down mechanism: multiple states system



Power down mechanism: multiple states system



Power down mechanism: multiple states system



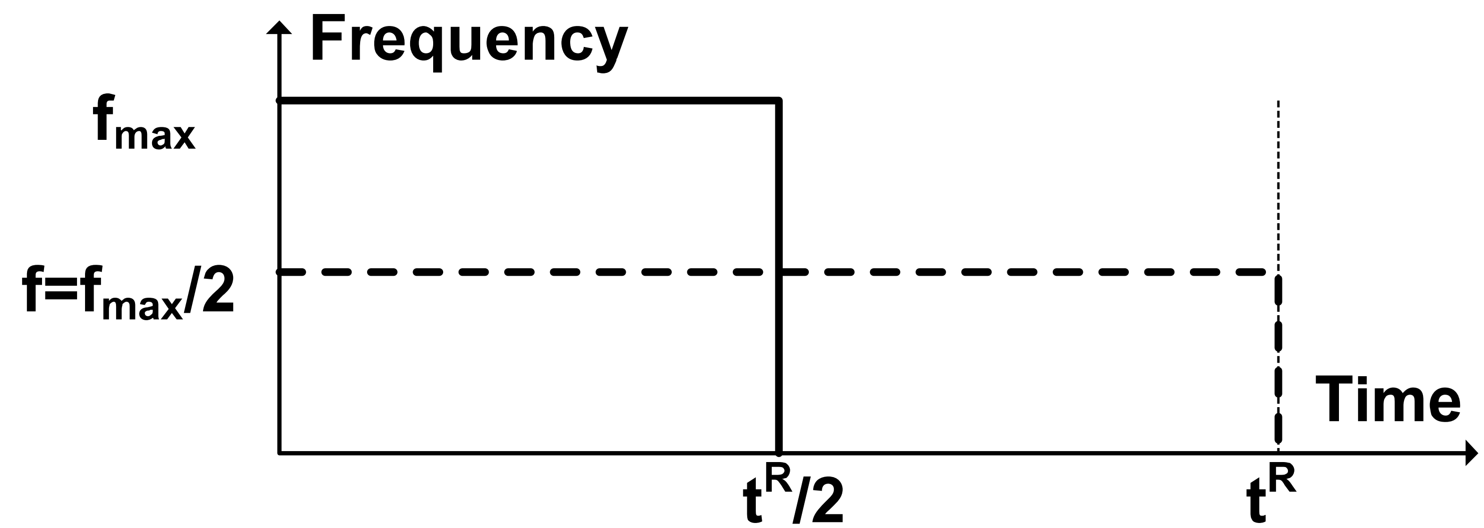
Dynamic Voltage and Frequency Scaling

$$P_{sw} = \frac{1}{2}\alpha C_L V_{dd}^2 f$$

- $\mathbf{P_{sw}}$ average switch power consumption
- α probability of output switch
- $\mathbf{C_L}$ load capacitance
- $\boldsymbol{f}$ clock frequency
- $\mathbf{V_{dd}}$ operating voltage

Dynamic Voltage and Frequency Scaling

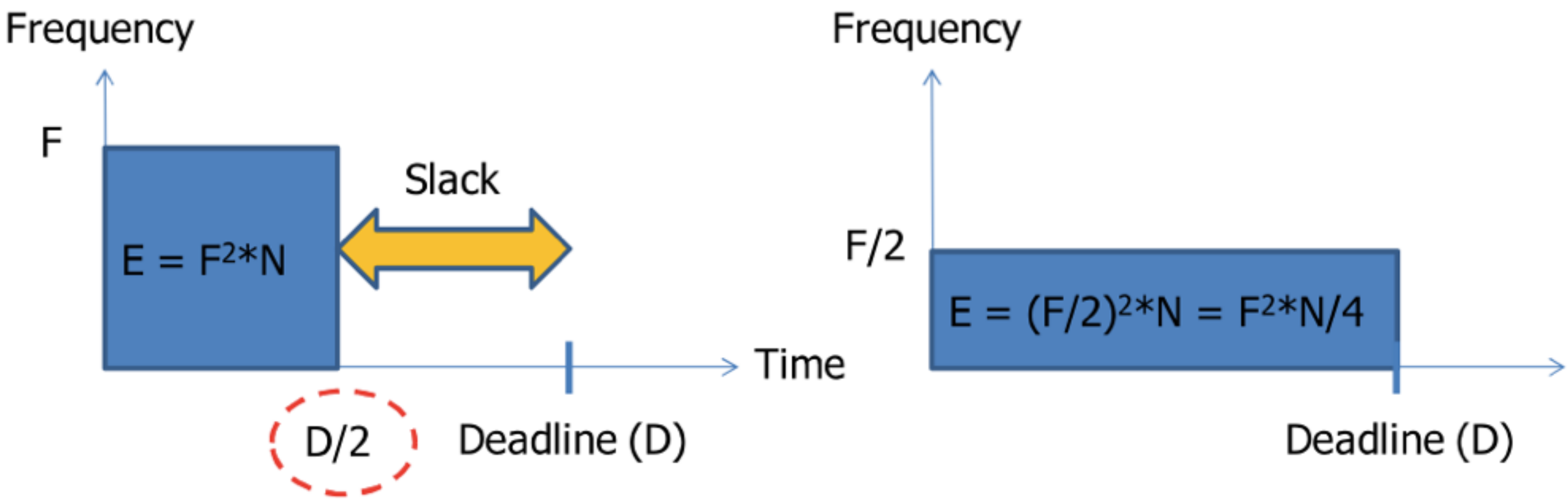
$$f \propto \frac{(V_{\mathrm{dd}} - V_{\mathrm{th}})^{\alpha}}{V_{\mathrm{dd}}}$$



- V_{dd} operating voltage
- V_{th} threshold voltage
- α is a measure of velocity saturation ($1 \leq \alpha \leq 2$)

$$P_{\mathrm{dyn}} \propto f^{3}$$

Dynamic Voltage and Frequency Scaling



- **N**: number of steps to complete the task

Media Access Control (MAC) Layer

Transmission and reception are energy expensive operations

Objective:

- minimise worthless transmission

How:

- minimise collisions
- minimise cost of collisions

MAC Layer: MACA and MACAW

- **A** sends Ready-to-Send (**RTS**)
- **B** responds with Clear-to-Send (**CTS**)
- **A** sends **DATA PACKET**
- (**B** acknowledge with ACK)
- **RTS** and **CTS** announce the duration of the data transfer
- Nodes overhearing **RTS** keep quiet for some time to allow **A** to receive **CTS**
- Nodes overhearing **CTS** keep quiet for some time to allow **B** to receive data
- (**A** will retransmit **RTS** if no **ACK** is received)

P. Karn, “MACA - A new channel access method for packet radio”, in Proceedings of the ARRL CRRL Amateur Radio 9th Computer Networking Conference, Redondo Beach, CA, Apr. 1990, pp. 134-140.

V. Bharghavan, A. Demers, S. Shenkar, and L. Zhang, “MACAW: A media access protocol for wireless LANs”, in Proceedings of ACM SIGCOMM’94, London, UK, Sept. 1994, pp. 212-225.

MAC Layer: MACA and MACAW

- **A** sends Ready-to-Send (**RTS**)
- **B** responds with Clear-to-Send (**CTS**)
- **A** s
- (**B** a
- **RT**
- Noc ... eive **CT**
- Noc ... eive data

Error Rate	RTS-CTS-DATA	RTS-CTS-DATA-ACK
0	40.41	36.76
0.001	36.58	36.67
0.01	16.65	35.52
0.1	2.48	9.93

Table 4: The throughput, in packets per second, achieved by a single TCP data stream between a pad and a base station in the presence of noise.

- (**A** will retransmit **RTS** if no **ACK** is received)

P. Karn, "MACA - A new channel access method for packet radio", in Proceedings of the ARRL CRRL Amateur Radio 9th Computer Networking Conference, Redondo Beach, CA, Apr. 1990, pp. 134-140.

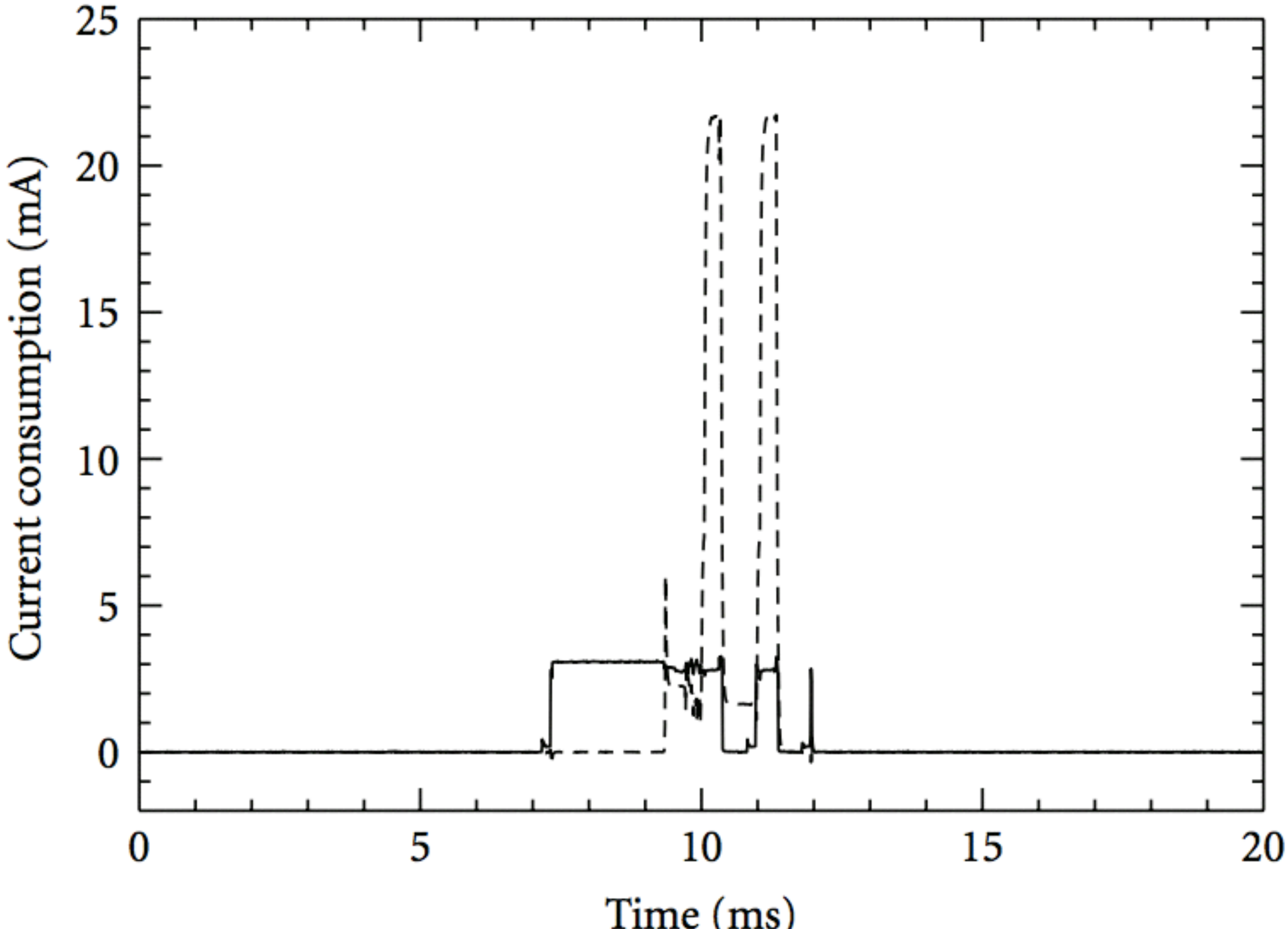
V. Bharghavan, A. Demers, S. Shenkar, and L. Zhang, "MACAW: A media access protocol for wireless LANs", in Proceedings of ACM SIGCOMM'94, London, UK, Sept. 1994, pp. 212-225.

Physical level: frame filtering

The IEEE 802.15.4 standard defines three possible methods to perform the assessment:

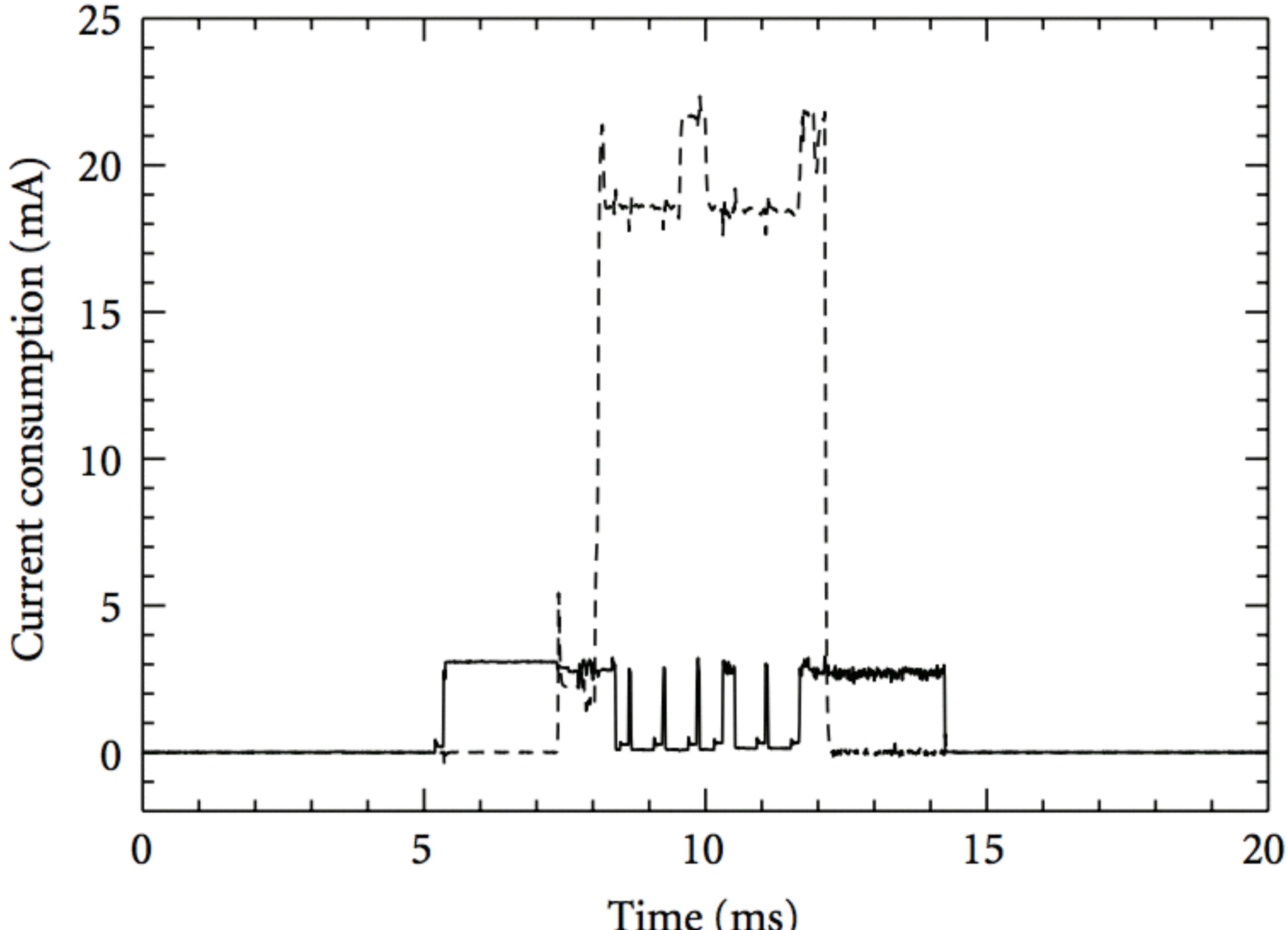
- Energy above threshold. If the energy detected is above a fixed threshold the CCA shall report a busy medium.
- Carrier sense only. This method checks for a signal with modulation and spreading characteristics of the IEEE 802.15.4. In this case the signal may be above or below the threshold.
- Carrier sense with energy above the threshold. This is a combination of the previous methods checking both signal characteristics and energy.

Channel Clear Assessment



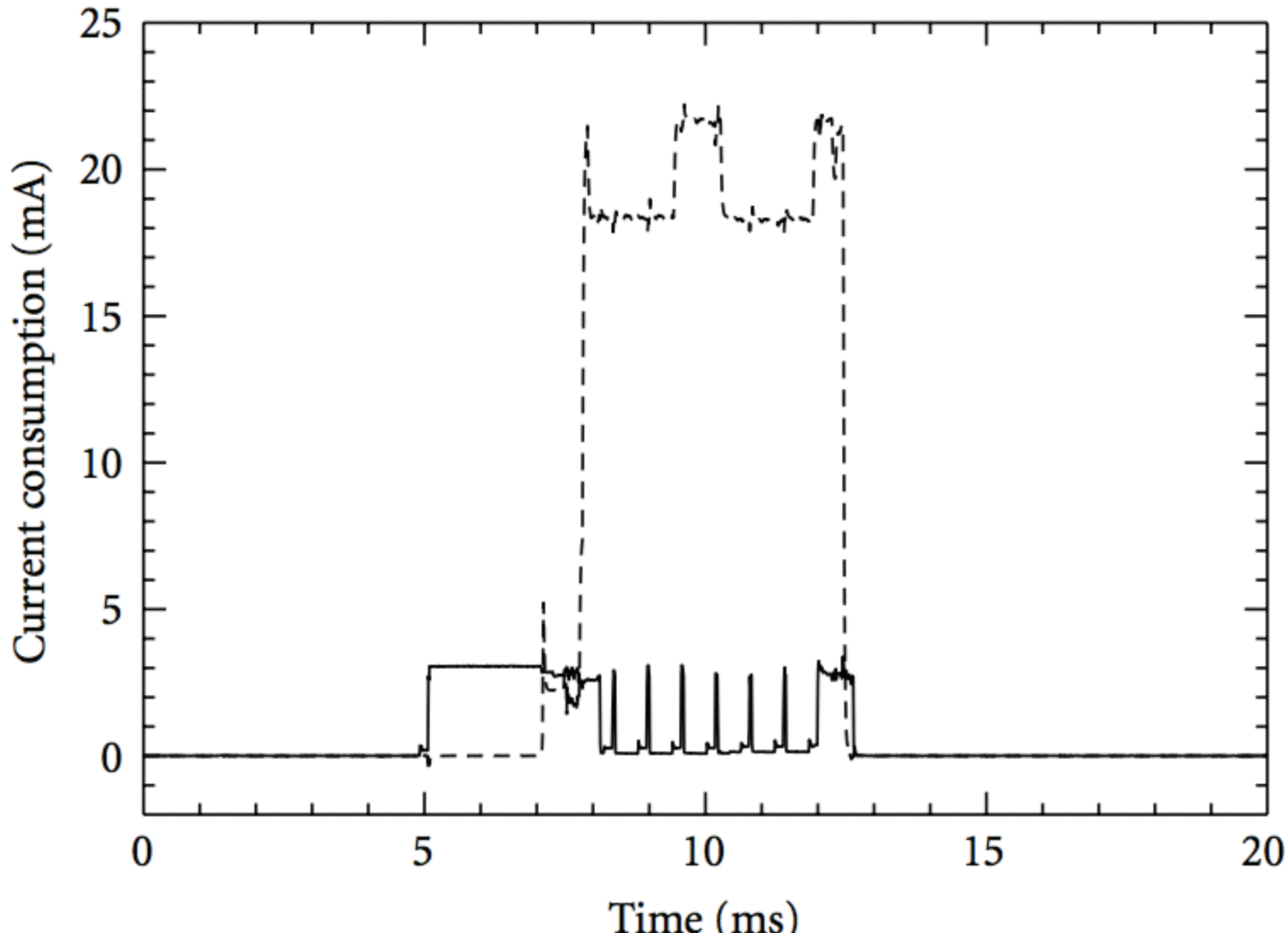
Lattanzi, Emanuele, and Alessandro Bogliolo. "VirtualSense: A Java-Based Open Platform for Ultra-Low-Power Wireless Sensor Nodes." International Journal of Distributed Sensor Networks 2012 (2012)

Broadcast reception and processing



Lattanzi, Emanuele, and Alessandro Bogliolo. “VirtualSense: A Java-Based Open Platform for Ultra-Low-Power Wireless Sensor Nodes.” International Journal of Distributed Sensor Networks 2012 (2012)

Broadcast reception



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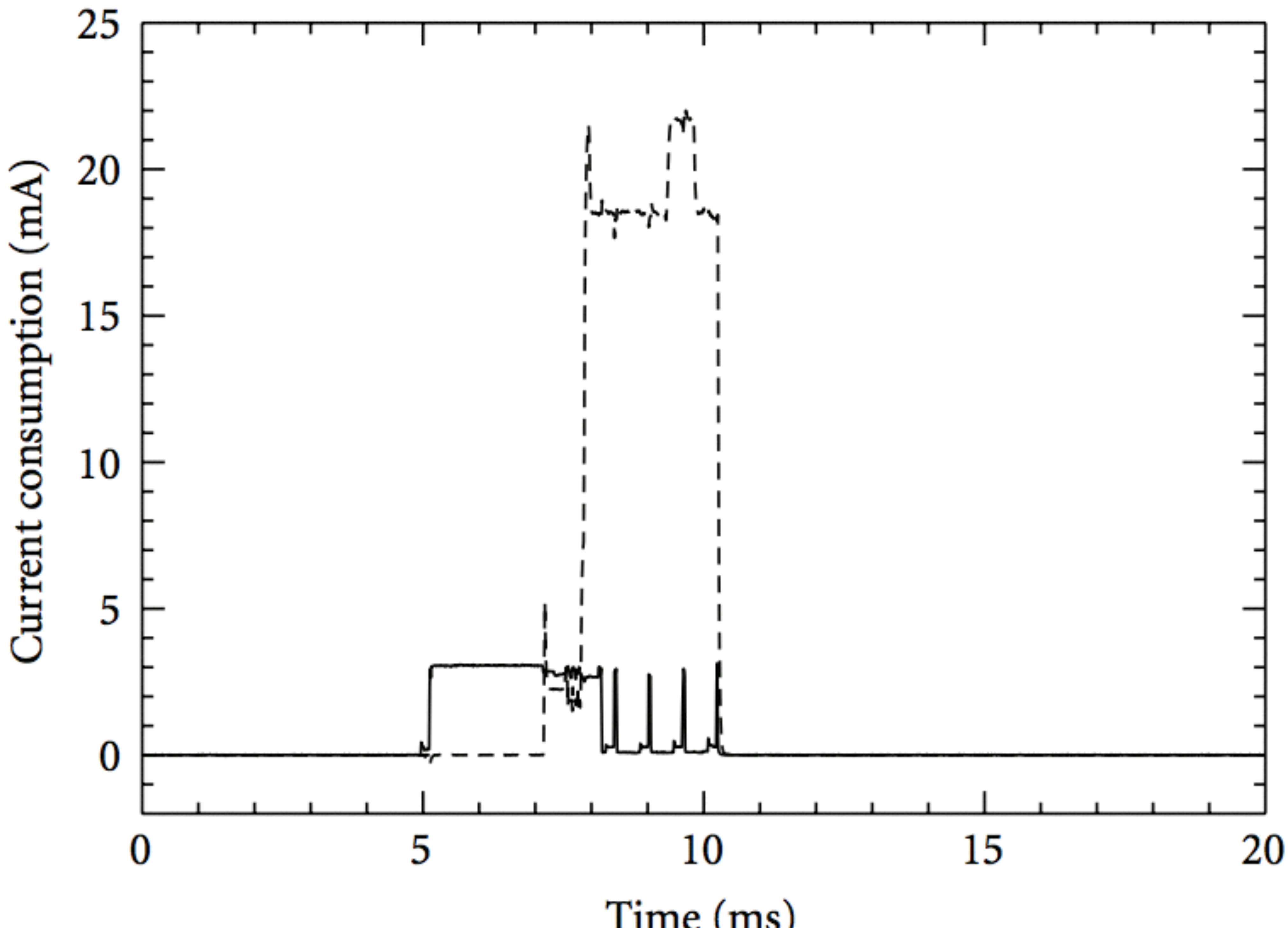
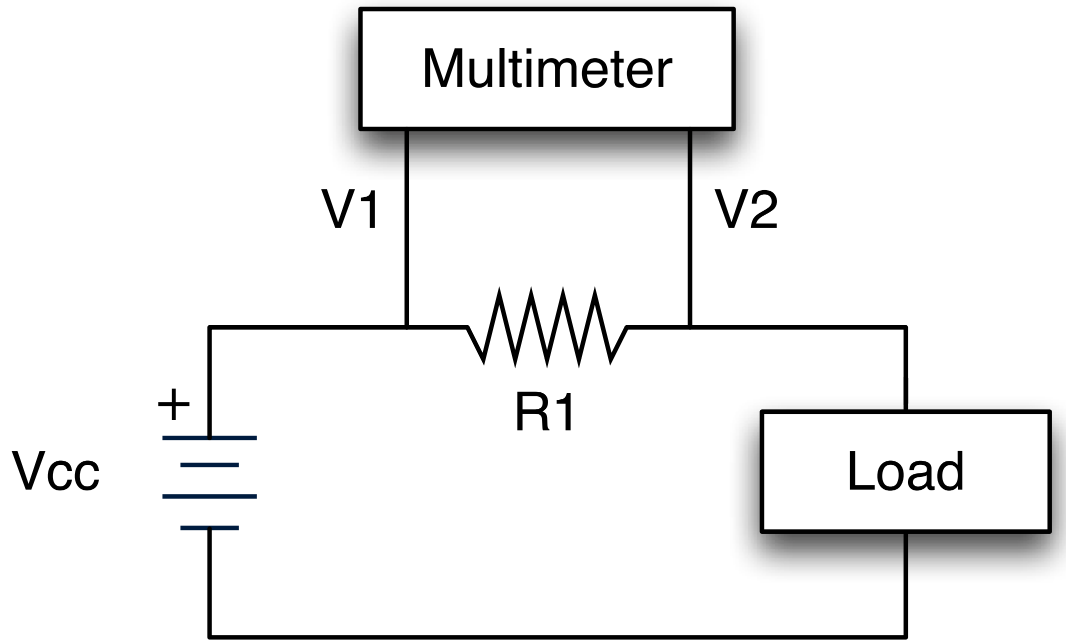
Frame filtering



Lattanzi, Emanuele, and Alessandro Bogliolo. “VirtualSense: A Java-Based Open Platform for Ultra-Low-Power Wireless Sensor Nodes.” International Journal of Distributed Sensor Networks 2012 (2012)

ENERGY CONSUMPTION MEASUREMENT

Shunt resistor



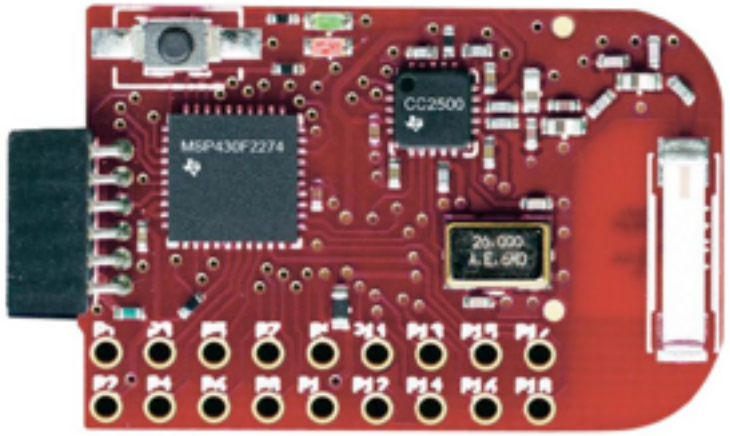
$$\hat{I} = \frac{\Delta V}{R_1} = \frac{V_2 - V_1}{R_1}$$

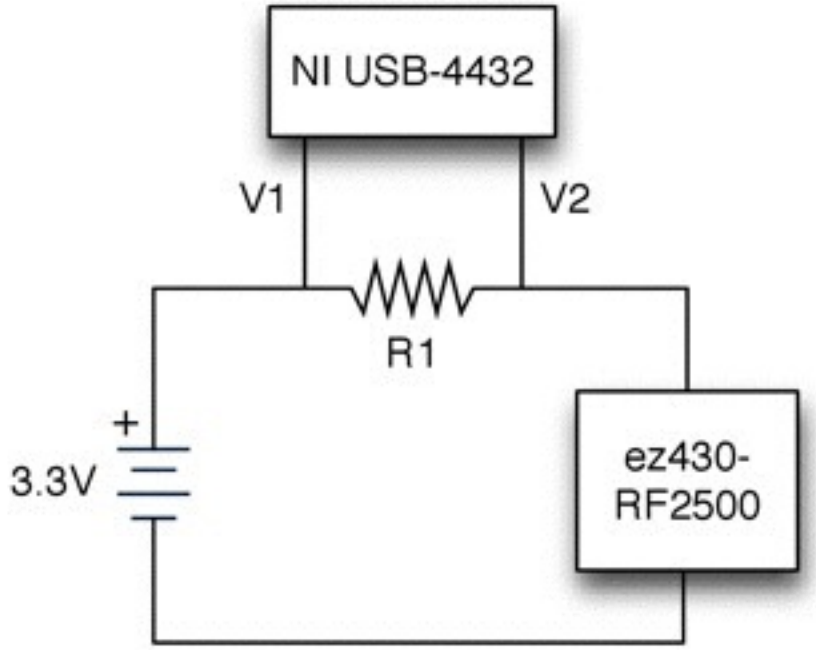
$$\hat{P} = \hat{I} V_0$$

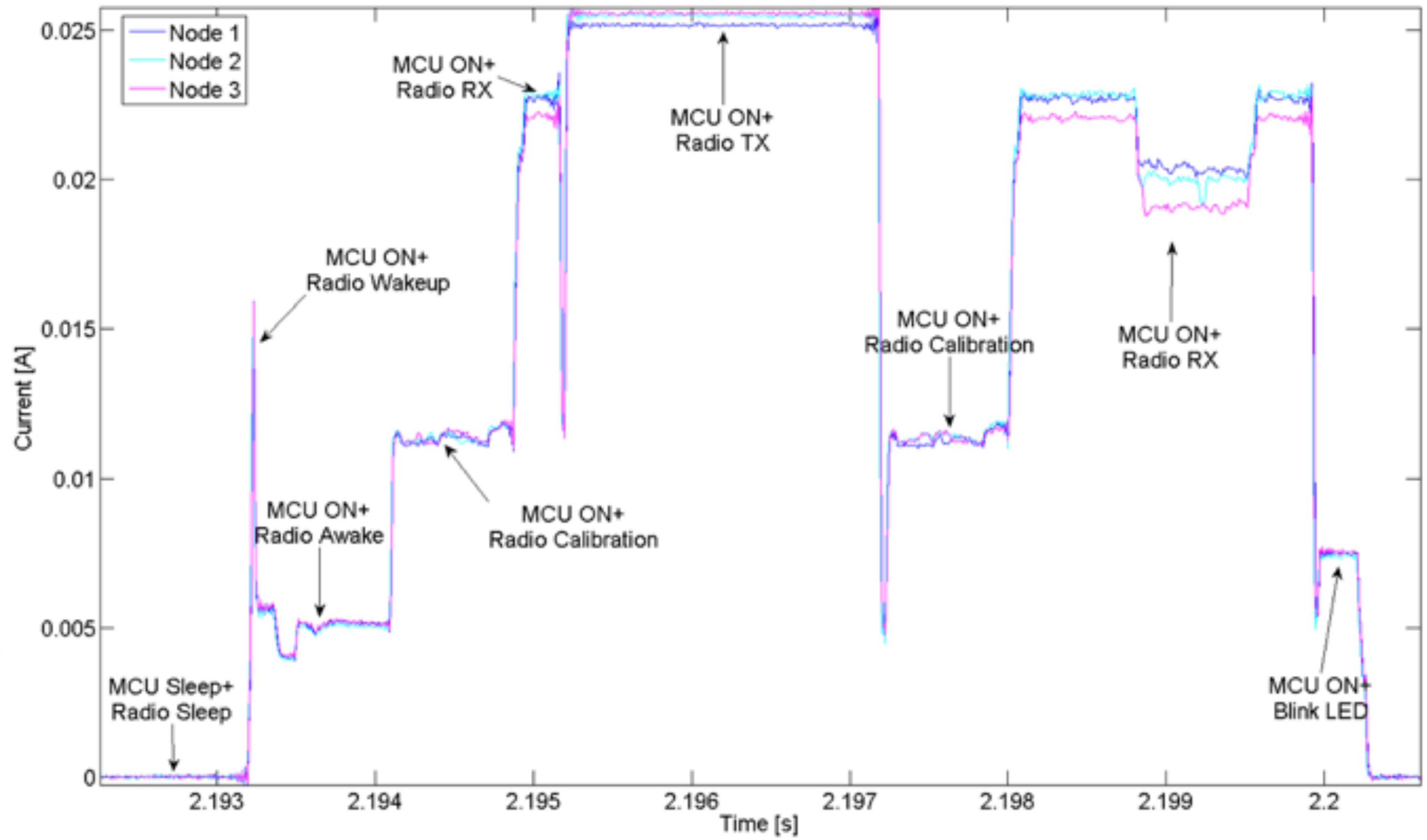
$$u(I) = \sqrt{u(\Delta V)^2 \frac{1}{R_1^2} + u(R_1)^2 \left(\frac{\Delta V}{R_1}\right)^2}$$

$$u(P) = \sqrt{u(\Delta V)^2 \left(\frac{V_0}{R_1}\right)^2 + u(R_1)^2 \left(\frac{V_0 \Delta V}{R_1^2}\right)^2 + u(V_0)^2 \left(\frac{\Delta V}{R_1}\right)^2}$$

ez430-RF2500 energy consumption

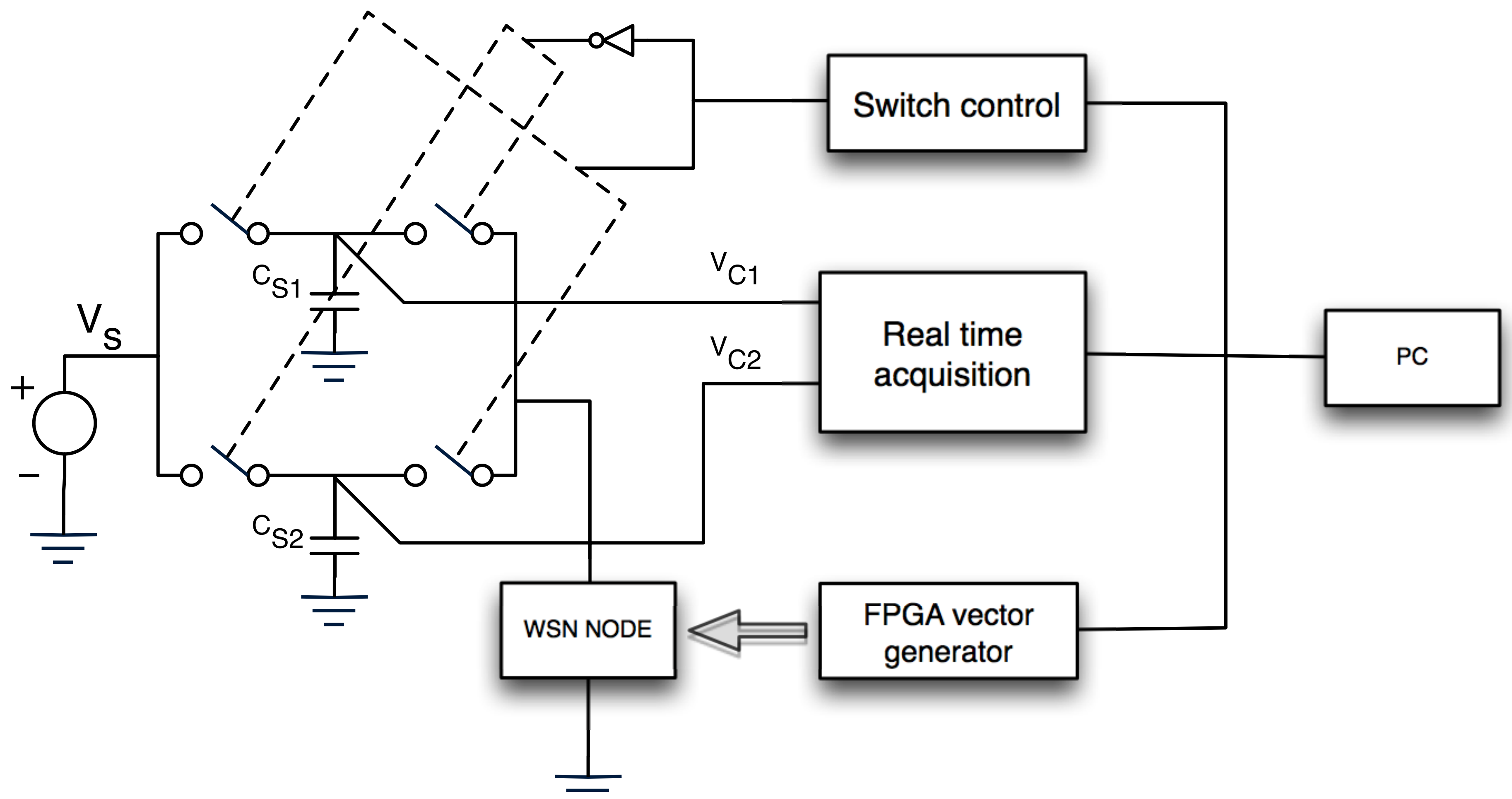






Power consumption assessment in wireless sensor networks. Antonio Moschitta and Igor Neri, ICT- Energy - Nanoscale Energy Management Concepts Towards Zero-Power Information and Communication Technology

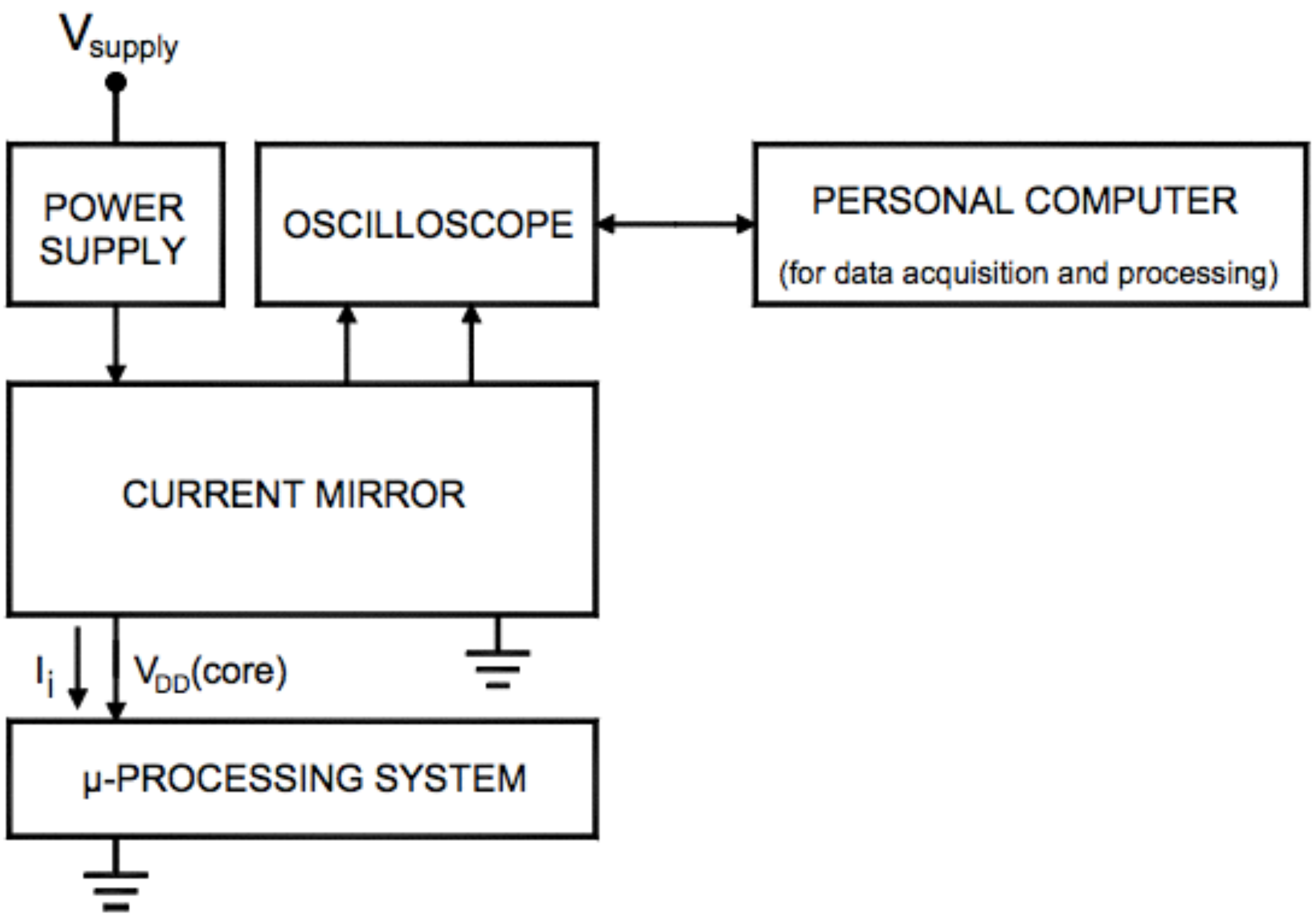
Switch capacitor

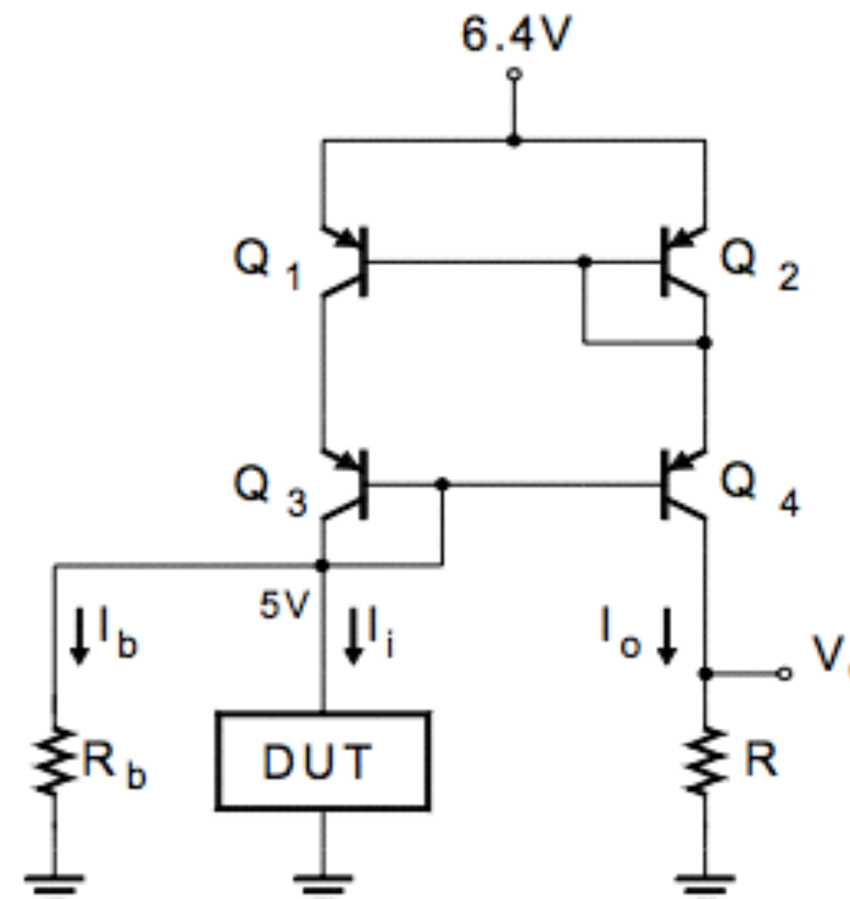


$$W = \frac{CV^2}{2}$$

Chang, Naehyuck, Kwanho Kim, and Hyung Gyu Lee. "Cycle-accurate energy measurement and characterization with a case study of the ARM7TDMI [microprocessors]." Very Large Scale Integration (VLSI) Systems, IEEE Transactions on 10.2 (2002): 146-154.

Current mirror

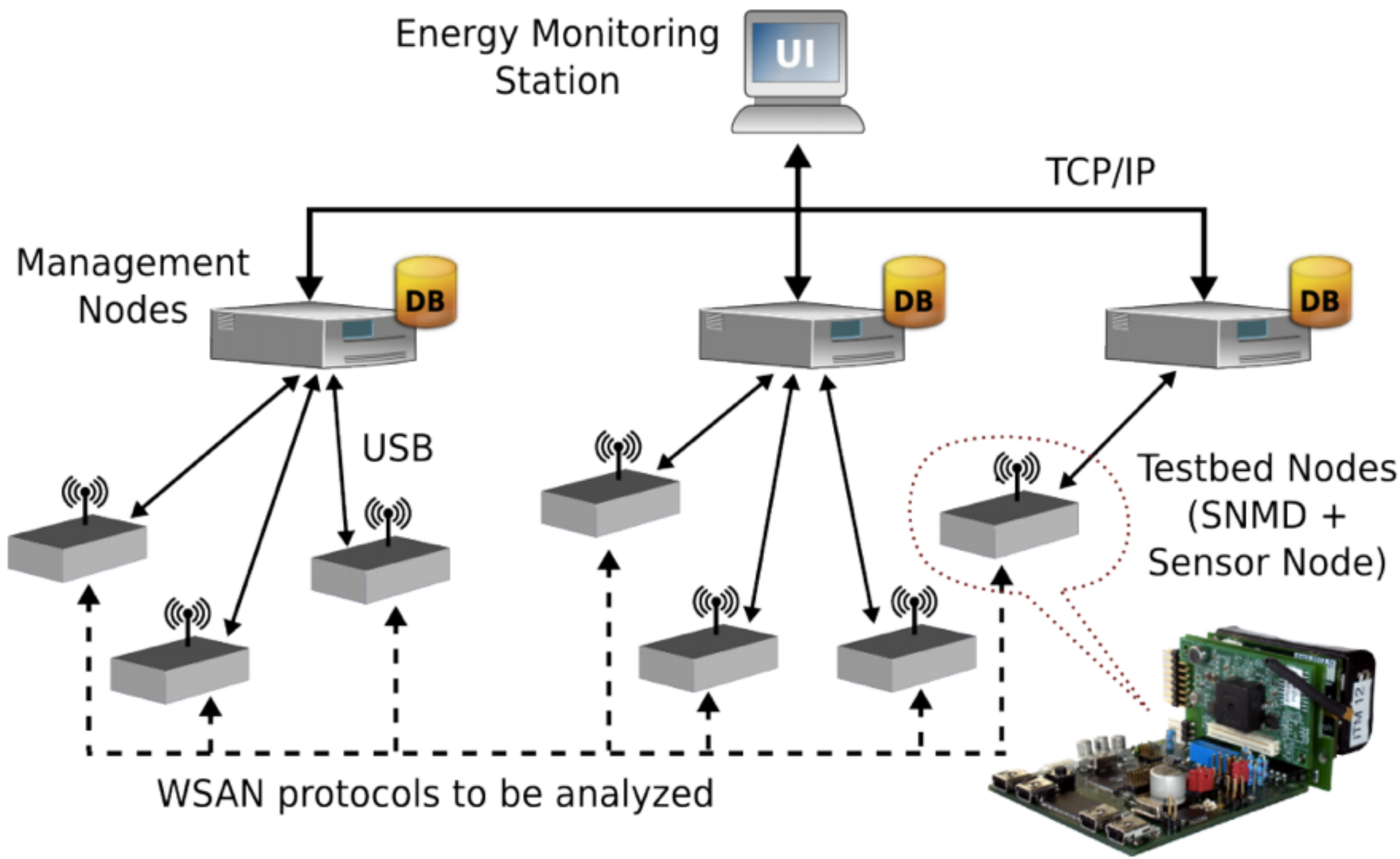




- Copying accuracy
- Time (frequency) response

T. Laopoulos, P. Neofotistos, C. A. Kosmatopoulos, and S. Nikolaidis," Measurement of Current Variations for the Estimation of Software-Related Power Consumption," IEEE Transactions on Instrumentation and Measurements, Vol. 52, no. 4, August 2003

SANDbed: Distributed Energy Measurements

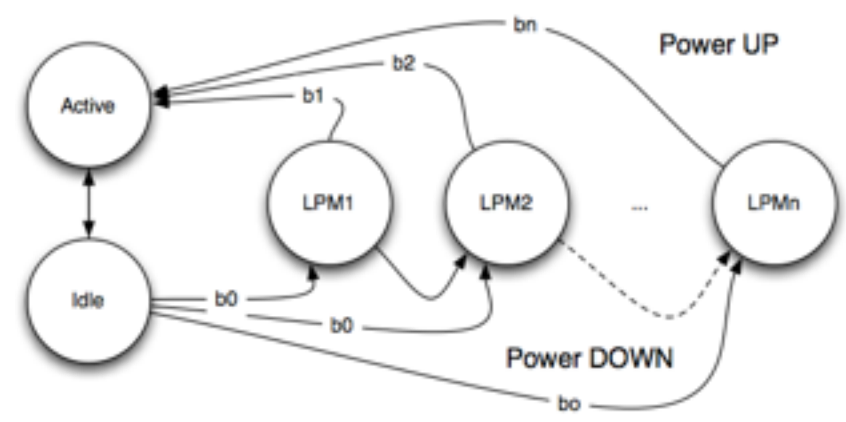


A. Hergenroder, J. Horneber, and J. Wilke. SANDbed: A WSAN Testbed for Network Management and Energy Monitoring. Hamburg, Germany, Aug. 2009. 8. GI/ITG KuVS Fachgesprach “Drahtlose Sensornetze”.

ENERGY CONSUMPTION MODELLING

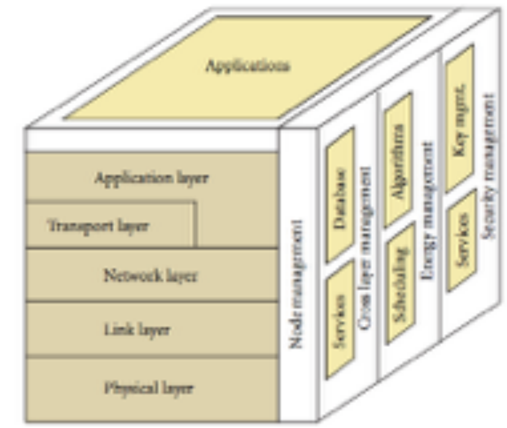
```
shell$ msp430-gcc --version
msp430-gcc (MSPGCC4_r4-20100210) 4.4.3
Copyright (C) 2010 Free Software Foundation, Inc.
This is free software; see the source for copying conditions.  There is NO
warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
```

Modelling strategies: Finite state machine



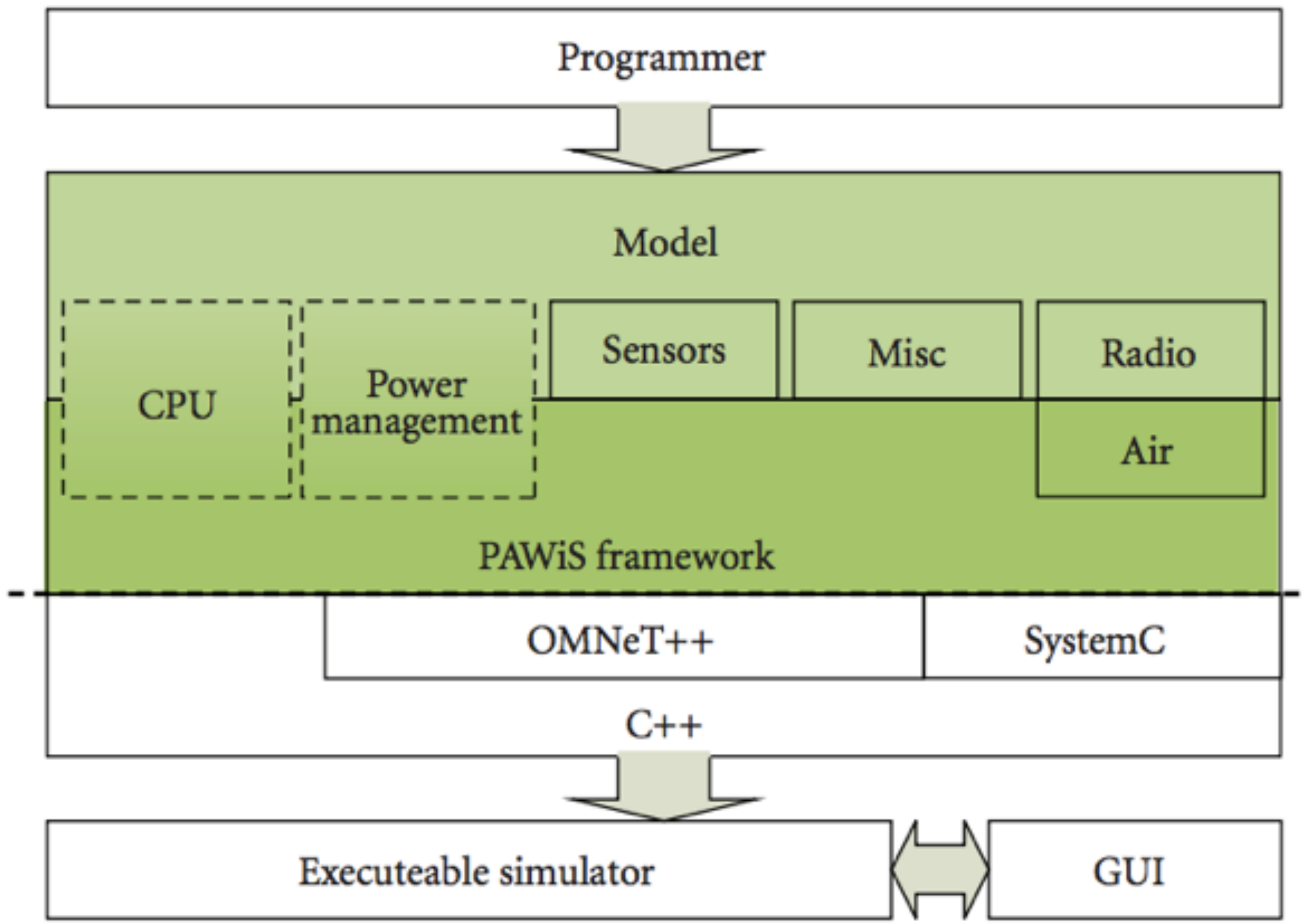
- **Pro**:
  - Easy to implement
  - Easy to simulate
- **Cons**:
  - Rough estimate of energy consumption
  - Do not address peripherals

Modelling strategies: Network focused simulation frameworks



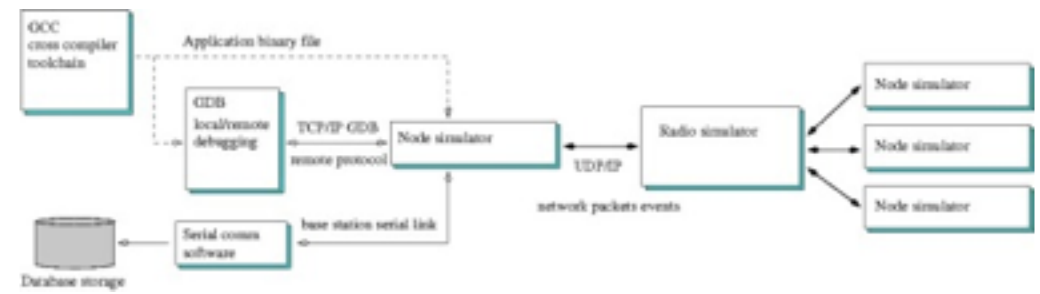
- **Pro**:
  - Fast simulation time
  - Includes network and MAC layers
- **Cons**:
  - Coarse representation of node state
  - Inaccurate energy consumption estimate

Modelling strategies: Network focused simulation frameworks - PAWiS



Johann, Glaser, et al. "Power aware simulation framework for wireless sensor networks and nodes." EURASIP Journal on Embedded Systems 2008 (2008).

Modelling strategies: Instruction-level simulators



- **Pro**:
  - Accurate energy consumption estimation
  - Tracking of node and peripheral states
  - Fine-grained timing
- **Cons**:
  - Strictly dependant on the platform
  - Need of accurate calibration
  - Simulation time can be long

Avrora

- Cycle accurate execution times.
- Online monitoring of program behaviour.
- The profiling utilities allow users to study their program's behavior in simulation.
- Detailed observation of program behavior without disturbing the simulation, and without modifying the simulator source code.
- The GDB debugger hooks allow source-level debugging and integrated development and testing.
- Graphical representation program's instructions that is useful for understanding how it is structured and what the compiler does with your code.
- The energy analysis tool can analyze energy consumption.
- The stack checker tool can be used to bound the maximum stack size used by your program.

http://compilers.cs.ucla.edu/avrora/

Worldsens Framework

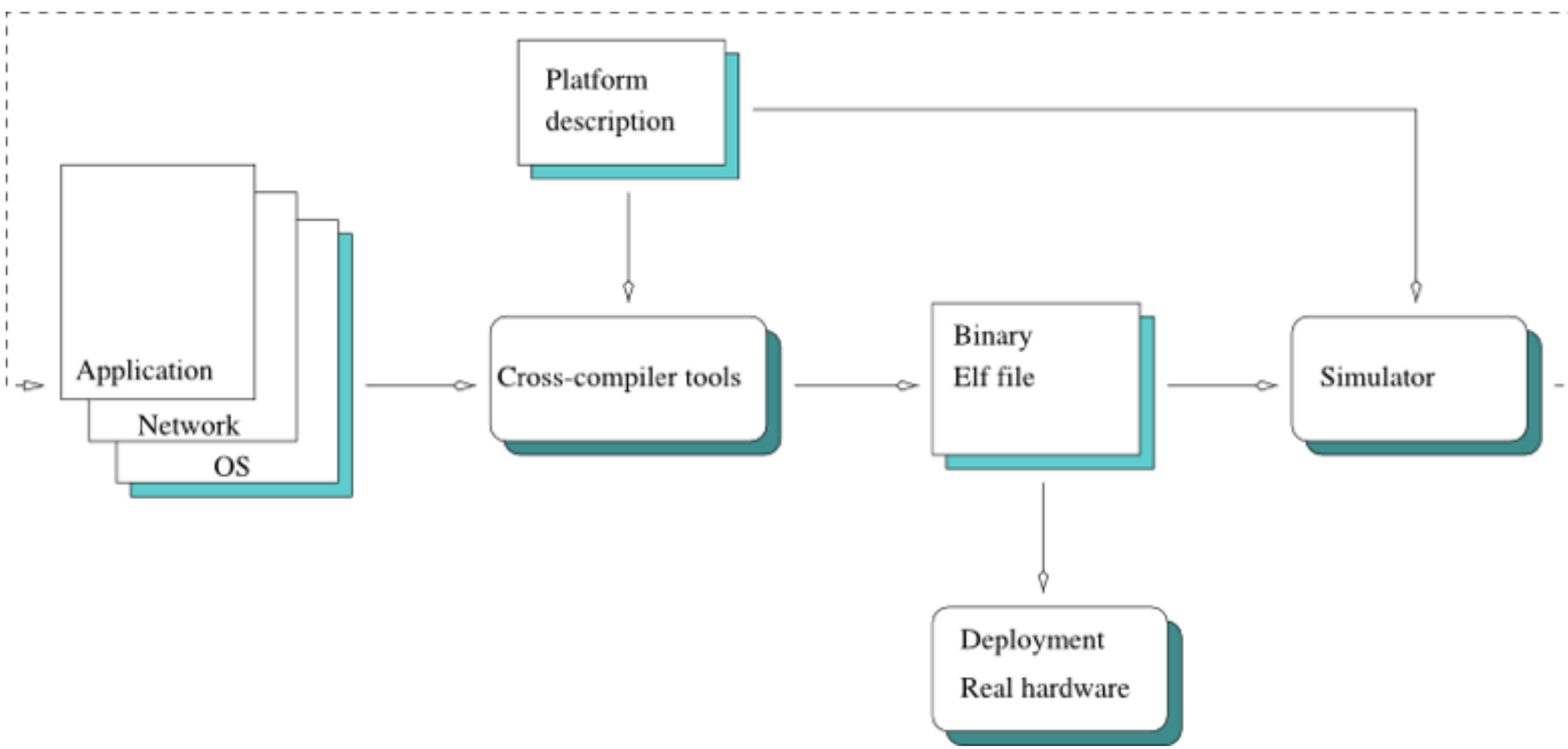
- **WSim**: node instruction-level and peripherals simulator
- **WSNet**: event based network simulator
- **eSimu**: energy consumption analysis and estimate

http://wsim.gforge.inria.fr/

Worldsens Framework: WSim

WSim is a full platform simulator that can run the target platform object code without modification

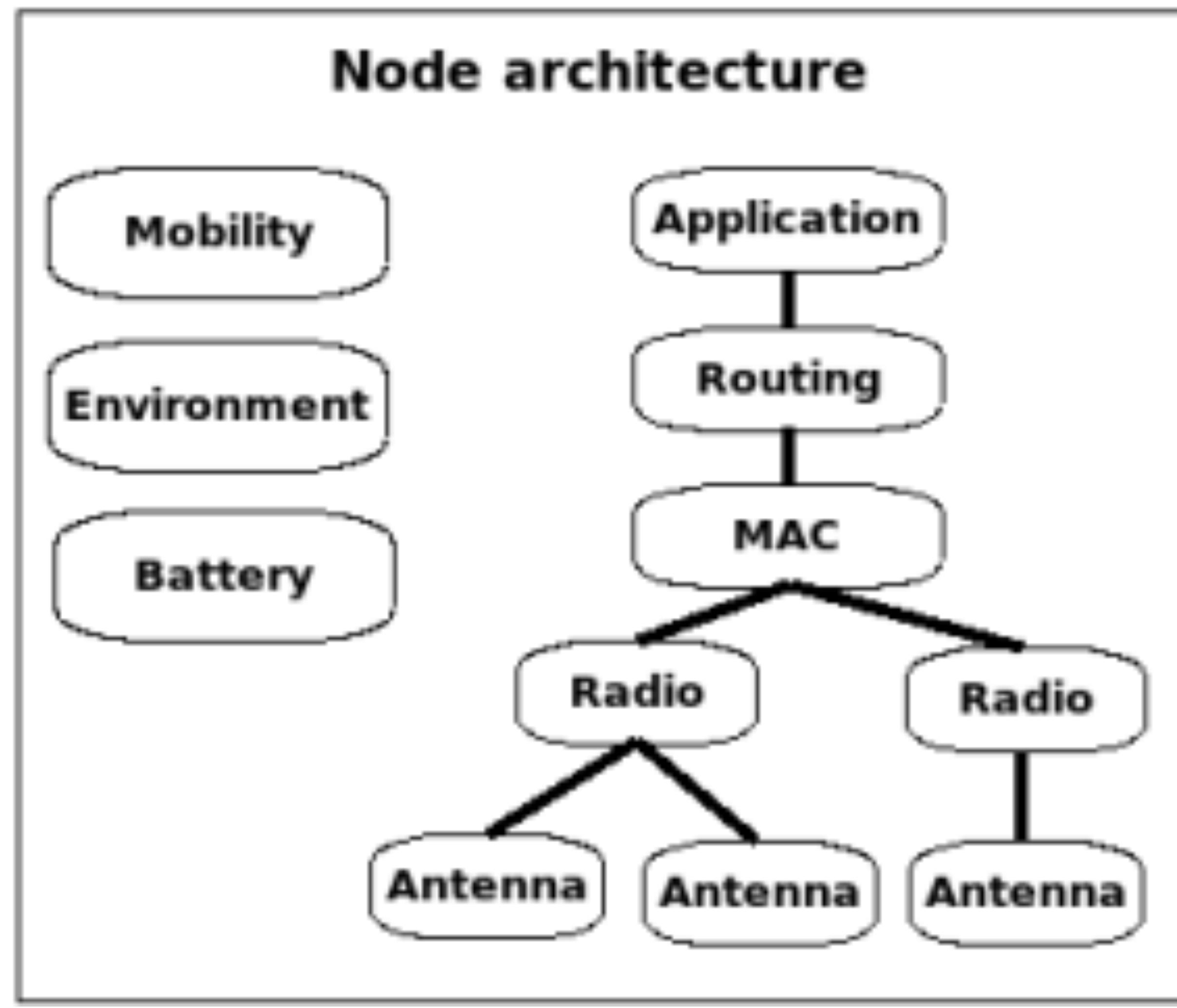
- **debugging**, **profiling** and **performance evaluation**



Worldsens Framework: WSNet

WSNet is an event-driven simulator for wireless networks

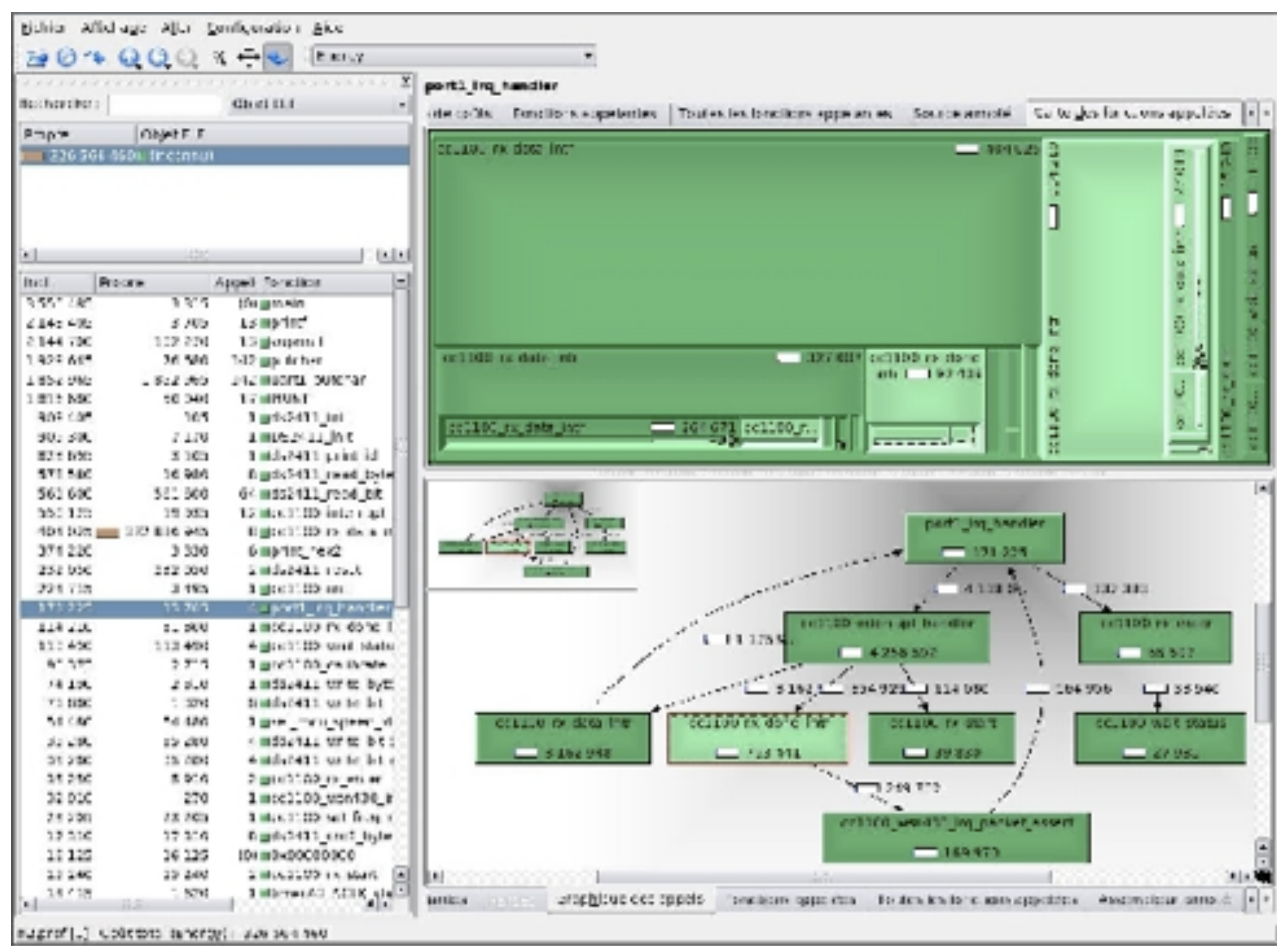
- mobility
- energy source
- routing protocols
- mac protocols
- radio interface
- antenna



Worldsens Framework: eSimu

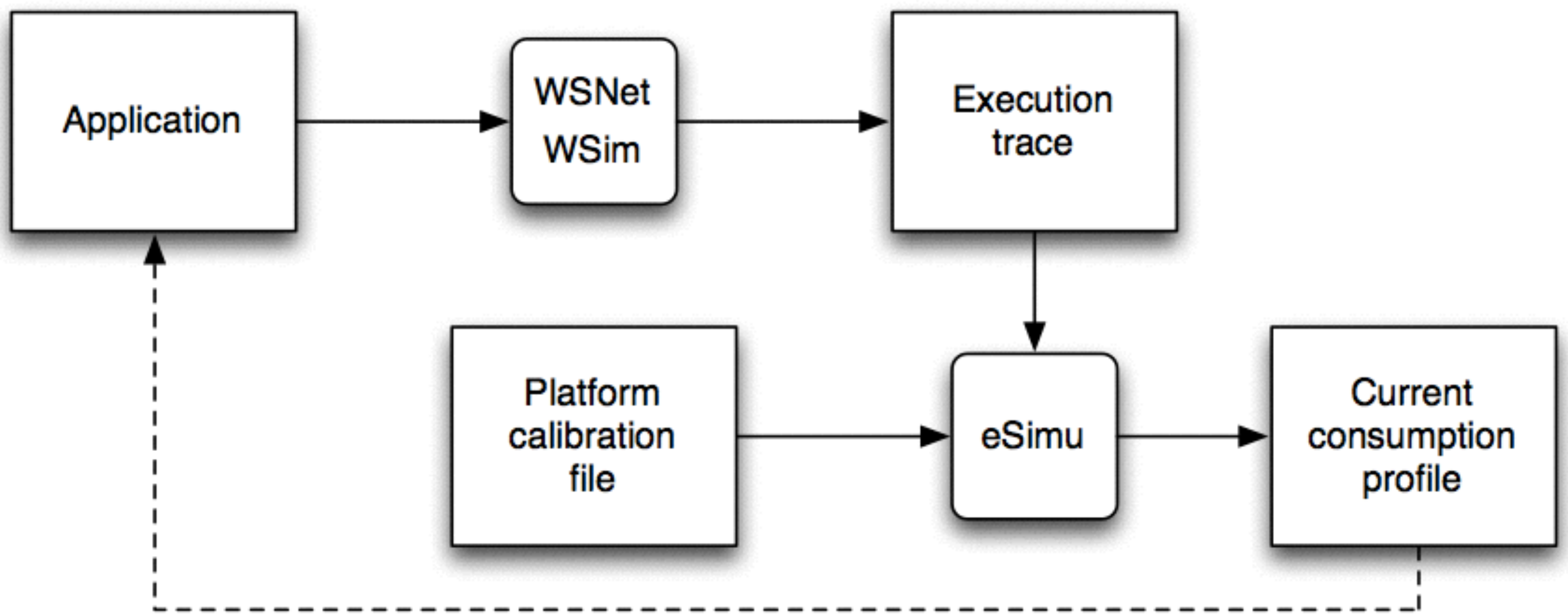
eSimu is a complete system energy model based on non-intrusive measurements

- cycle accurate simulation tools to give energy consumption feedback for embedded systems software programming
- whole system consumption including peripherals

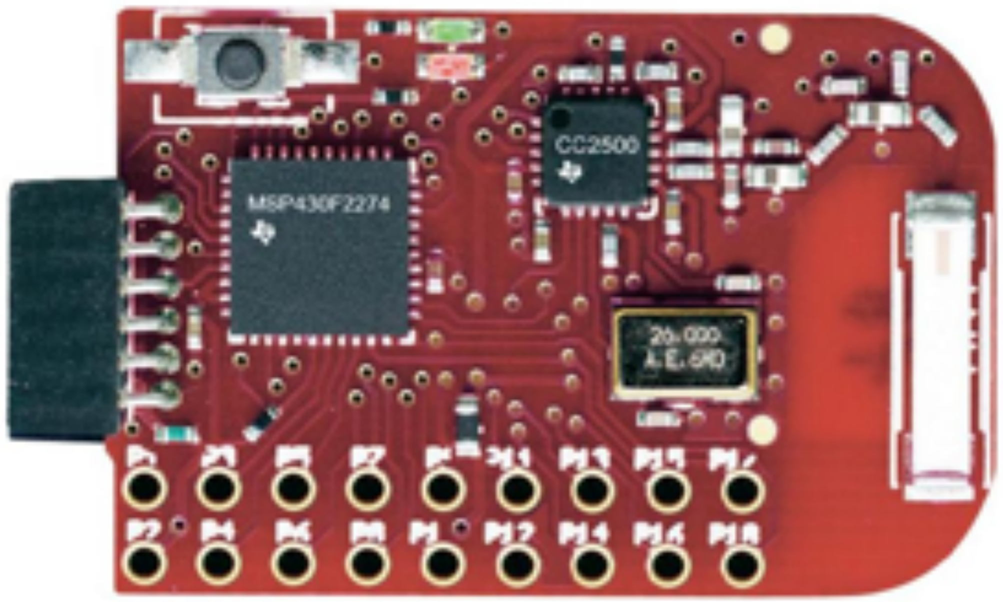


$$\xi_{slot} = \xi_{CPU} + \sum_{blocks} \xi_{bl}$$

Worldsens Framework: workflow



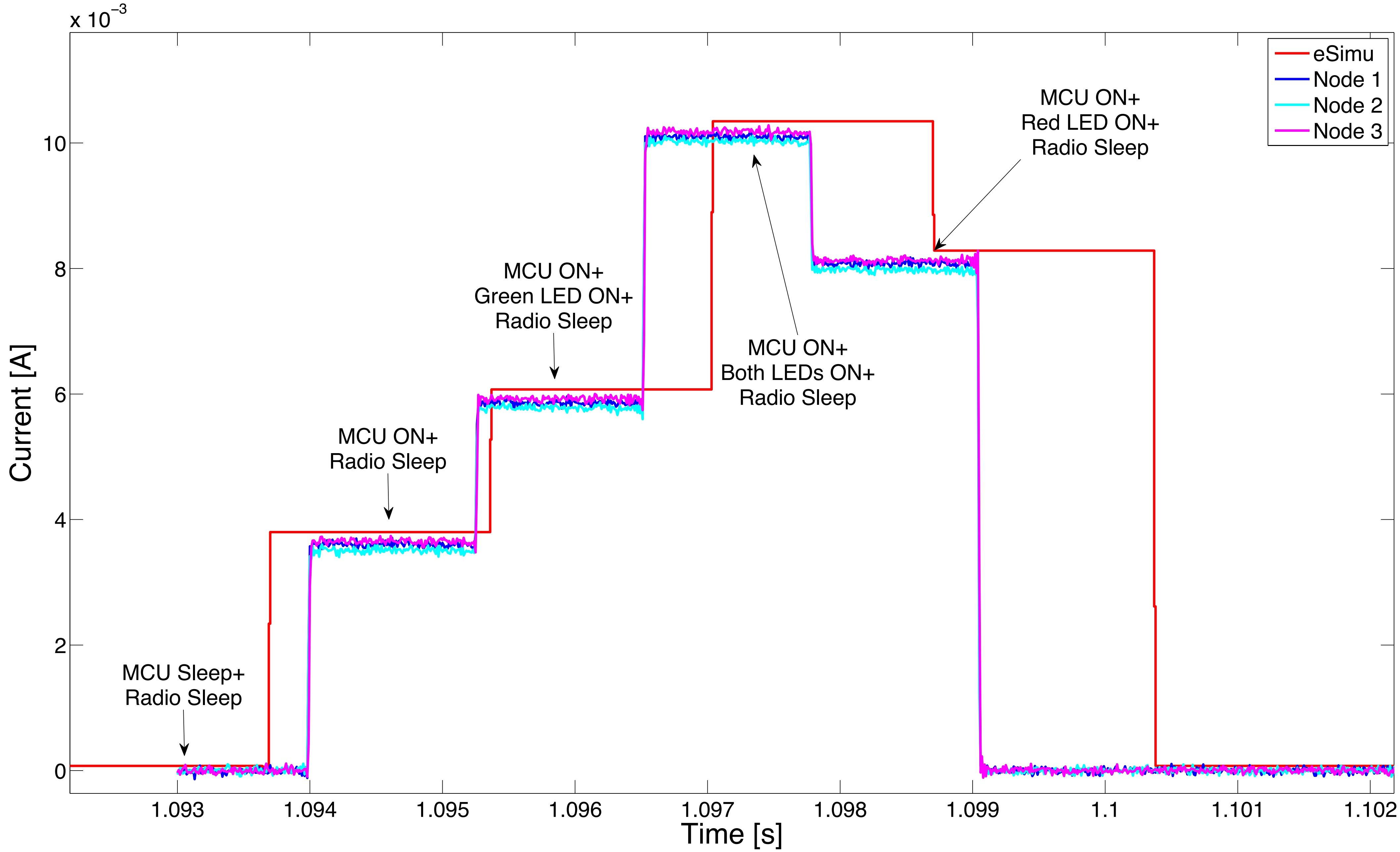
Worldsens Framework: ez430-RF2500



Highlighted and fixed issues:

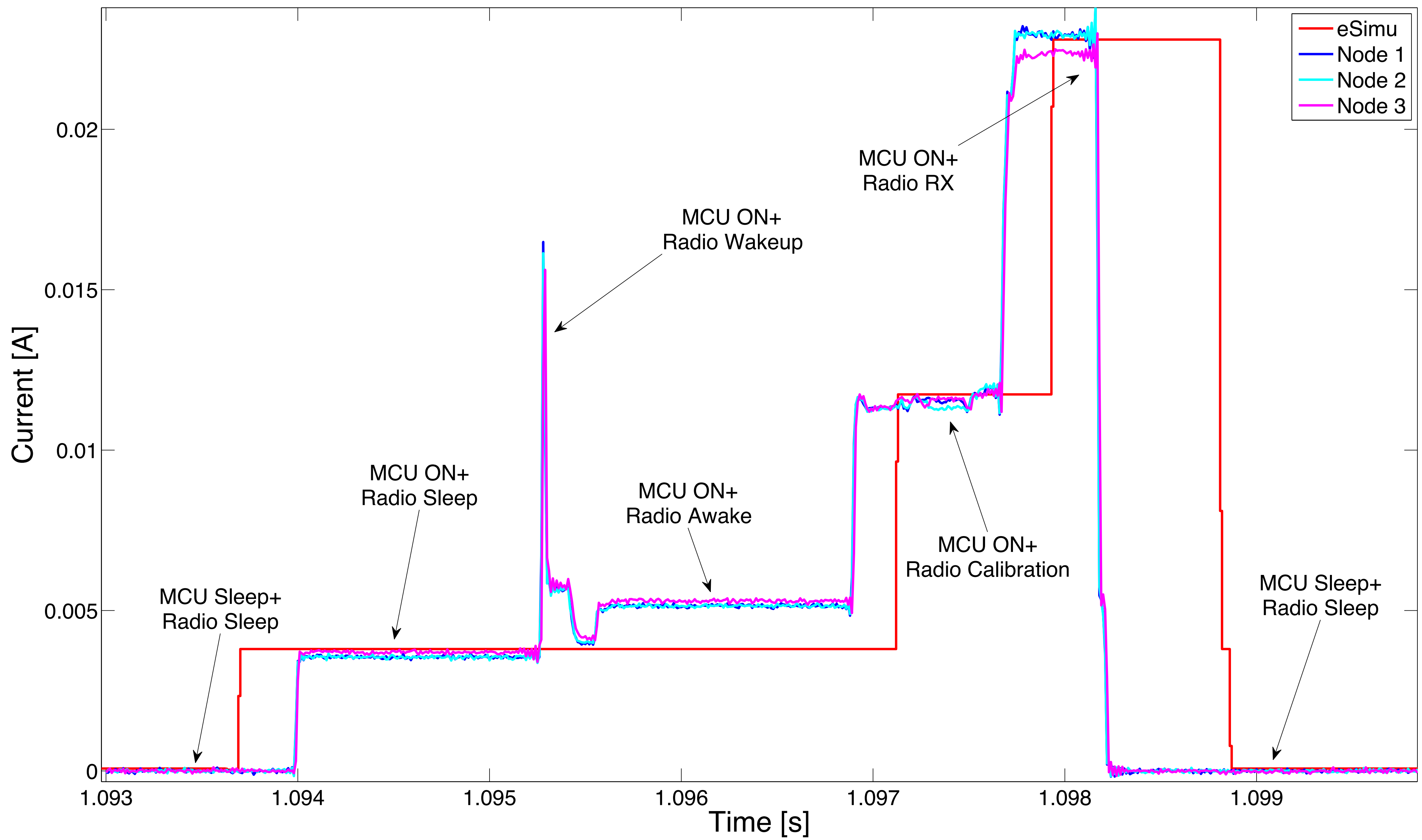
- Missing calibration file for the ez430-RF2500 platform energy consumption.
- Incomplete hardware modeling.
- Strict trade off on time analysis between execution time and granularity.
- The simulated clock time doesn’t match the real execution time.
- Incomplete implementation of transition states of the radio module.

ez430-RF2500 current consumption: measurements and simulations: LEDs



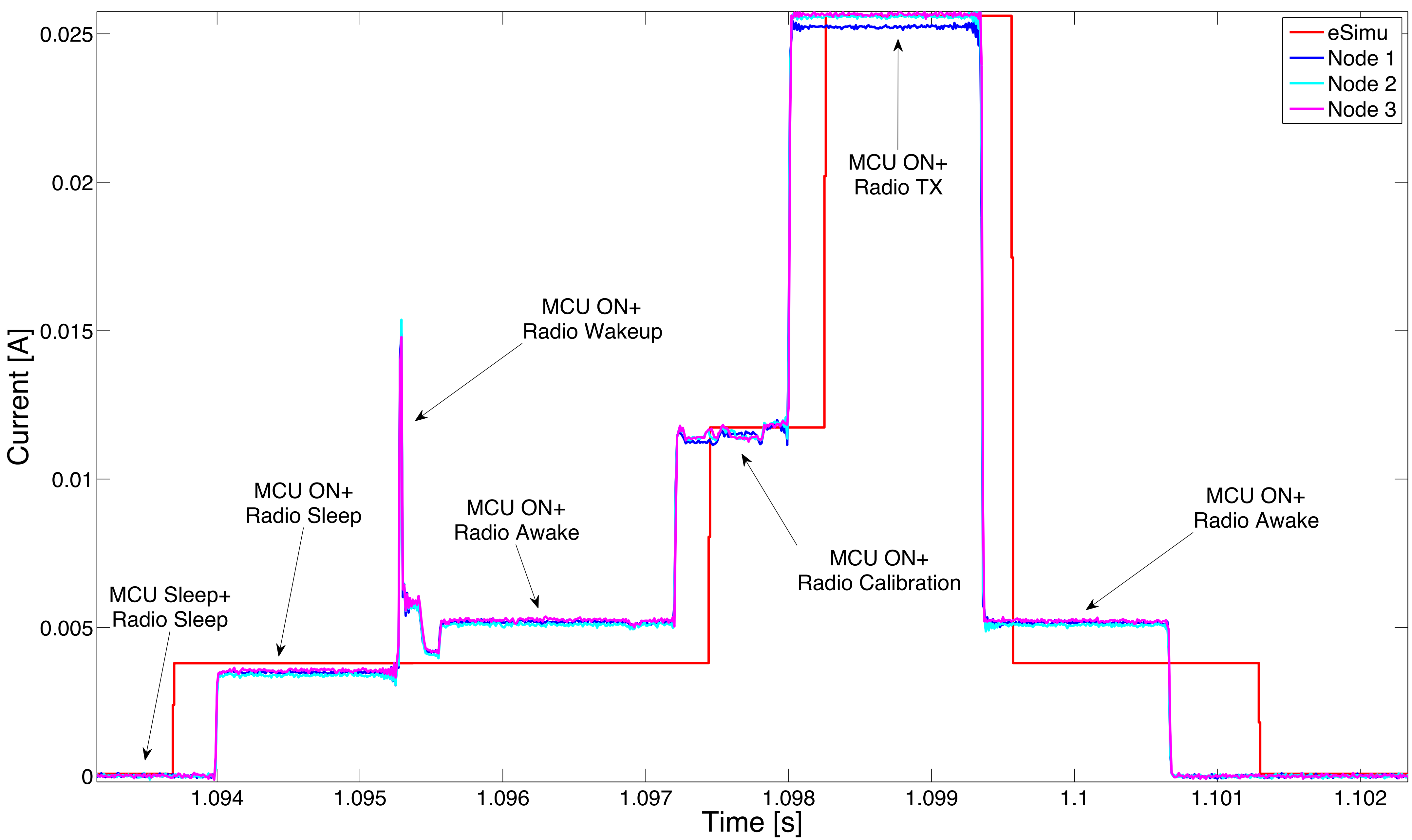
Power consumption assessment in wireless sensor networks. Antonio Moschitta and Igor Neri, ICT- Energy - Nanoscale Energy Management Concepts Towards Zero-Power Information and Communication Technology

ez430-RF2500 current consumption: measurements and simulations: RX



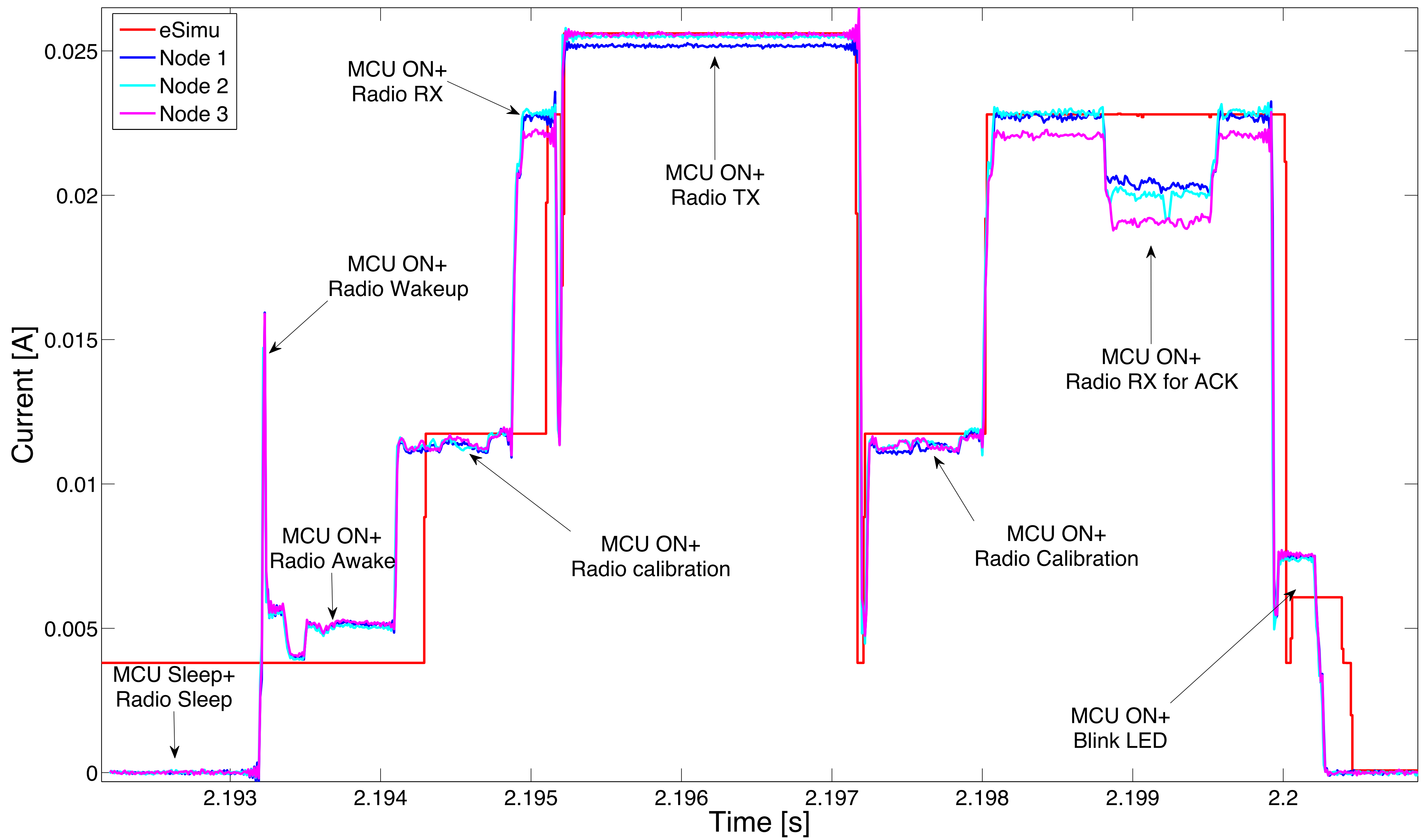
Power consumption assessment in wireless sensor networks. Antonio Moschitta and Igor Neri, ICT- Energy - Nanoscale Energy Management Concepts Towards Zero-Power Information and Communication Technology

ez430-RF2500 current consumption: measurements and simulations: TX

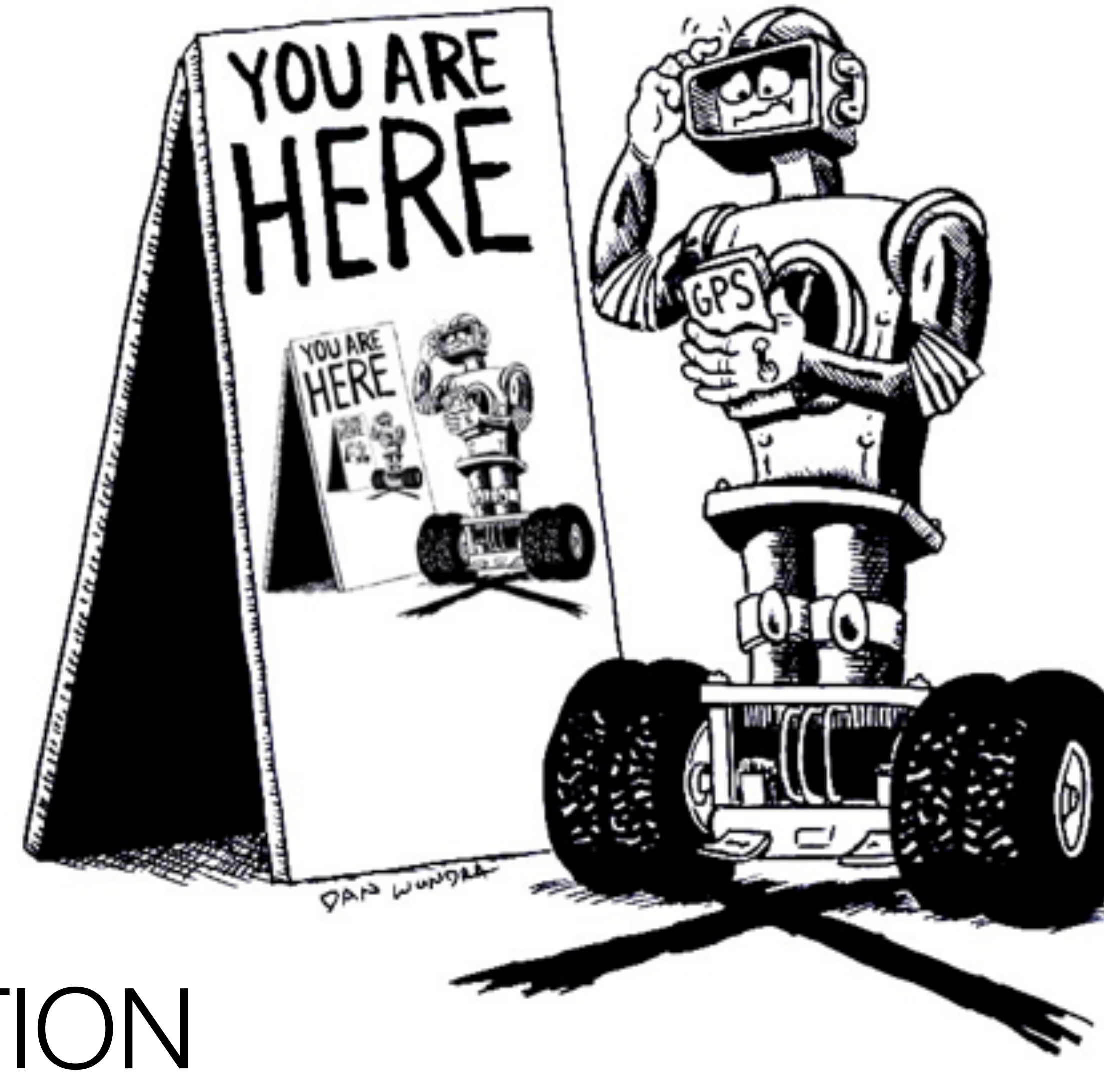


Power consumption assessment in wireless sensor networks. Antonio Moschitta and Igor Neri, ICT- Energy - Nanoscale Energy Management Concepts Towards Zero-Power Information and Communication Technology

ez430-RF2500 current consumption: measurements and simulations: TX with ACK

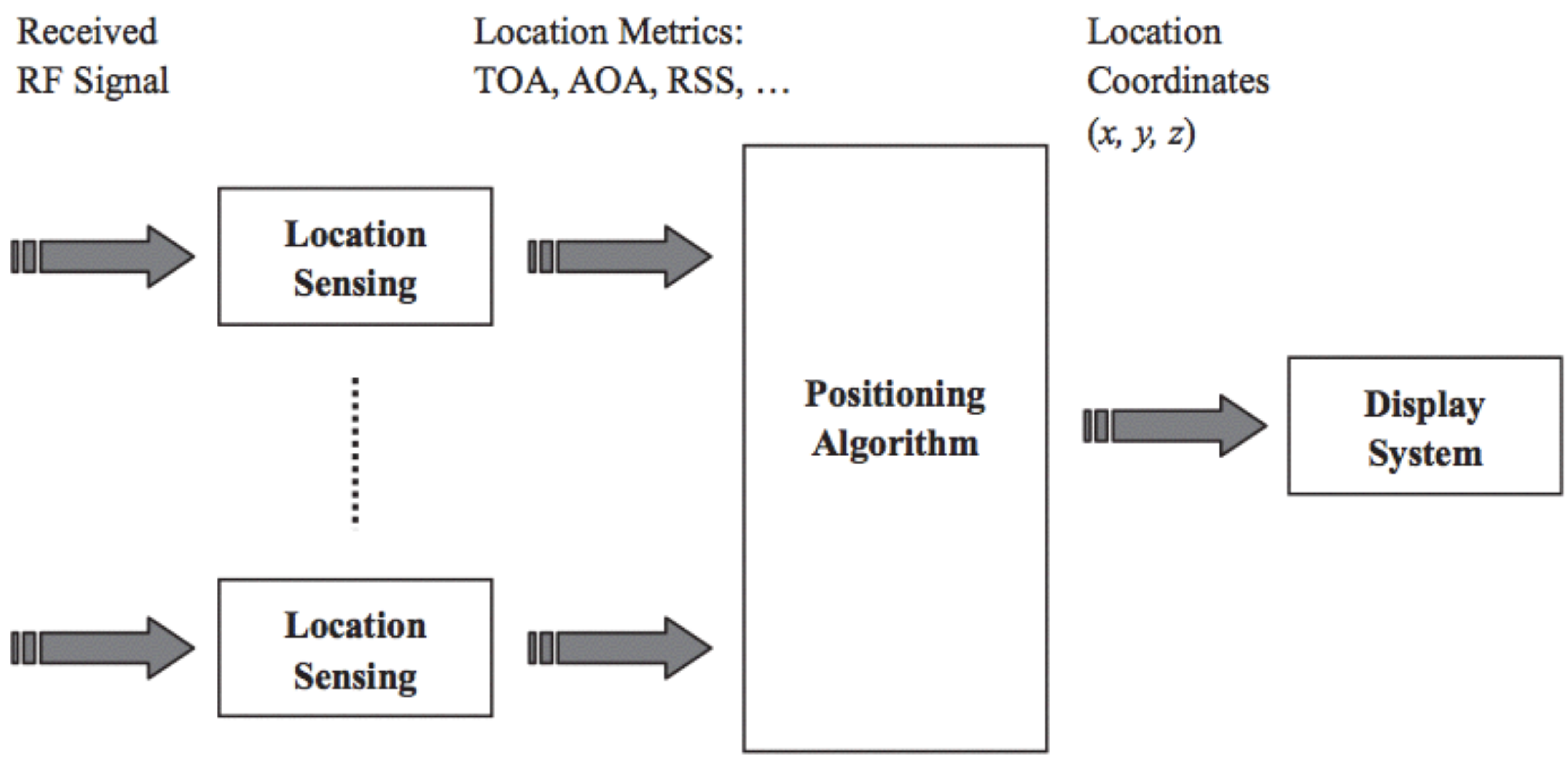


Power consumption assessment in wireless sensor networks. Antonio Moschitta and Igor Neri, ICT- Energy - Nanoscale Energy Management Concepts Towards Zero-Power Information and Communication Technology

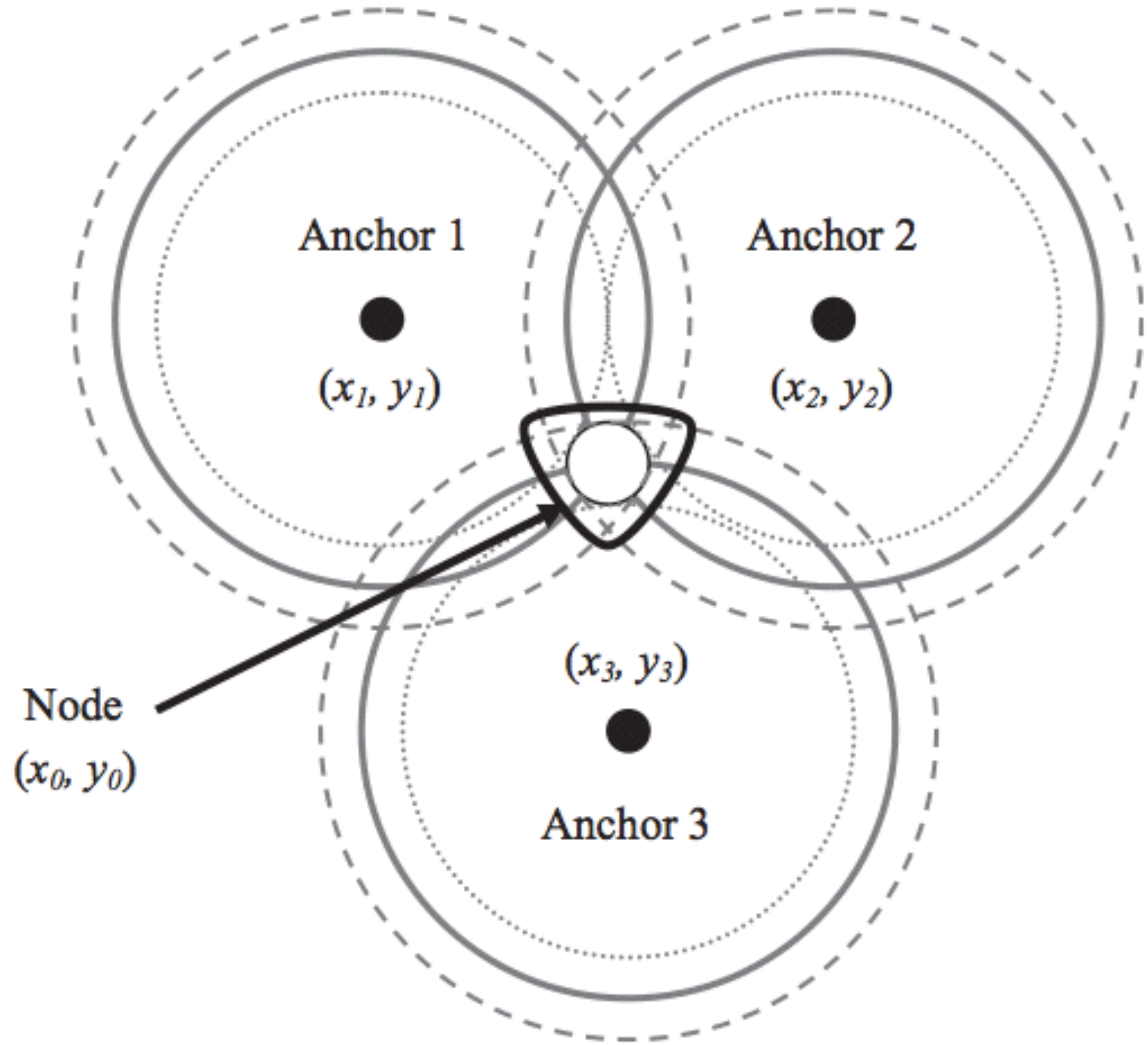


APPLICATION EXAMPLE:
ENERGY AWARE LOCALIZATION

Node localization

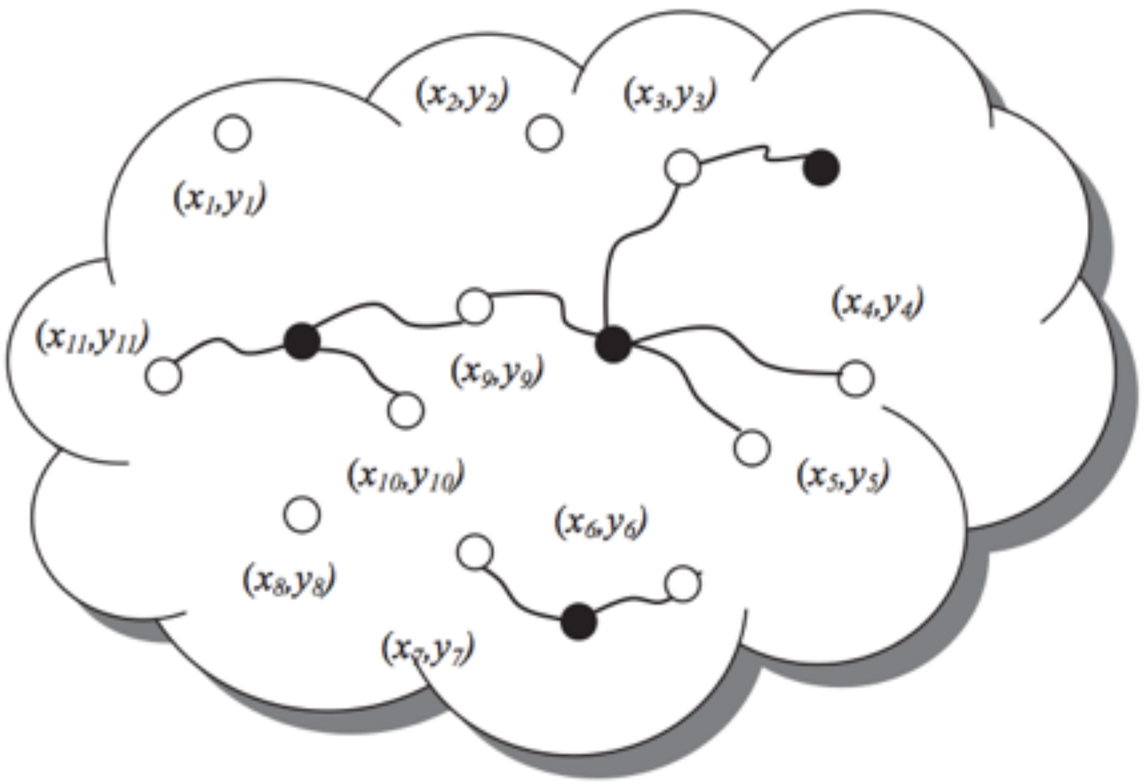


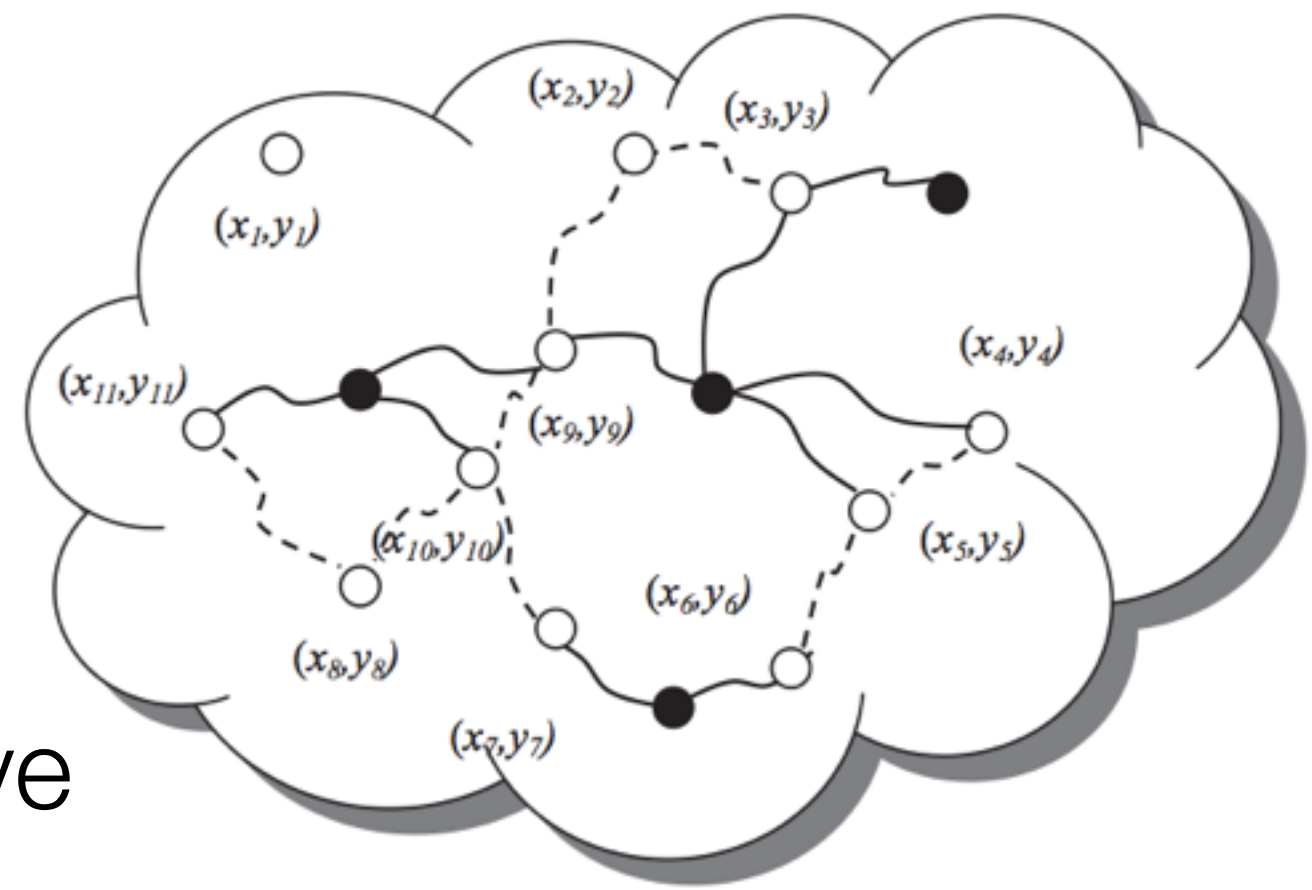
Node localization



Node localization

Not cooperative



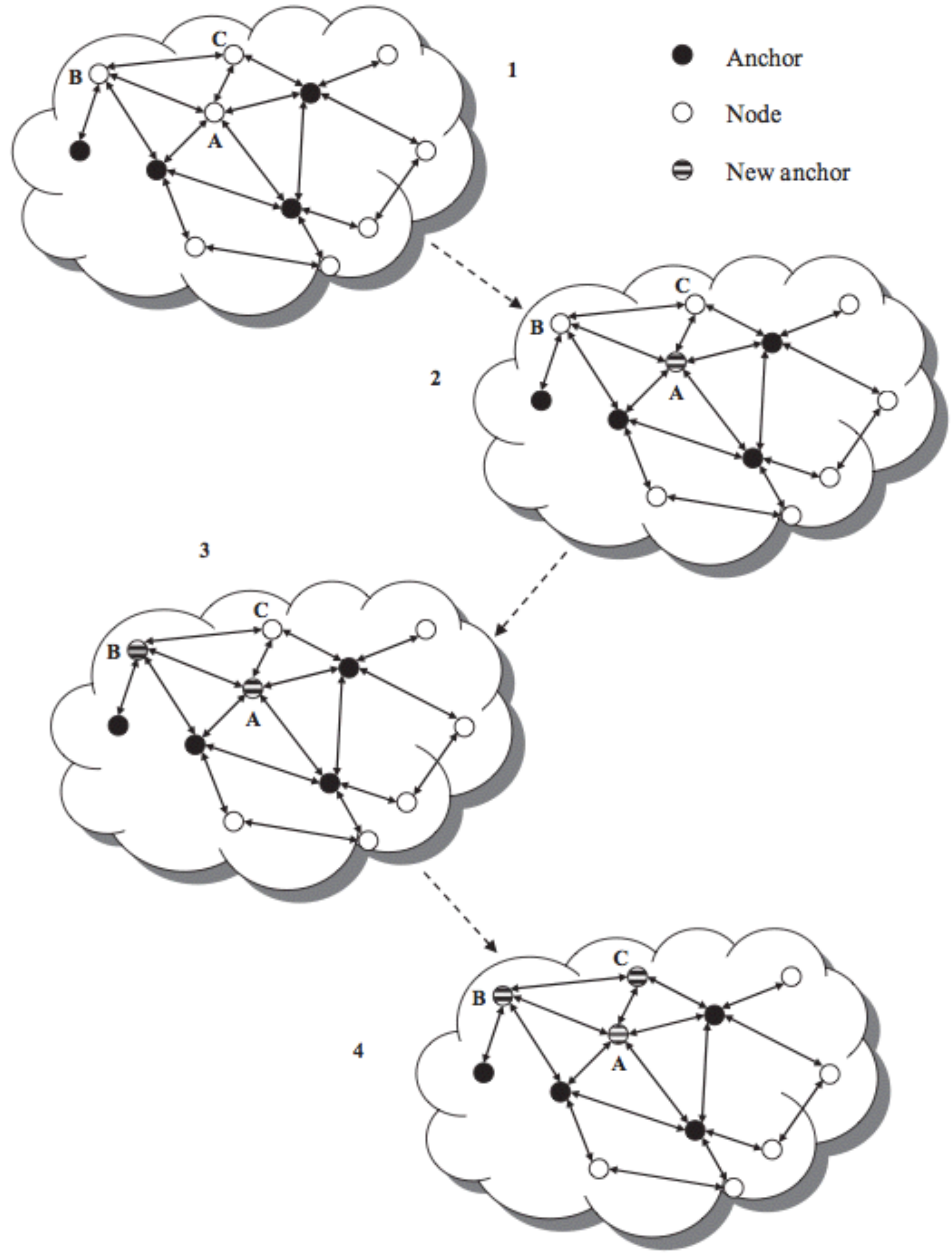


Cooperative

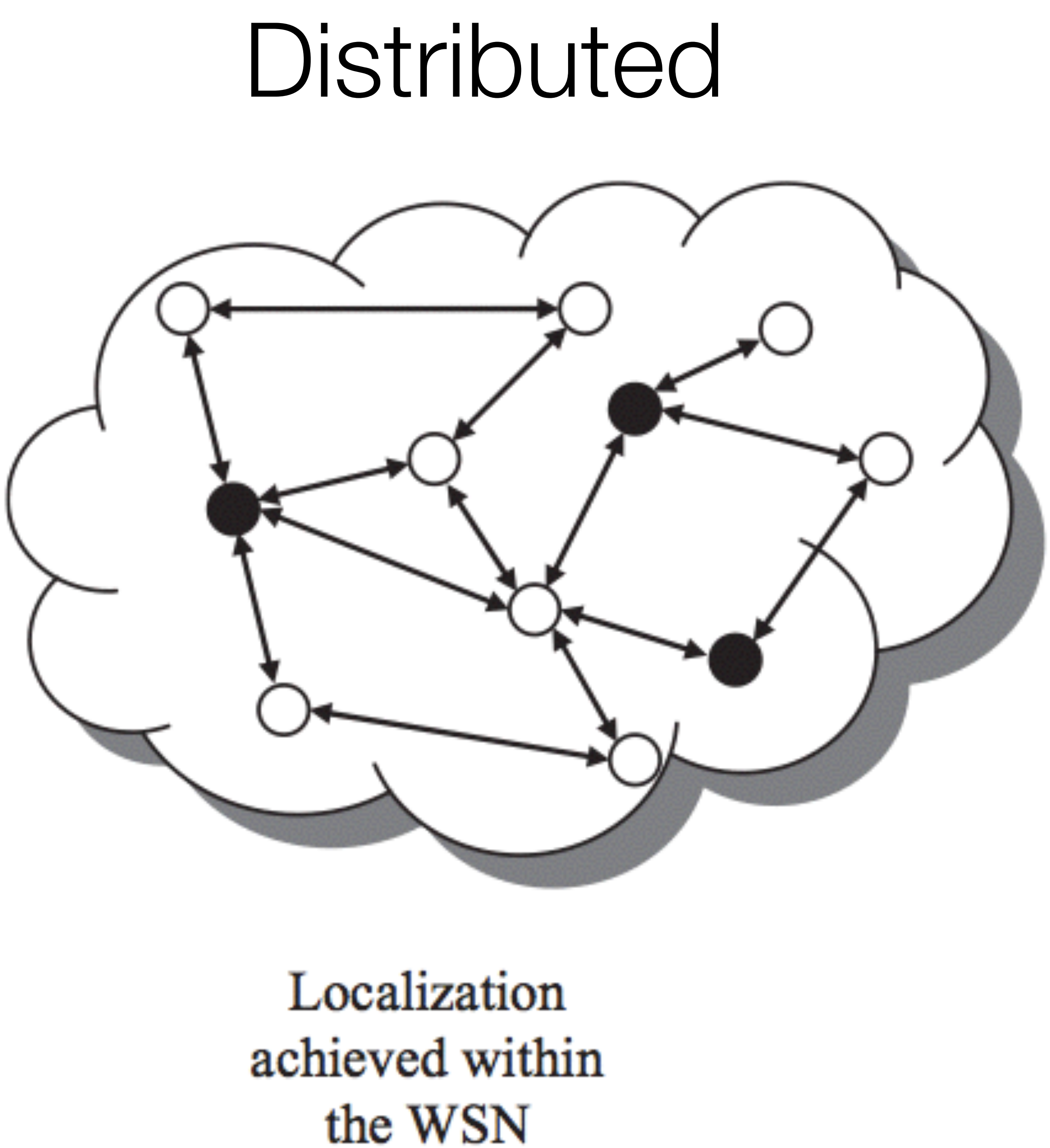
Recursive position estimation

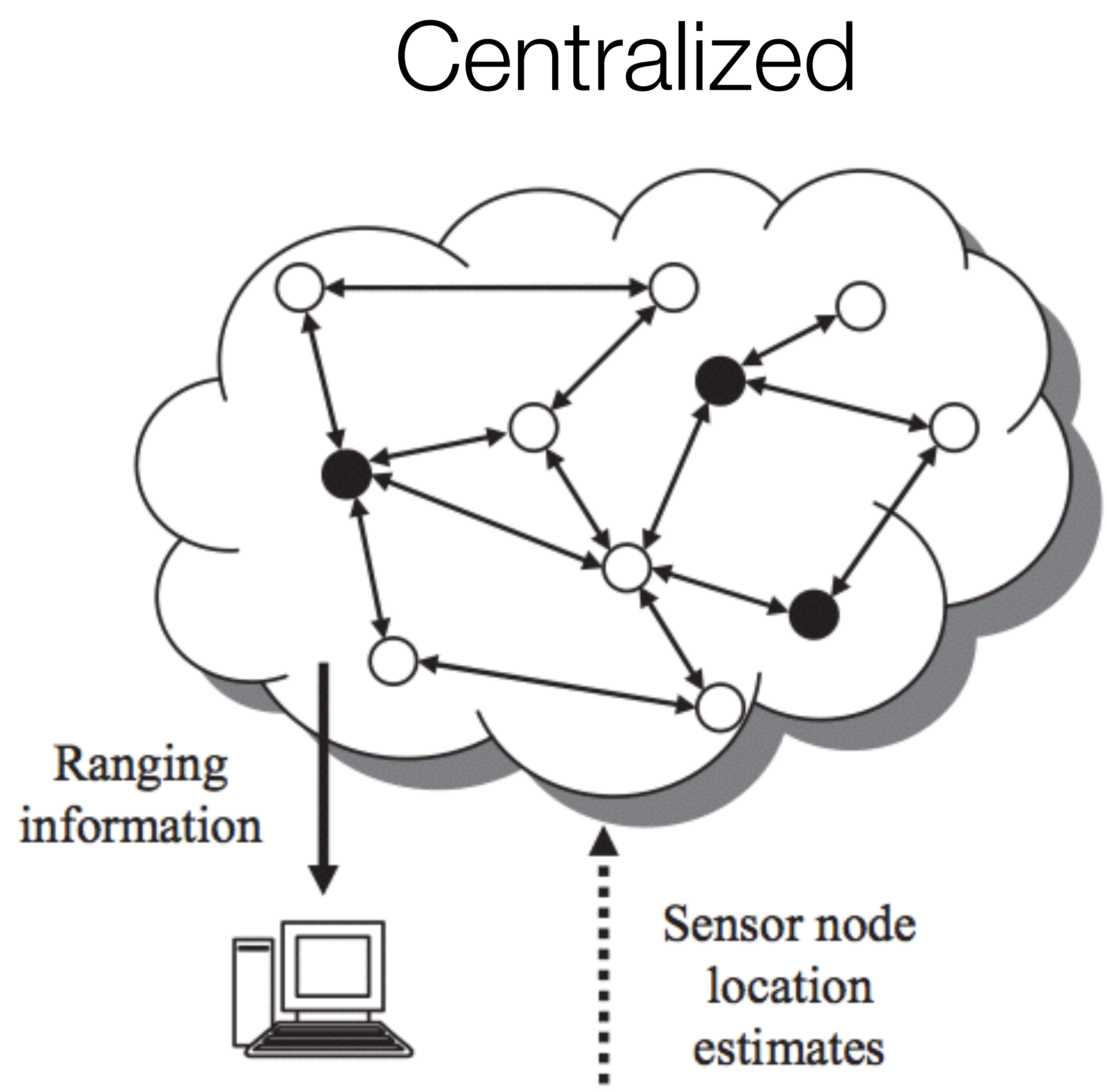
The node joins the existing anchors and helps the remaining nodes in the localization process.

- Node A is the only node in the network that has ranging measurements to three other anchors
- It obtains a position estimate
- Node B, with the help of newly transformed A, obtains a position estimate
- …



Node localization





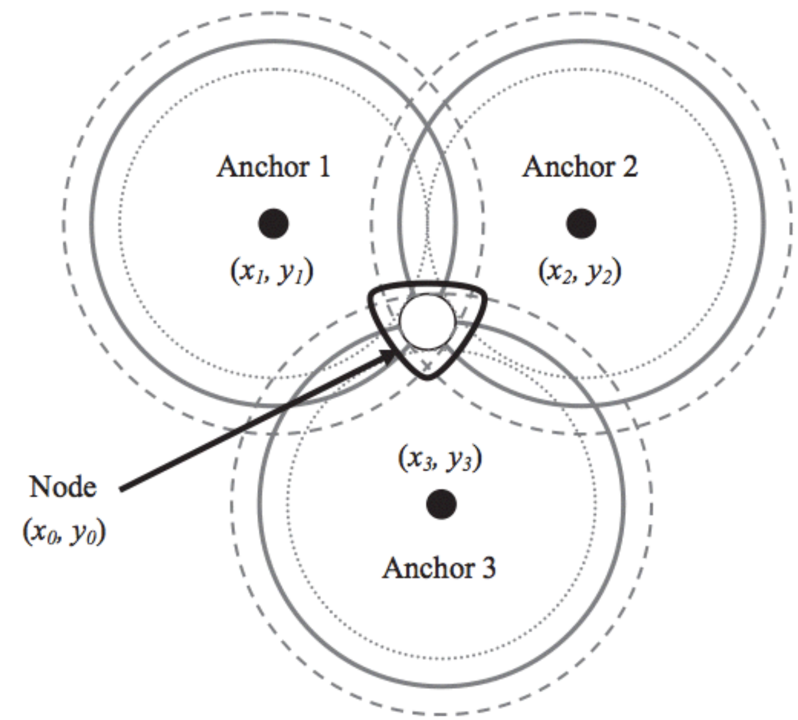
Node localization: position estimation

Least-Squares Algorithm

$$\hat{d}_i = \|\boldsymbol{\theta} - \boldsymbol{\varphi}_i^a\| + \varepsilon_i + \tilde{z}_i = \sqrt{(x - x_i^a)^2 + (y - y_i^a)^2} + \varepsilon_i + \tilde{z}_i$$

$\boldsymbol{\theta} = [x, y]$ node position

$\boldsymbol{\varphi}_i = [x_i^a, y_i^a]$ *i*-th anchor position



$$\mathbf{F}(\boldsymbol{\theta}) = \begin{bmatrix} \sqrt{(x - x_1^a)^2 + (y - y_1^a)^2} \\ \vdots \\ \sqrt{(x - x_M^a)^2 + (y - y_M^a)^2} \end{bmatrix}$$

The problem of localization is essentially to obtain a solution from this set of nonlinear equations

$$E[\hat{\boldsymbol{\theta}}] = [\mathbf{d} - \mathbf{F}(\hat{\boldsymbol{\theta}})]^H [\mathbf{d} - \mathbf{F}(\hat{\boldsymbol{\theta}})]$$

That is equivalent to minimize this equation

Node localization: position estimation

Least-Squares Algorithm

$$E[\hat{\boldsymbol{\theta}}] = [\mathbf{d} - \mathbf{F}(\hat{\boldsymbol{\theta}})]^H [\mathbf{d} - \mathbf{F}(\hat{\boldsymbol{\theta}})]$$

$$\mathbf{F}(\boldsymbol{\theta}) \approx \mathbf{F}(\boldsymbol{\theta}_0) + \mathbf{J}(\boldsymbol{\theta} - \boldsymbol{\theta}_0)$$ Linearization of F(θ) using first-order Taylor series expansion

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f_1}{\partial \theta_1} & \cdots & \frac{\partial f_1}{\partial \theta_M} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_N}{\partial \theta_1} & \cdots & \frac{\partial f_N}{\partial \theta_M} \end{bmatrix}_{\boldsymbol{\theta}=\boldsymbol{\theta}_0}$$

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} \\ \frac{\partial f_3}{\partial x} & \frac{\partial f_3}{\partial y} \end{bmatrix} = \begin{bmatrix} \frac{x - x_1^a}{\sqrt{(x-x_1^a)^2 + (y-y_1^a)^2}} & \frac{y - y_1^a}{\sqrt{(x-x_1^a)^2 + (y-y_1^a)^2}} \\ \frac{x - x_2^a}{\sqrt{(x-x_2^a)^2 + (y-y_2^a)^2}} & \frac{y - y_2^a}{\sqrt{(x-x_2^a)^2 + (y-y_2^a)^2}} \\ \frac{x - x_3^a}{\sqrt{(x-x_3^a)^2 + (y-y_3^a)^2}} & \frac{y - y_3^a}{\sqrt{(x-x_3^a)^2 + (y-y_3^a)^2}} \end{bmatrix}$$

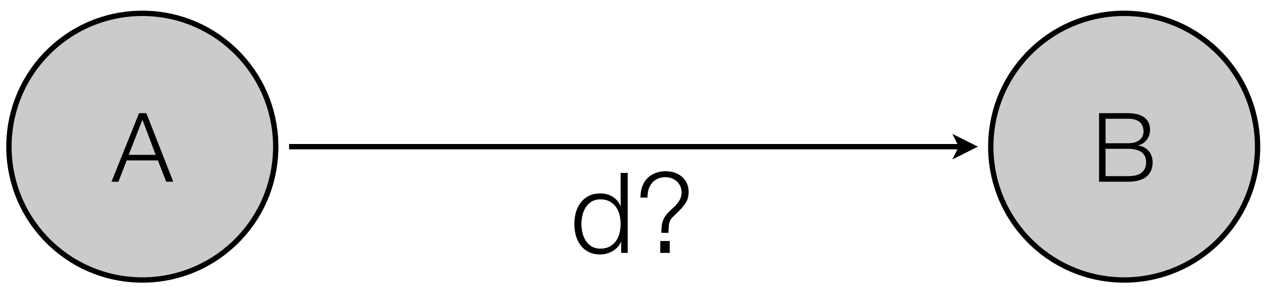
$$\hat{\boldsymbol{\theta}} = \boldsymbol{\theta}_0 + (\mathbf{J}^H \mathbf{J})^{-1} \mathbf{J}^H [\mathbf{d} - \mathbf{F}(\boldsymbol{\theta}_0)]$$

$$\hat{\boldsymbol{\theta}}_{i+1} = \hat{\boldsymbol{\theta}}_i + (\mathbf{J}^H \mathbf{J})^{-1} \mathbf{J}^H [\mathbf{d} - \mathbf{F}(\hat{\boldsymbol{\theta}}_i)]$$ Iterate to avoid local minimum or error due linearization

Received signal strength

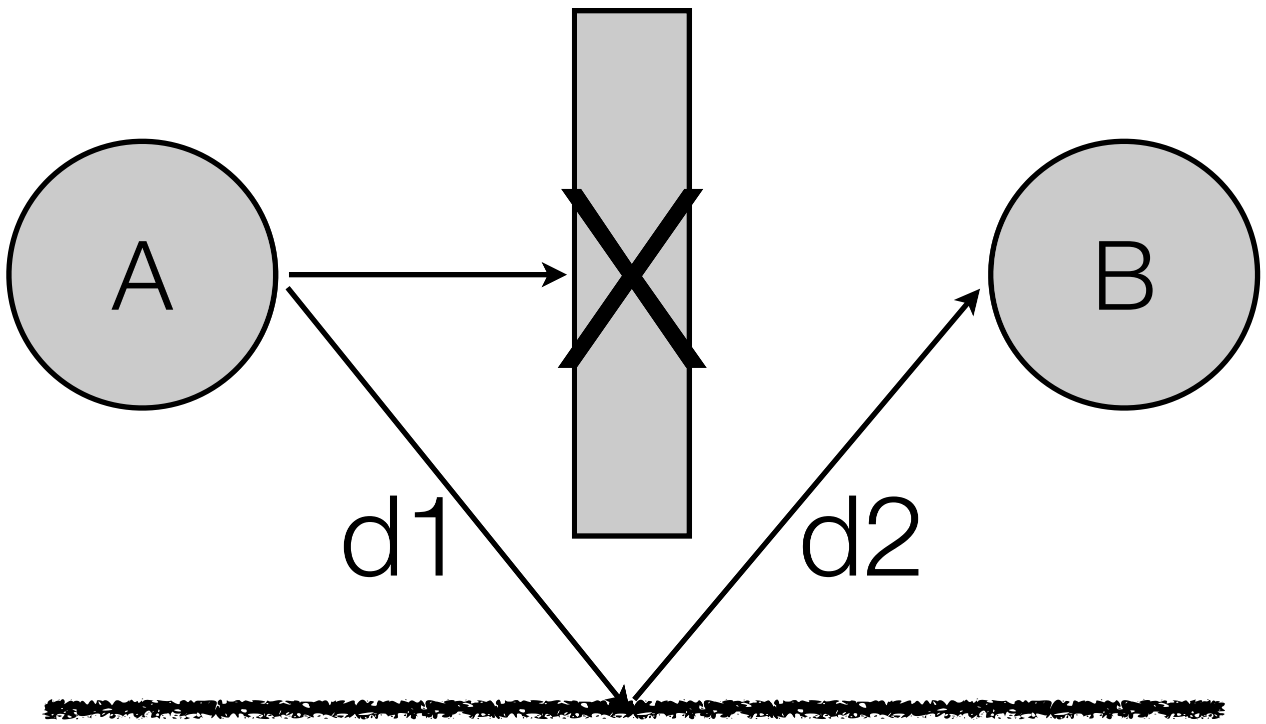
- **PRO**:
  - **low-power**: the RSS of the transmitted signals can be measured during communications without presenting additional energy requirements
  - **simple and cheap**: RSS measurements are relatively inexpensive and simple to implement (RSS indicator provided by the radio module)
- **CONS**:
  - **unreliable**: signal propagation depends on the environment (especially in indoor)
  - **need calibration**: manufacture tolerance and environmental condition

Received signal strength: signal propagation



$$P_{dBm} = 10log_{10}\left(\frac{(A_{tx}k_0)^2}{2d^2}\right) + 30$$

Received signal strength: signal propagation



$$P_{dBm} = 10log_{10}\left(\frac{(A_{tx}k_0)^2}{2d^2}\right) + 30$$

d=d1+d2

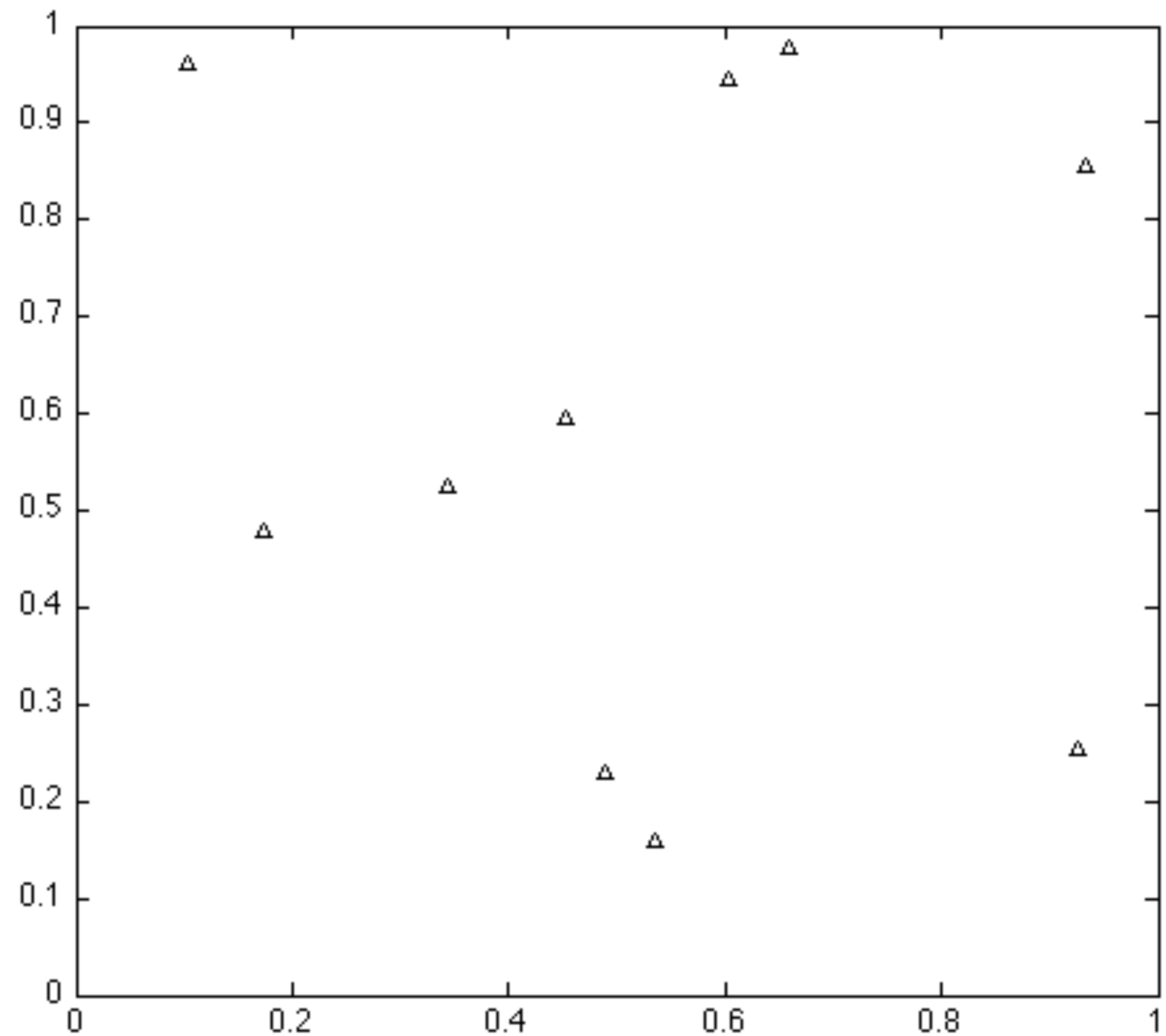
WSN simulator localization: RSS based

- RSS based on true distance from anchor
- Distance from anchor estimated on RSS + noise
- Using estimated distance estimate node position using least-squares algorithm

100 Nodes

10 Anchors

1.0 Radio range



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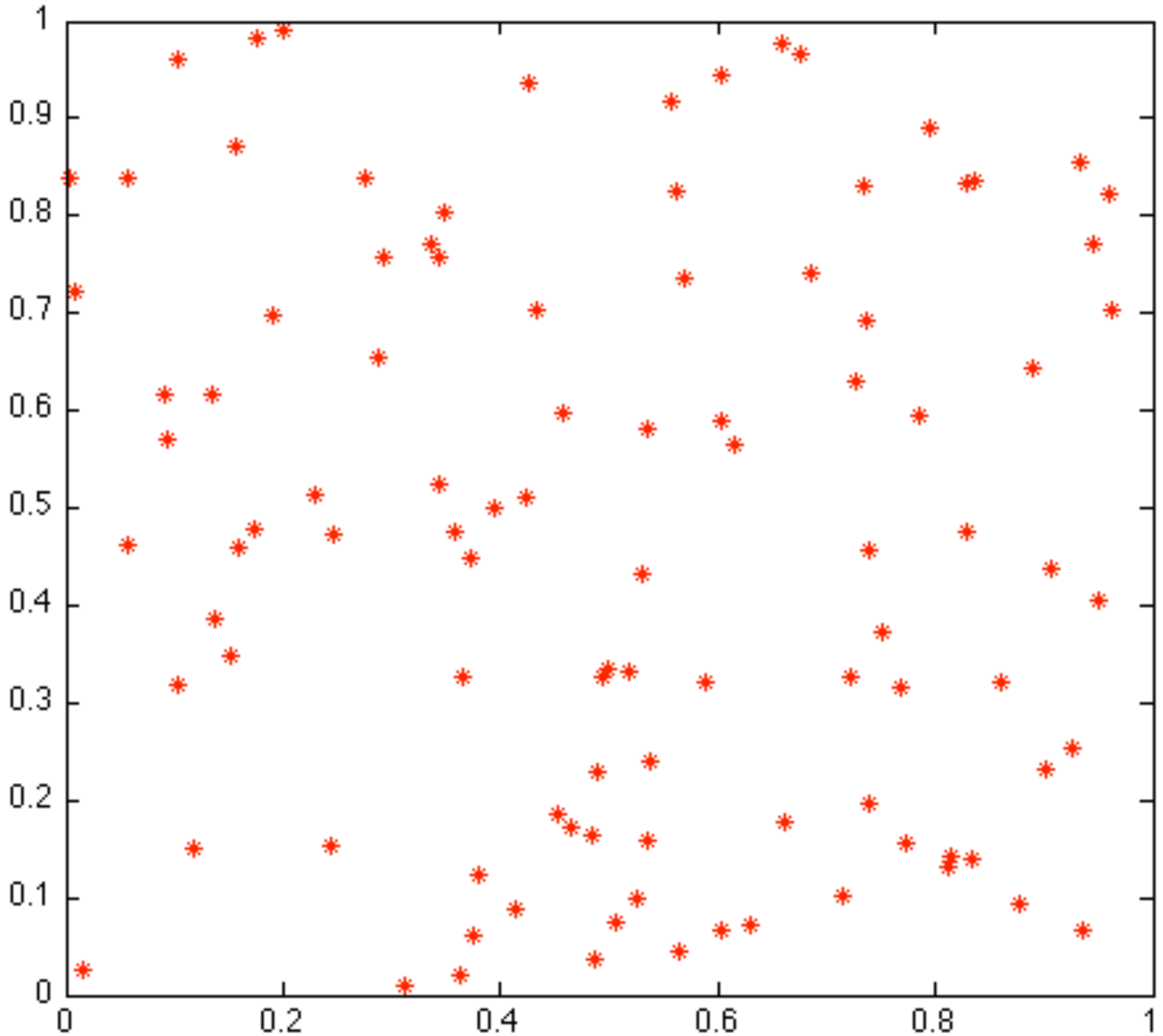

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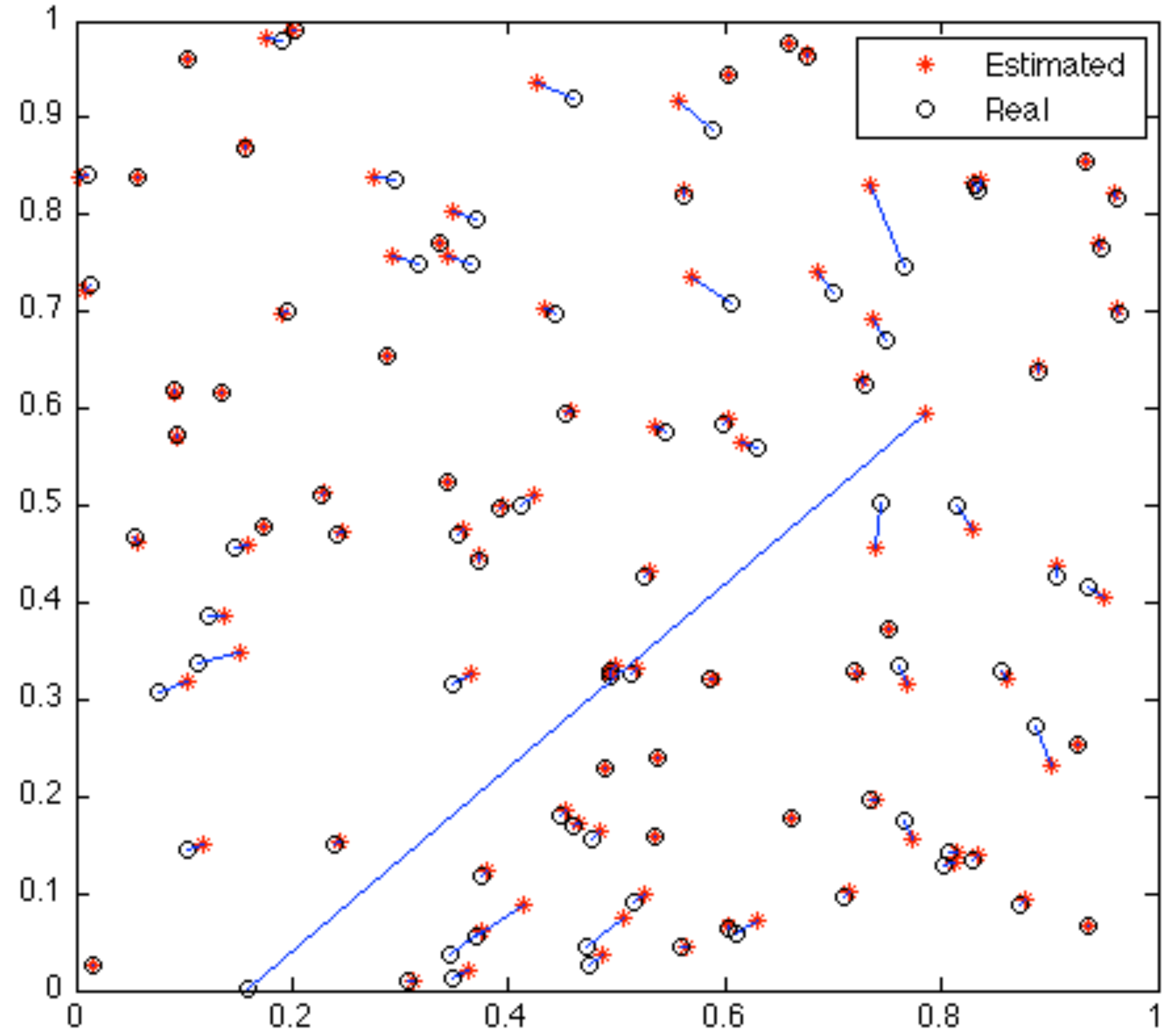

WSN simulator localization: RSS based

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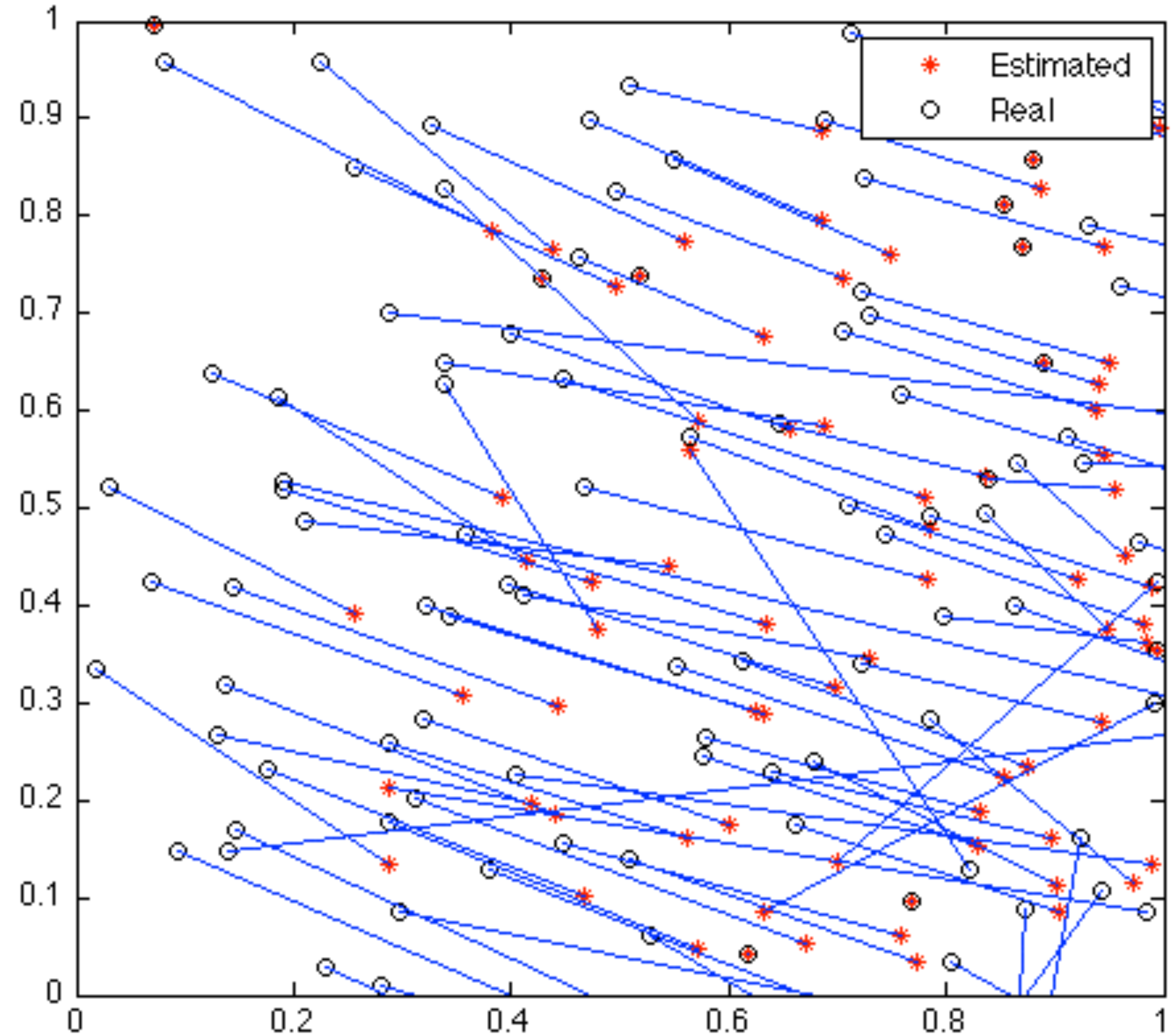
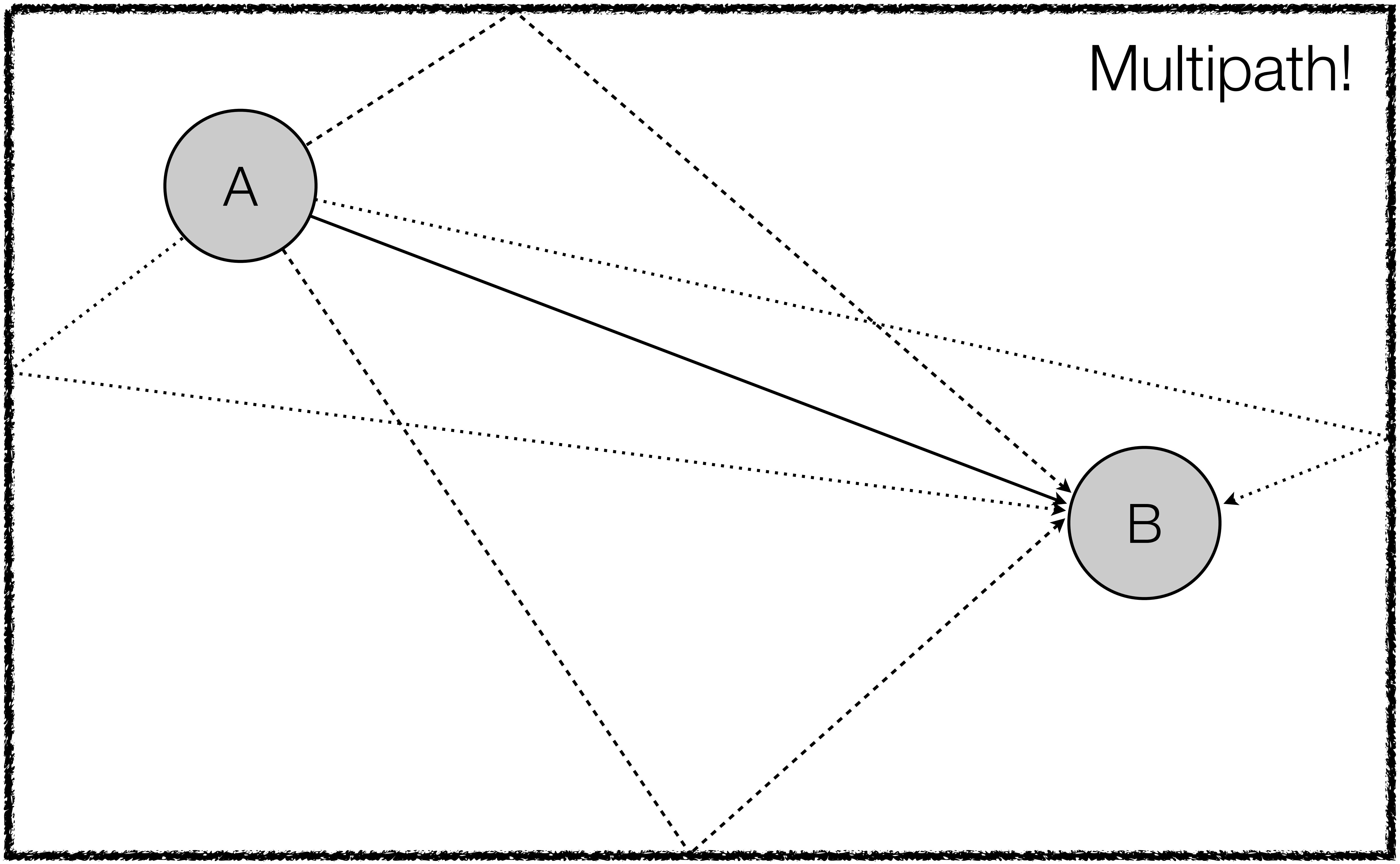
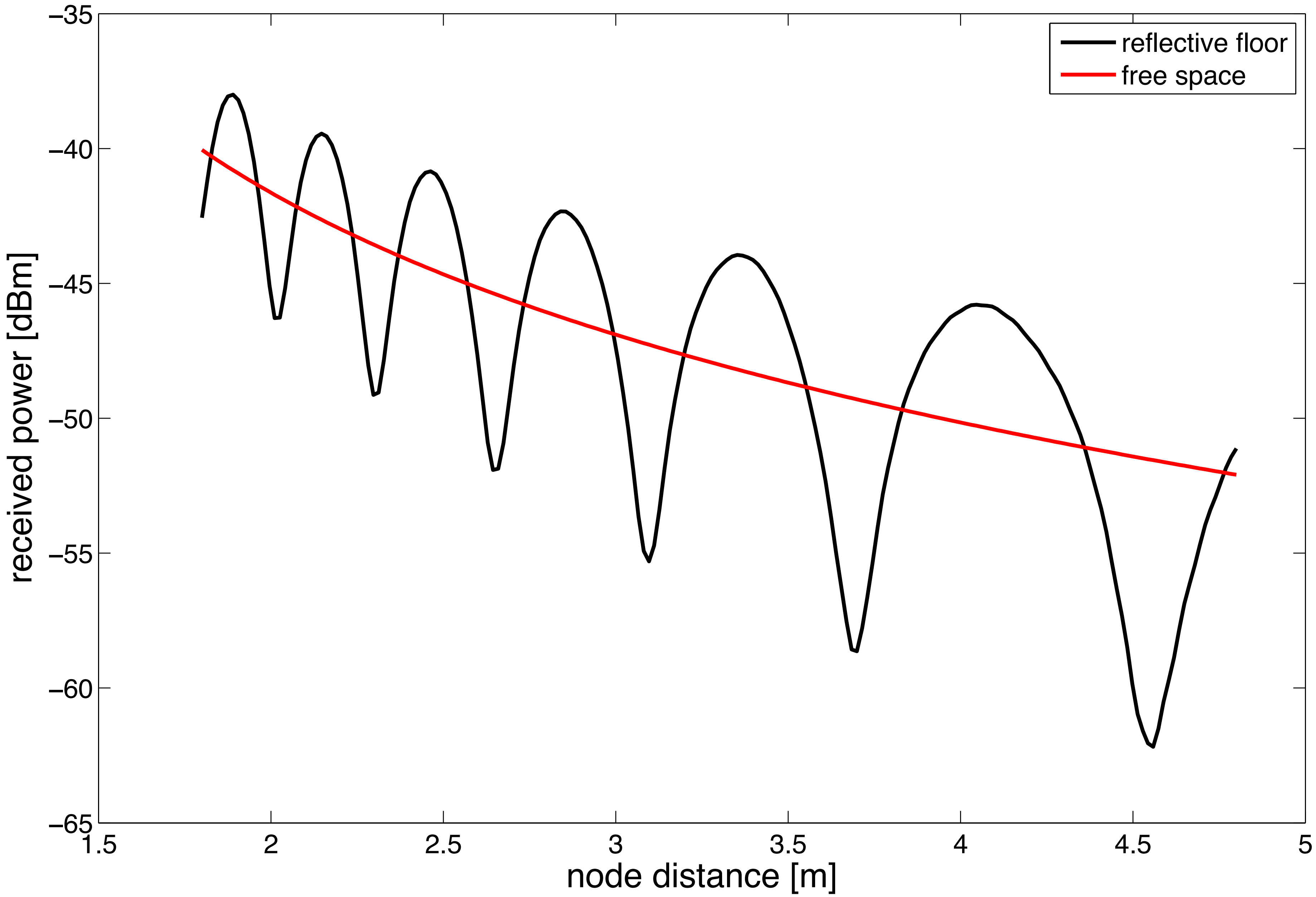
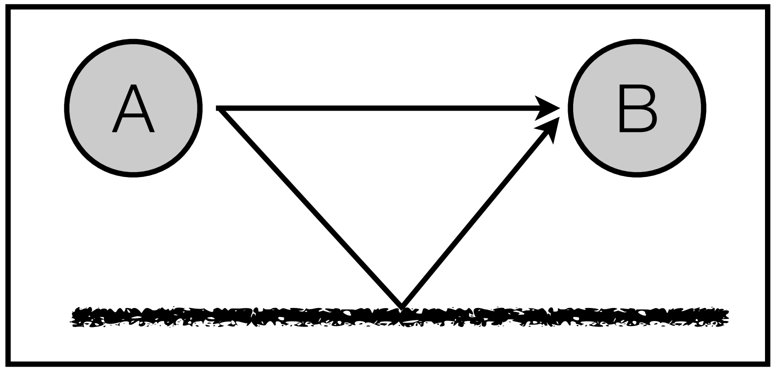


Received signal strength: signal propagation



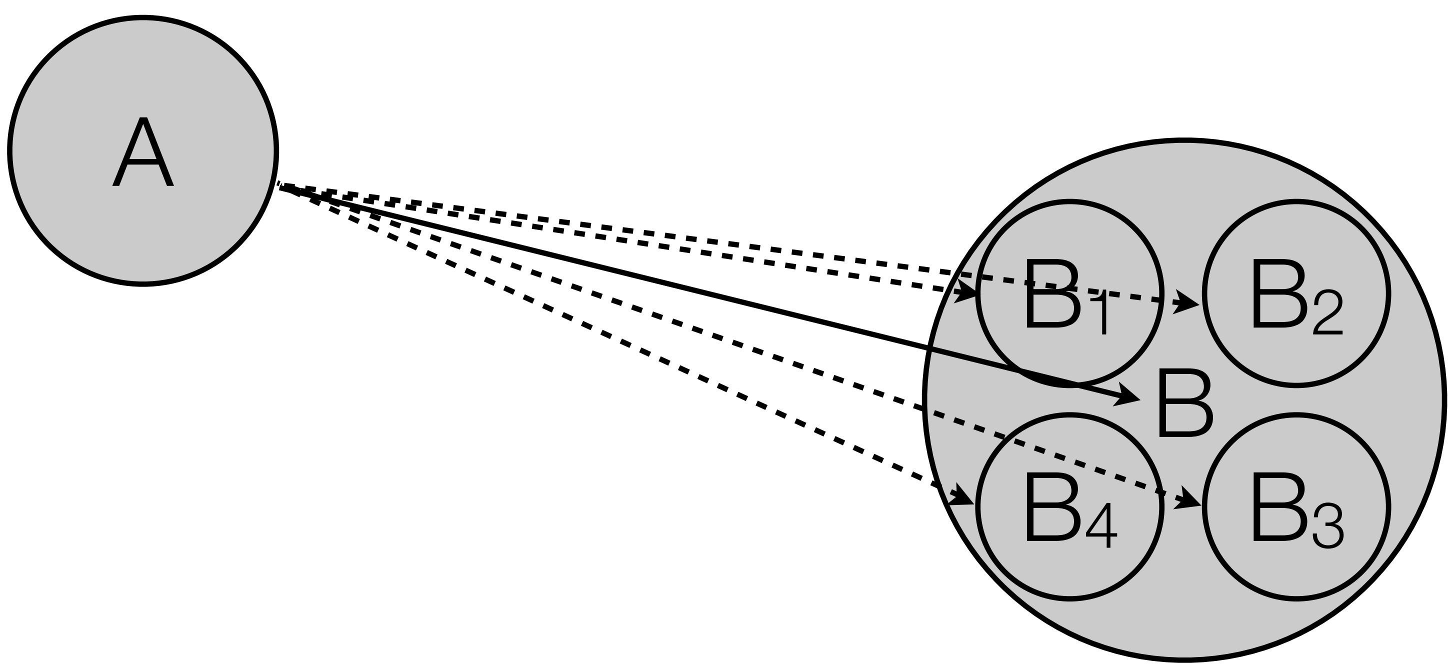
Received signal strength: multipath





Multipath mitigation strategies

- Space diversity approach (SIMO/MIMO) using multiple transceiver/antenna:
    - multipath is not expected to affect all transceivers simultaneously
    - averaging may mitigate variations



$$\hat{d}_{AB} = f(P_{rxAB_1}, P_{rxAB_2}, \ldots, P_{rxAB_N})$$

Simulation model

- Box shaped room
- Line of sight conditions
- Optical ray-tracing propagation model
- Isotropic antenna
- Transmitted signal: $s_{tx}(t)=A_{tx}\sin(2\pi f_0 t)$
- Received signal: combination of LOS signal and single reflection for each wall

Simulation model

$$s(t) = \sum_{i=0}^{6} s_i(t),$$

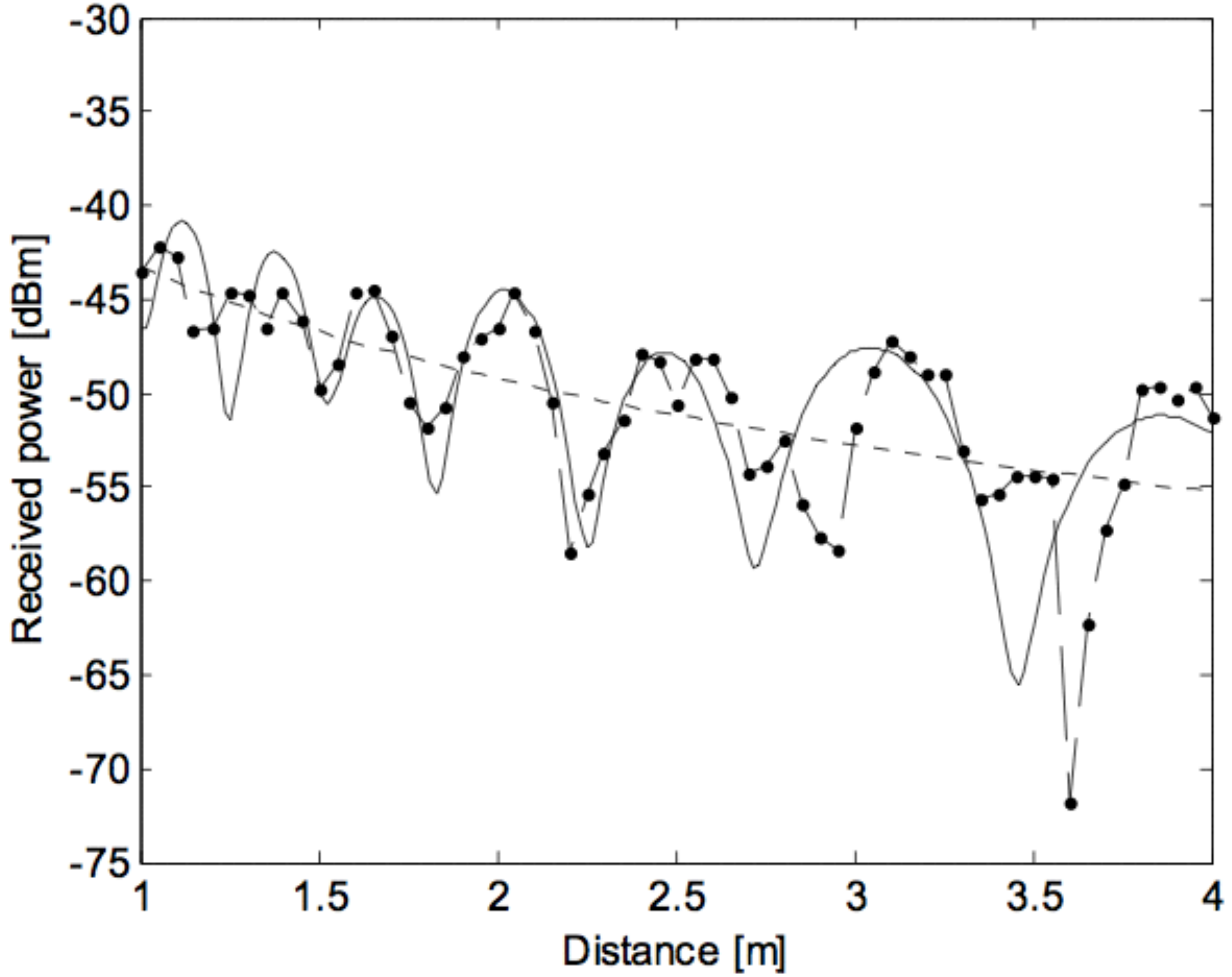
$$s_i(t) = \begin{cases} A_{tx} F(d_0) G_0 \sin\left(2\pi f_0 \left(t - \frac{d_0}{c}\right)\right), i = 0 \\ \\ A_{tx} F(d_i) |\Gamma_i| G_i \sin\left(2\pi f_0 \left(t - \frac{d_i}{c}\right) + \varphi_i\right), i = 1, \ldots, 6 \end{cases}$$

$$\varphi_i = \angle \Gamma_i,$$

$$F(d_i) = c/(4\pi f_0 d_i)$$

Simulator validation

@2.405 GHz



Moschitta, A., et al. "Characterization of a geometrical wireless signal propagation model for indoor ranging techniques." Instrumentation and Measurement Technology Conference (I2MTC), 2012 IEEE International. IEEE, 2012.

Strategy 0: average

$$RSS_{C0} = \frac{1}{N} \sum_{n=0}^{N-1} P_{rxdBm,n}$$

$P_{rxdBm,n}$ power received by the n*th* transceiver

Strategy 1: remove data below the minimum

- Known the room site the minimum RSS from direct signal can be computed
- Rationale: measurement below the minimum are certainly affected by fading
- Strategy: remove measurement below the minimum and average

$$RSS_{C1} = \begin{cases} \frac{1}{N_1} \sum_{n=0}^{N_1-1} P_{rxdBm,n} & N_1 > 0 \\ P_{min,dBm} & N1 = 0 \end{cases}$$

- N_1 number of measurement over the minimum

Strategy 2: minimum correction

- The received power measurements collected by the N transceivers are preliminarily corrected, substituting the measurement below the limit with the limit itself

$$RSS_{C2} = \frac{1}{N} \sum_{n=0}^{N-1} max(P_{rxdBm,n}, P_{min,dBm})$$

Strategy 3: correction and maximum removal

- The maximum collected value is discarded then Strategy 2 is applied

$$RSS_{C3} = \frac{1}{N-1} \sum_{n=0}^{N-2} max(P_{rxdBm,n}, P_{min,dBm})$$

Strategy 4: correction and min-max average

- The received power measurements collected by the N transceivers are preliminarily corrected, substituting the measurement below the limit with the limit itself

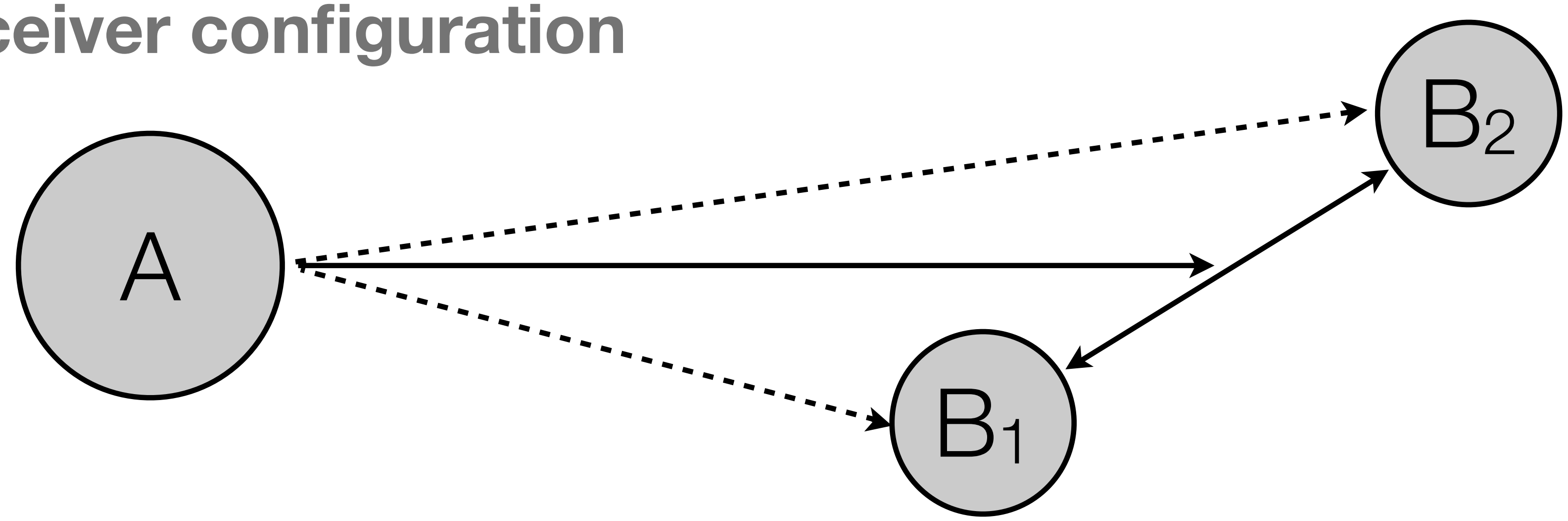
- Arithmetic mean of the maximum and minimum corrected values

$$RSS_{C4} = \frac{RSS_{max} - RSS_{min}}{2}$$

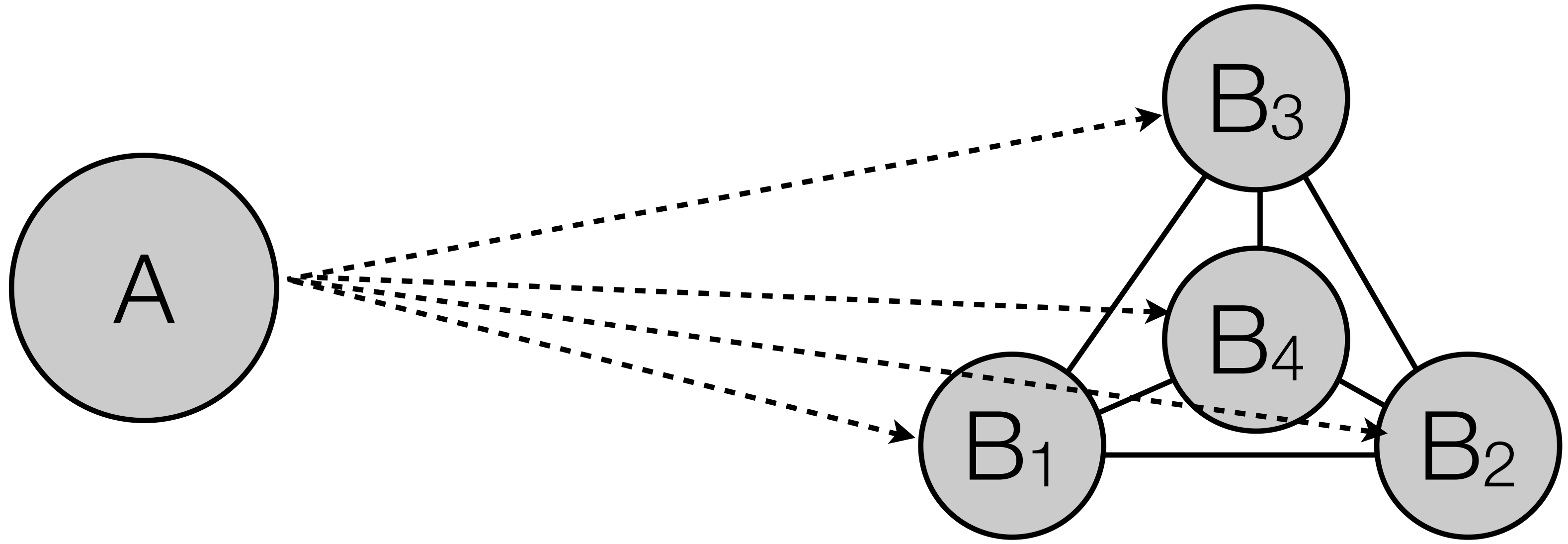
$$RSS_{max} = max(P_{cdBm,0}, \ldots, P_{cdBm,N-1})$$
$$RSS_{min} = min(P_{cdBm,0}, \ldots, P_{cdBm,N-1})$$

Virtual node configuration

double transceiver configuration

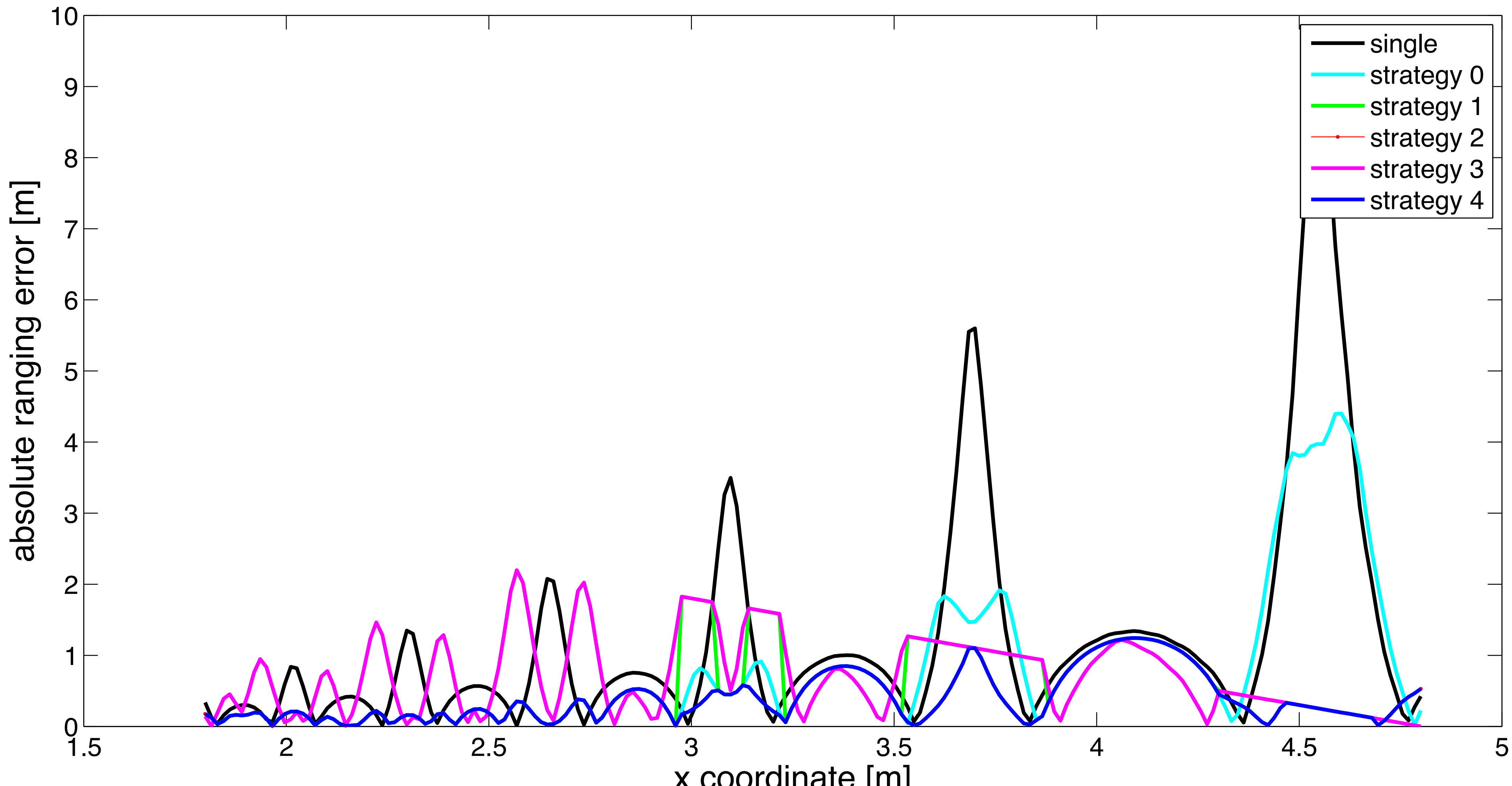


tetrahedral configuration



node orientation
may be random

Double transceiver: moving trough a line in the room



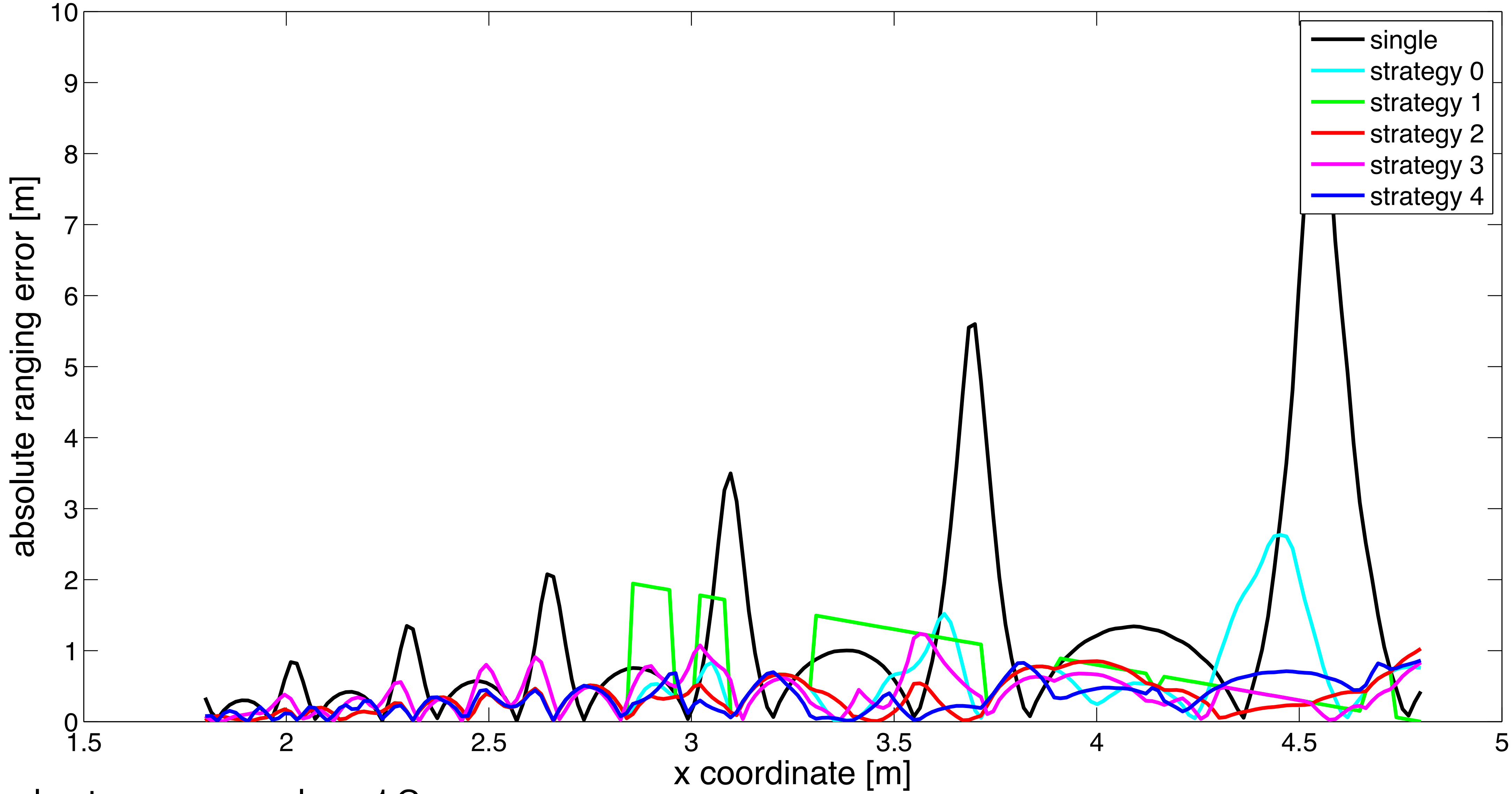
distance between nodes 16cm

anchor position (0.8, 3, 1)

target node spans through the line from (1.8, 3, 1) to (4.8, 3, 1)

A simple ranging technique based on received signal strength measurements in a narrowband 2.4 GHz channel: a space diversity approach, I. Neri et al., M&N 2013

Tetrahedral conf: moving trough a line in the room



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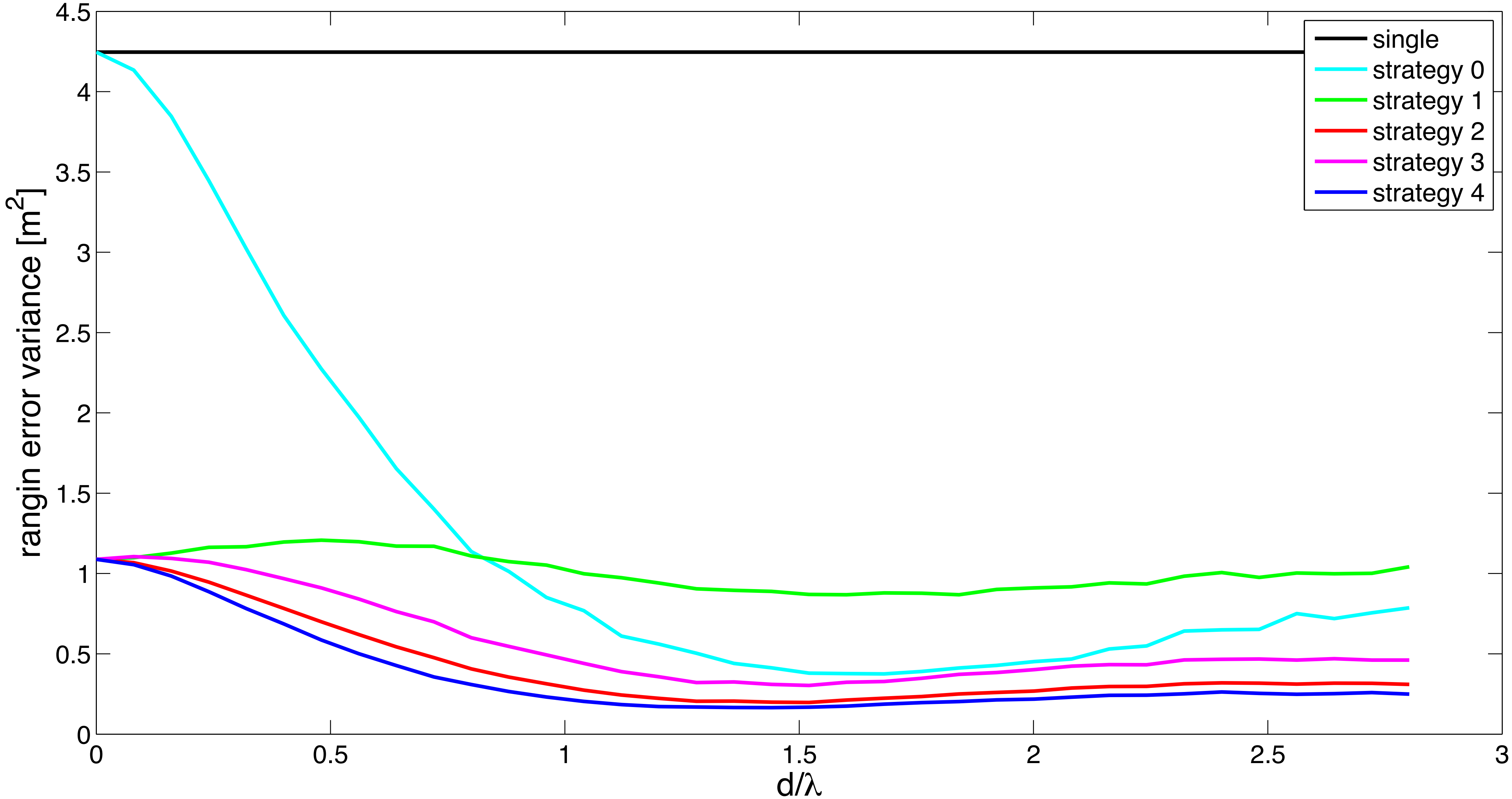
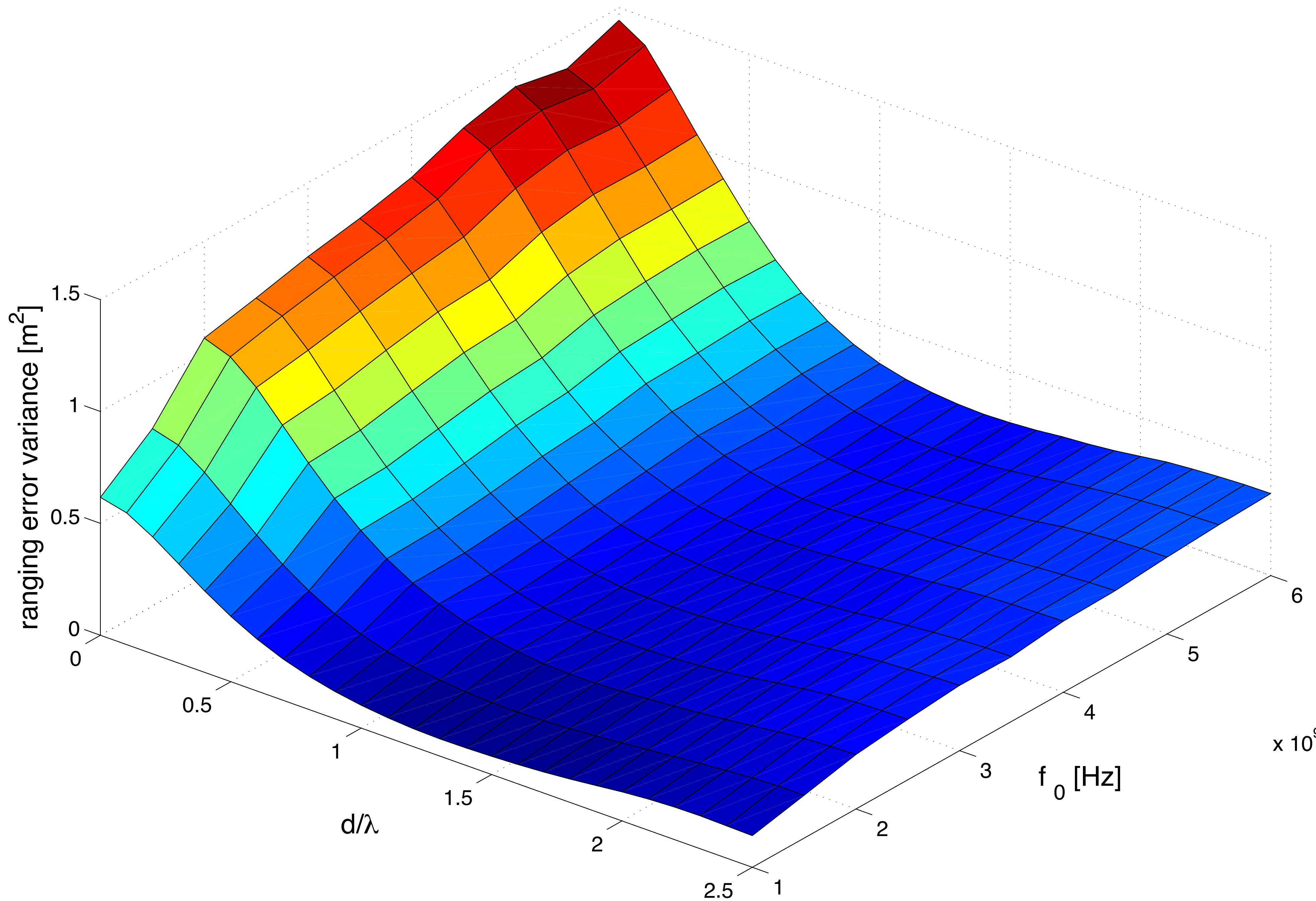
Mobile node transceivers distance optimization



A simple ranging technique based on received signal strength measurements in a narrowband 2.4 GHz channel: a space diversity approach, I. Neri et al., M&N 2013

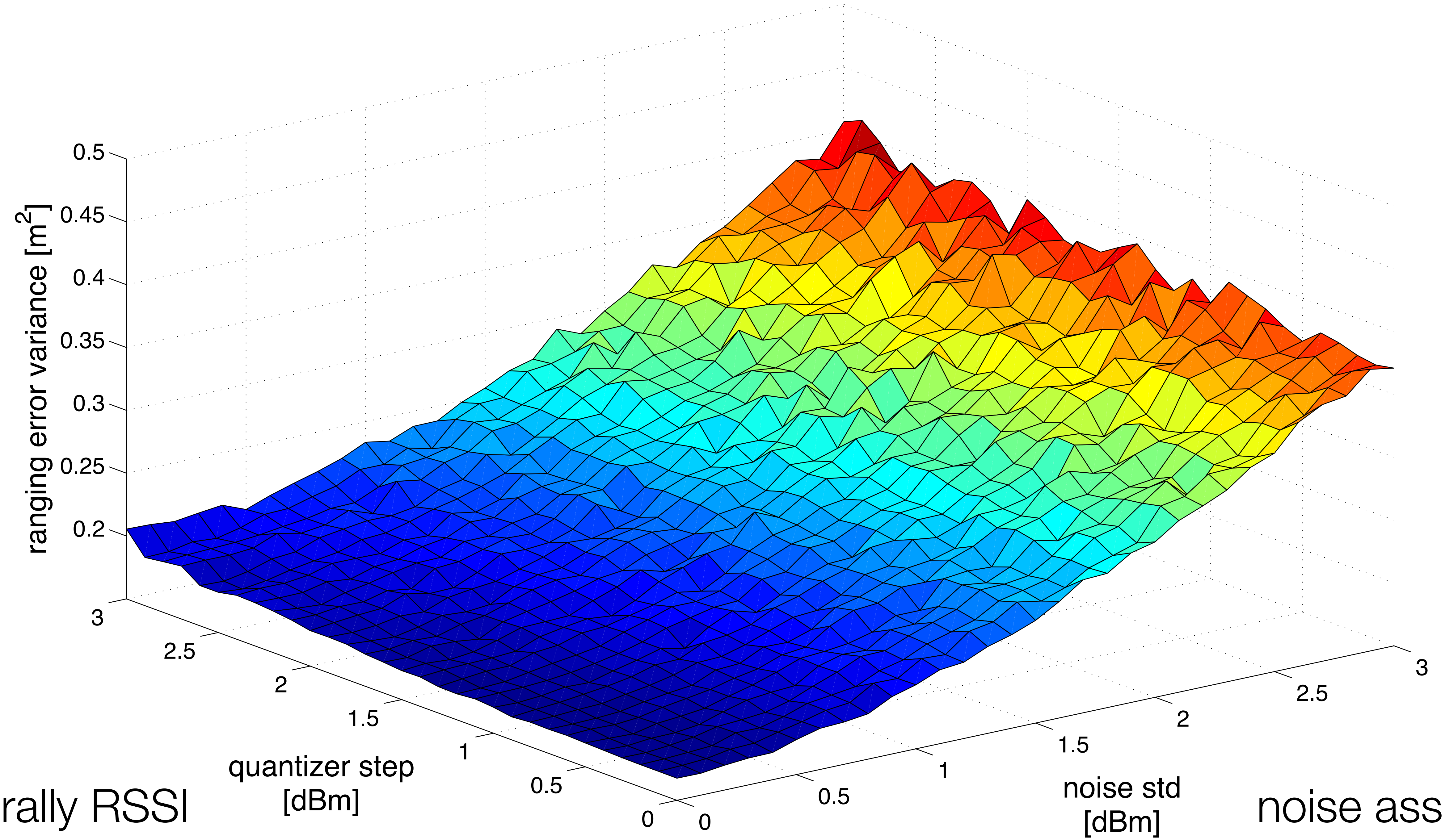
Frequency dependance on the optimal d/λ factor



optimal factor d\λ ≅1.4 -> 17.5cm for 2.4GHz

A simple ranging technique based on received signal strength measurements in a narrowband 2.4 GHz channel: a space diversity approach, I. Neri et al., M&N 2013

Quantization and noise

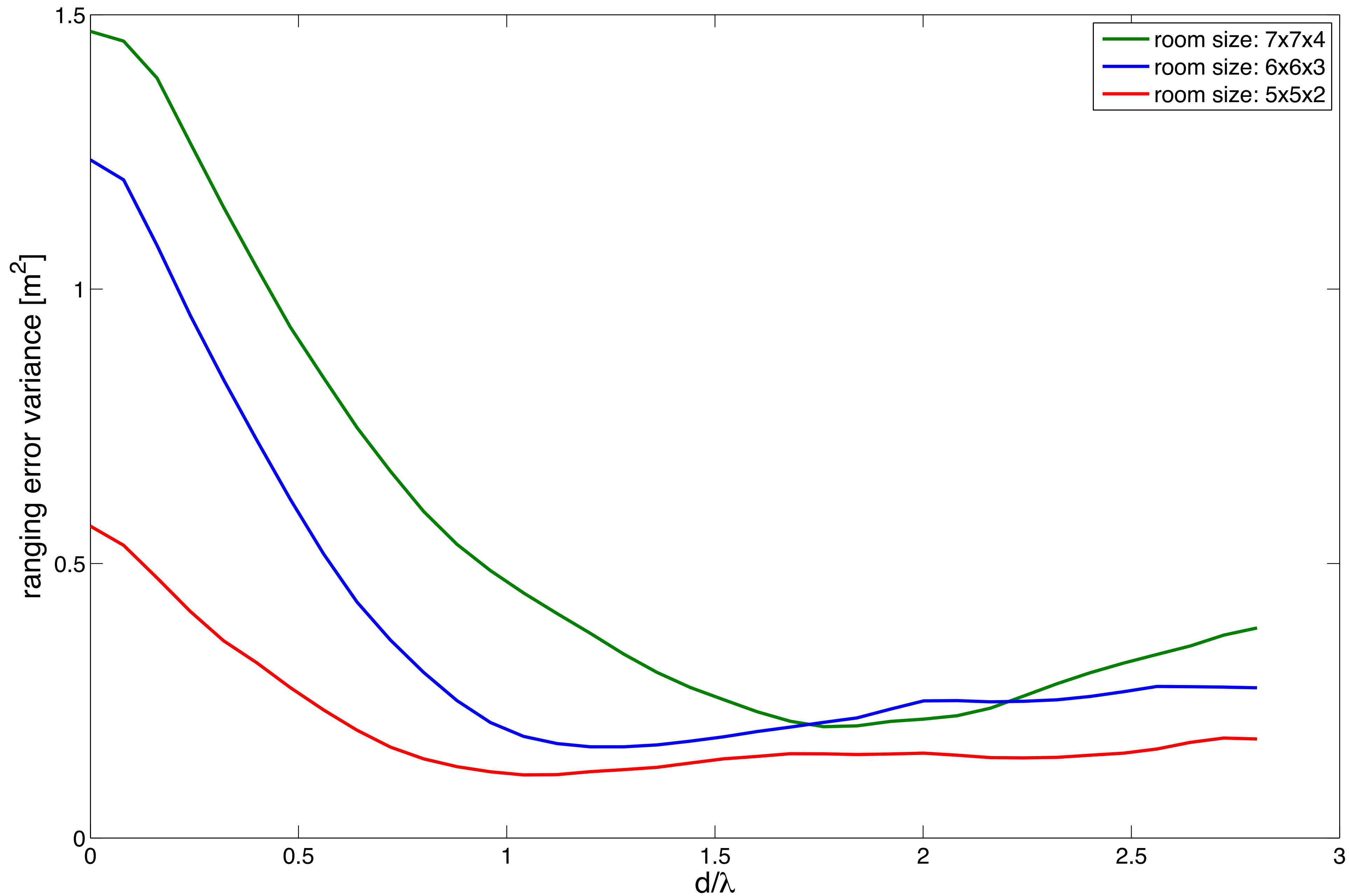


generally RSSI quantization step = 1/2 dBm

noise assumed as zero mean AWGN in dBm

A simple ranging technique based on received signal strength measurements in a narrowband 2.4 GHz channel: a space diversity approach, I. Neri et al., M&N 2013

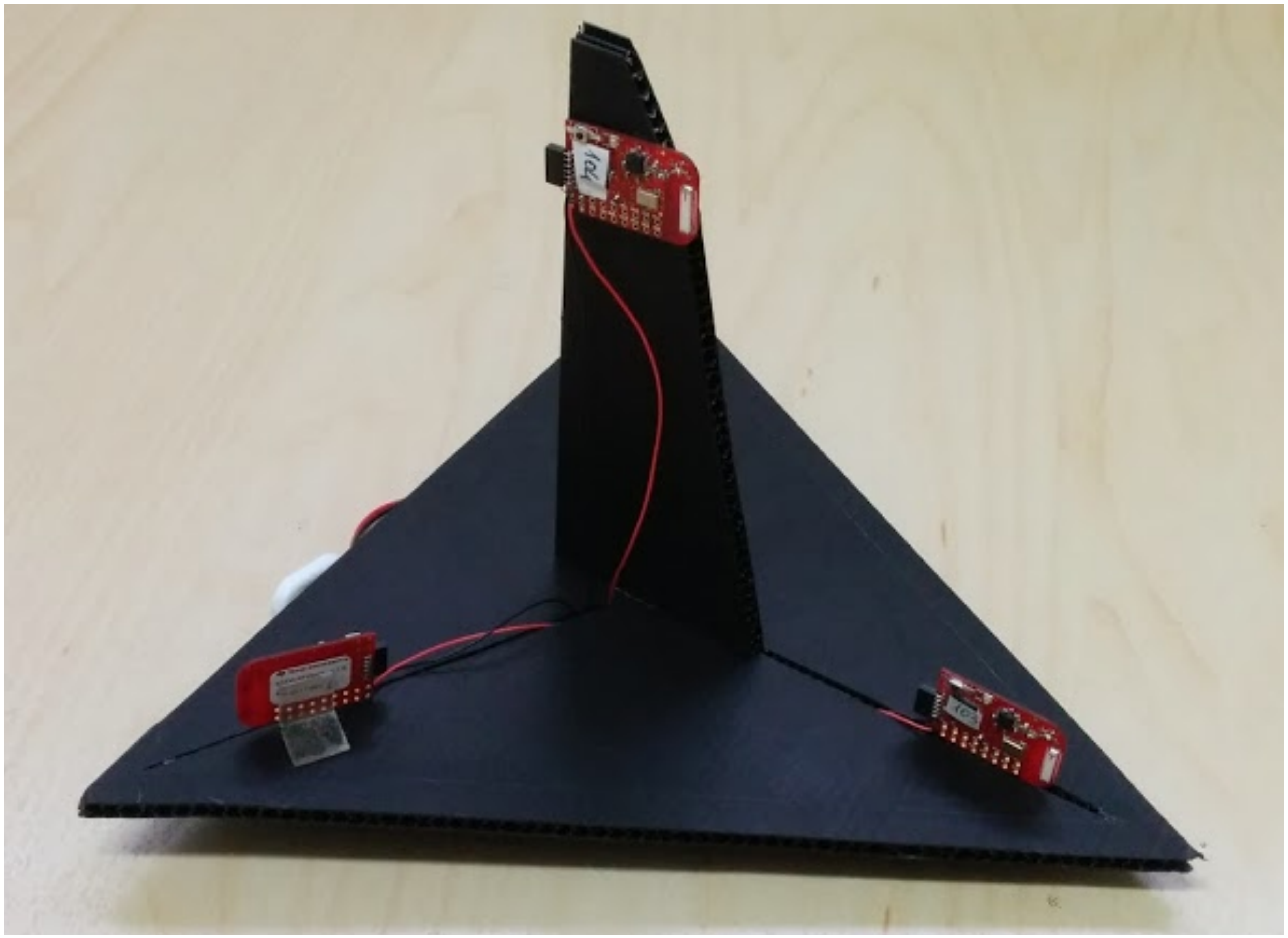
Room size



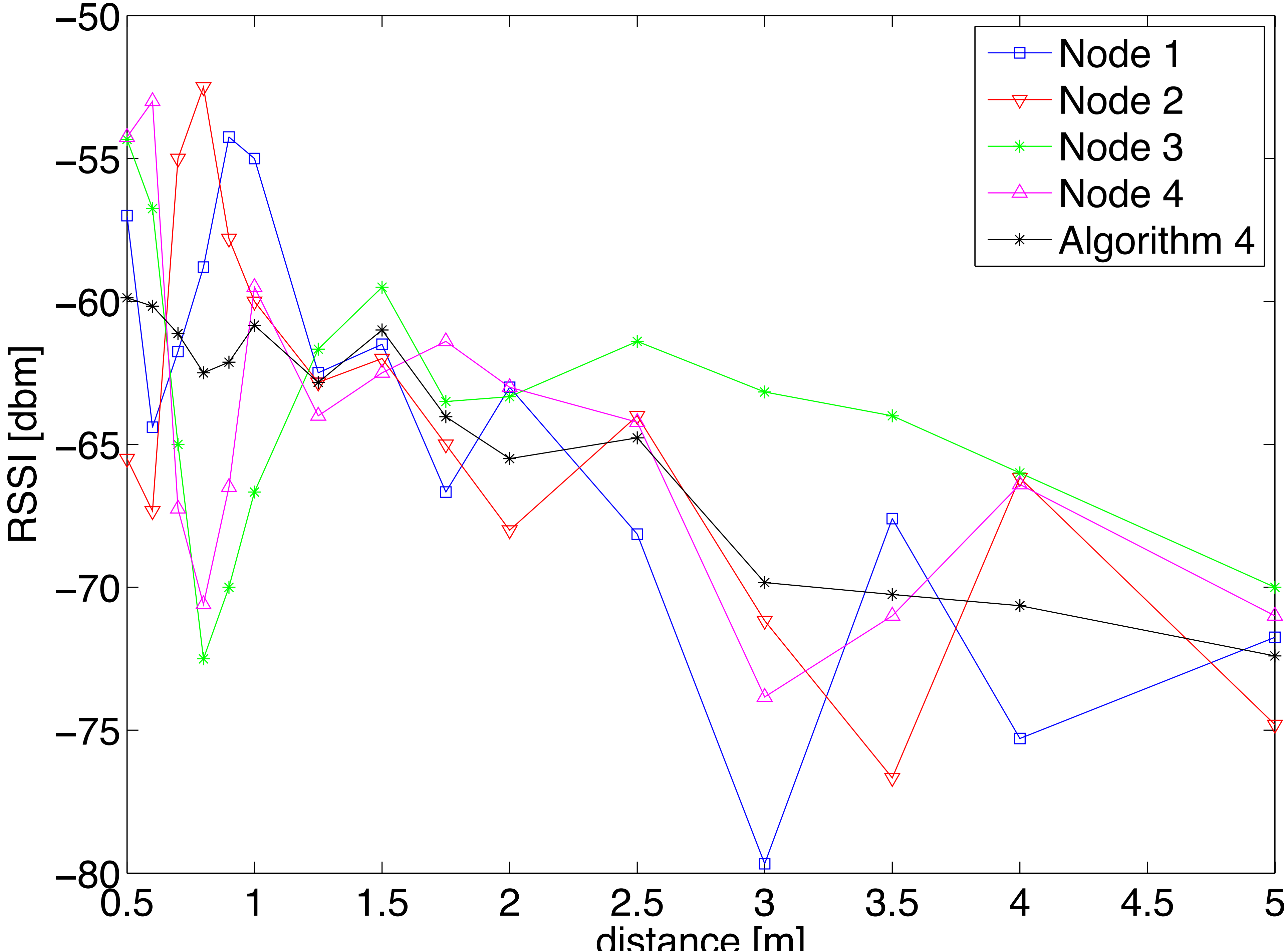
optimal factor d\λ depends on the room geometry

A simple ranging technique based on received signal strength measurements in a narrowband 2.4 GHz channel: a space diversity approach, I. Neri et al., M&N 2013

Experiment



Experiment



−50
−55
−60
−65
−70
−75
−80
RSSI [dbm]
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
distance [m]
Node 1
Node 2
Node 3
Node 4
Algorithm 4

Localization energy budget

- In multiple antennas/transceivers scenario the number of transmissions increases
- Estimated cost per communications: 221µJ
- For a two-transceivers macronode additional 221µJ needed
- For a tetrahedral macronode additional 633µJ needed

Thank you for your attention!

igor.neri@nipslab.org