System Study of a 60 GHz Wireless-Powered Monolithic Sensor System

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Where innovation starts

Outline

- Motivation
  - Wireless-Powered
  - Monolithic
  - 60 GHz
- System Overview
- System-Level Energy Budget Calculation
  - Comparison with a 2.4 GHz RFID system
- Conclusions

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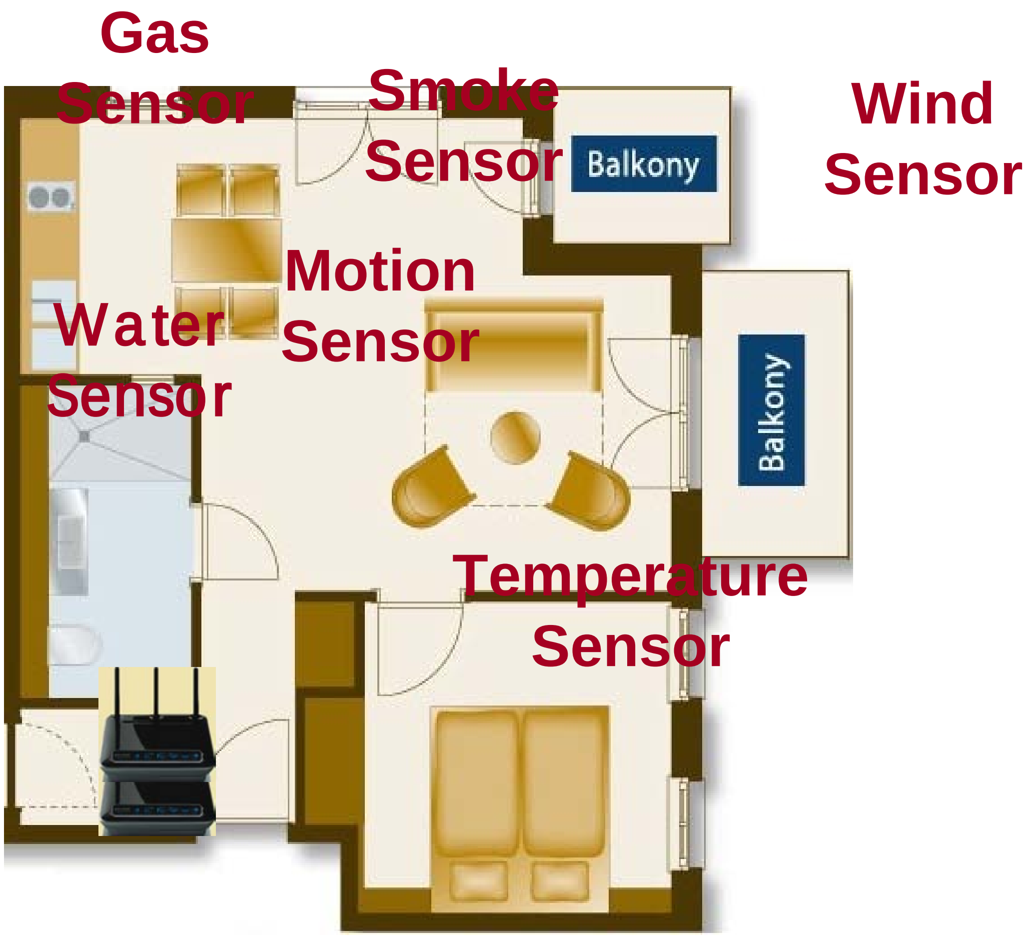
Sensors are Going Wireless



Battery-Operated Wireless Sensors

Advantage:

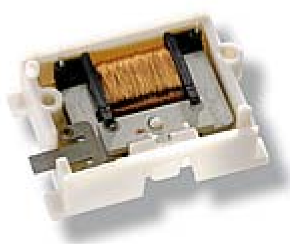
- Easy deployment
- Lifetime of many years

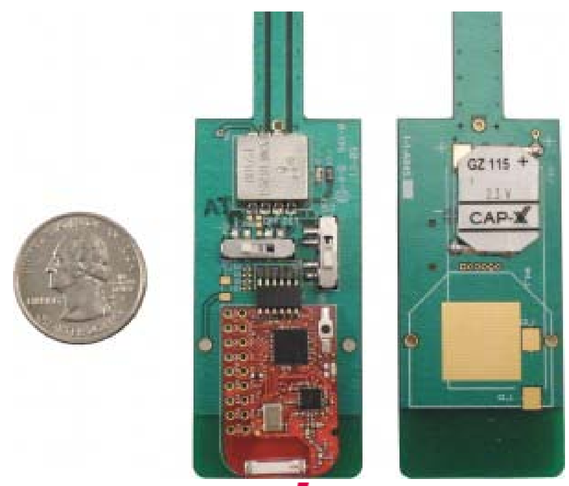
Disadvantage:

- Limited life time
- Battery replacement
- Big Size
- Relative higher cost

Wireless-Powered Wireless Sensors

- **Self-Powered sensors using energy harvesting**
  - **Vibration/Motion**
  - **Temperature difference**
  - **Light**
  - **Pressure**
  - **RF**
  - **…**





Wireless-Powered Wireless Sensors

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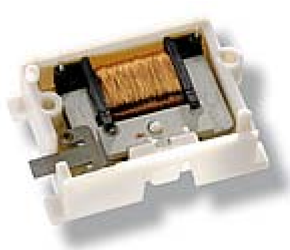

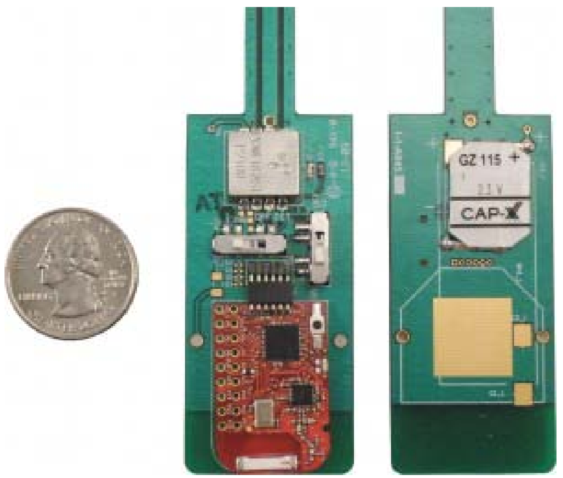

Energy Harvesting using RF (i.e. Wireless-Powered) is a natural choice for Wireless Sensors.

Monolithic

- **Current energy scavenging sensors implement sensing and energy scavenging in two separate modules:**
  - **Larger size and higher price;**
  - **Not robust in harsh environments or on moving objects.**

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Monolithic

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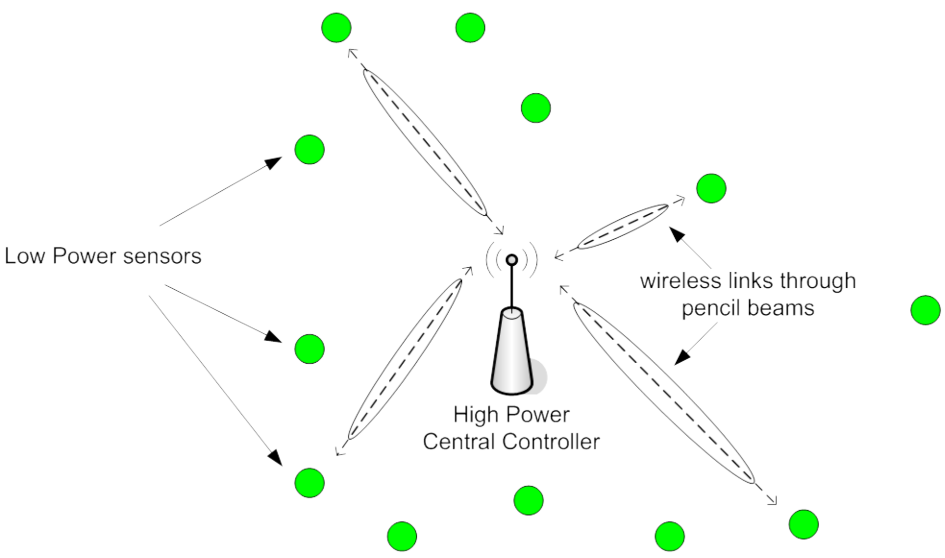
- **Monolithic sensor nodes:**
  - **On-chip energy harvesting, sensing and transceiving**
  - **Ultra low power TxRx**
  - **Small size (mm^2)**

60 GHz

- Small wavelength (5*mm*), possible to
  - Integrate antenna on-chip,
  - Create large antenna arrays to
    - provide high antenna gain,
    - Create highly directional pencil beams.

- Wide bandwidth available at 60 GHz enables
  - High data rate in the order of Gbits/s,
  - short transmission burst.

60 GHz Wireless-Powered Monolithic Sensor System



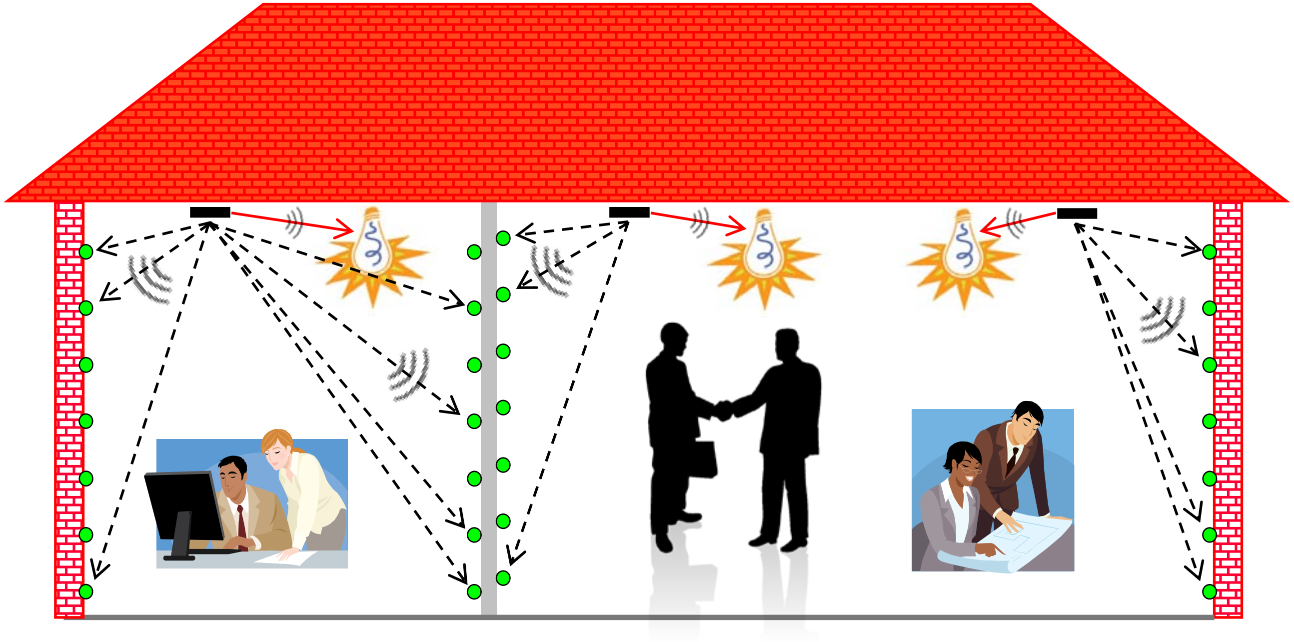
•Fully integrated sensor nodes with on-chip sensing, antenna, transceiver and energy scavenging.
•Central controller wirelessly transmits data and energy to sensor nodes.

A typical sensing cycle

1. Downlink: central controller sends energy and data to a sensor;
2. Uplink: the sensor sends required info. back to central controller.

•Work in ongoing in the STW project "PREMISS"(<u>P</u>ower <u>RE</u>duced <u>M</u>onolith<u>I</u>c <u>S</u>ensor <u>S</u>ystem).

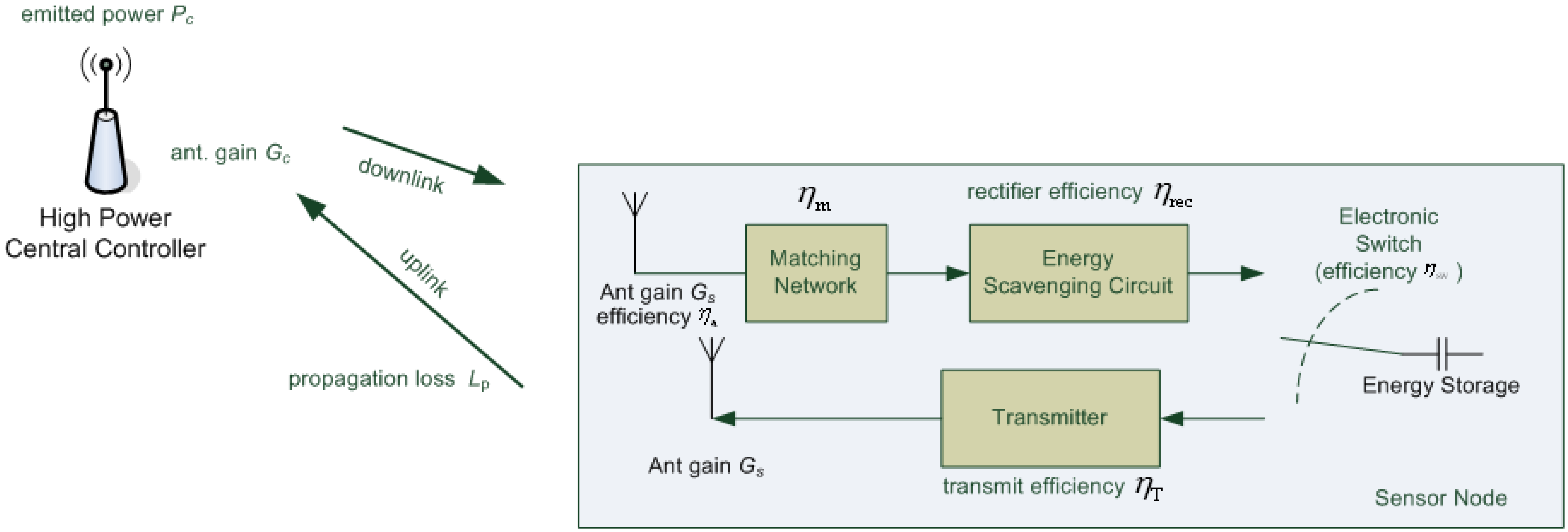
Possible Applications



Smart Wall

•Temperature measurement
•Proximity sensing (used for e.g. lighting control)
•Presence detection and tracking
•Activity monitoring

System Architecture



Central Controller Antenna gain and Path Loss

- **At the central controller, the antenna gain**

$$G_c = 10 \times \log_{10}(N_{\mathrm{a}})$$

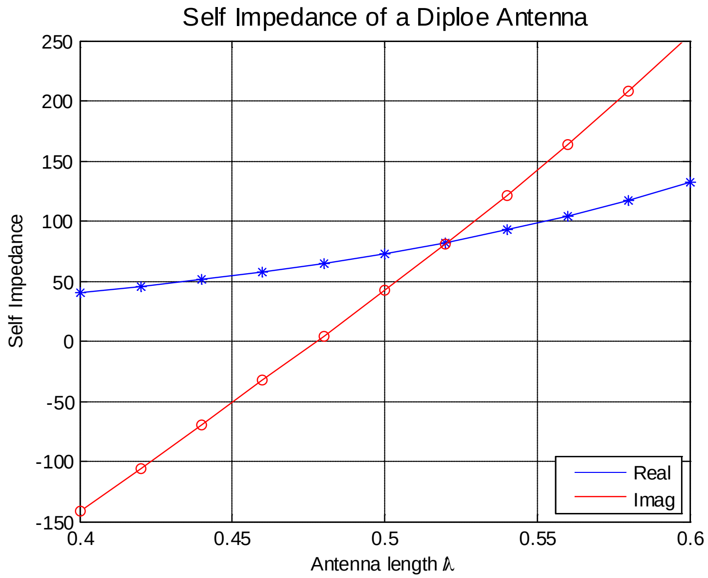
- **Free space propagation loss**

$$L_{\mathrm{P}} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$$

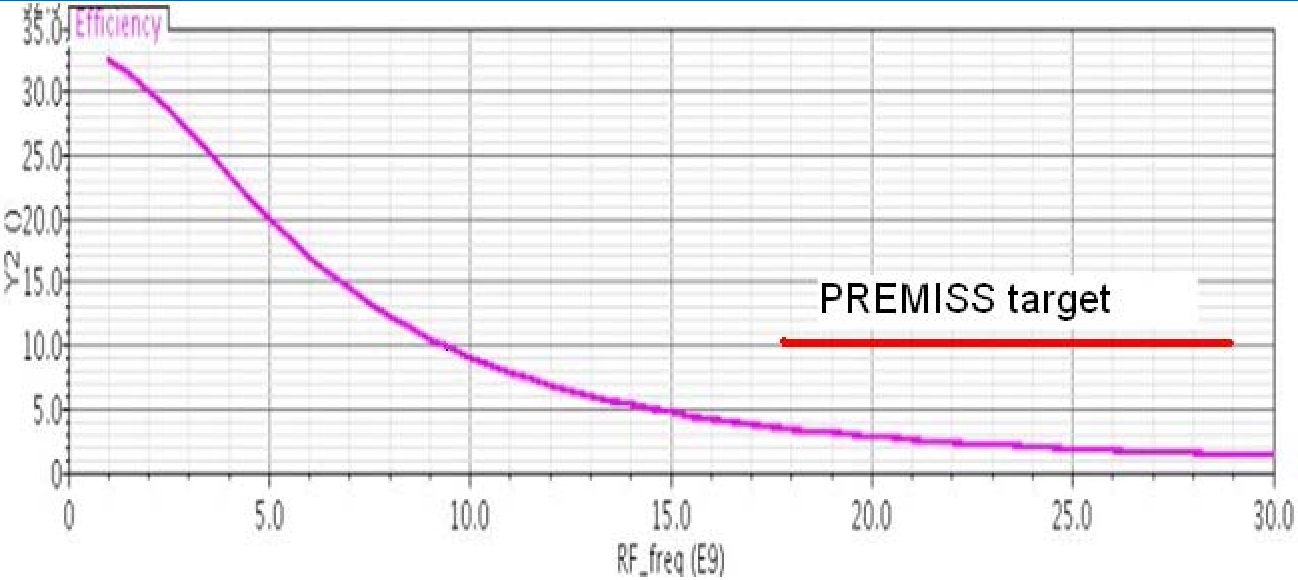
Sensor antenna related considerations

- **At 60 GHz, integration of antenna on chip is possible.**
- **Due to lossy substrate, the antenna efficiency is lower.**

•Due to small chip size (e.g. 1mm^2 for the PREMISS project), the antenna impedance becomes more capacitive and results in more loss on the matching network.



Rectifier Efficiency



- The rectifier efficiency is heavily dependent on the frequency.
- At 2.4 GHz, 31% was achievable using 65 nm CMOS technology at an input power level of -19 dBm.
- For 60 GHz applications, the efficiency drops to 2% using state-of-the-art design.
- We project an improvement to about 10% for 60 GHz systems.

Loss on Electronic Switch and Capacitor Leakage.

- **An electronic switch is required to switch the energy storage capacitor between charging and discharging mode.**
- **The efficiency of this switch can be assumed 90%.**
- **For the application considered in PREMISS, the energy stored is immediately used for transmission. Hence energy leakage is negligible.**

Downlink Energy Budget

- **The available power at the capacitor**

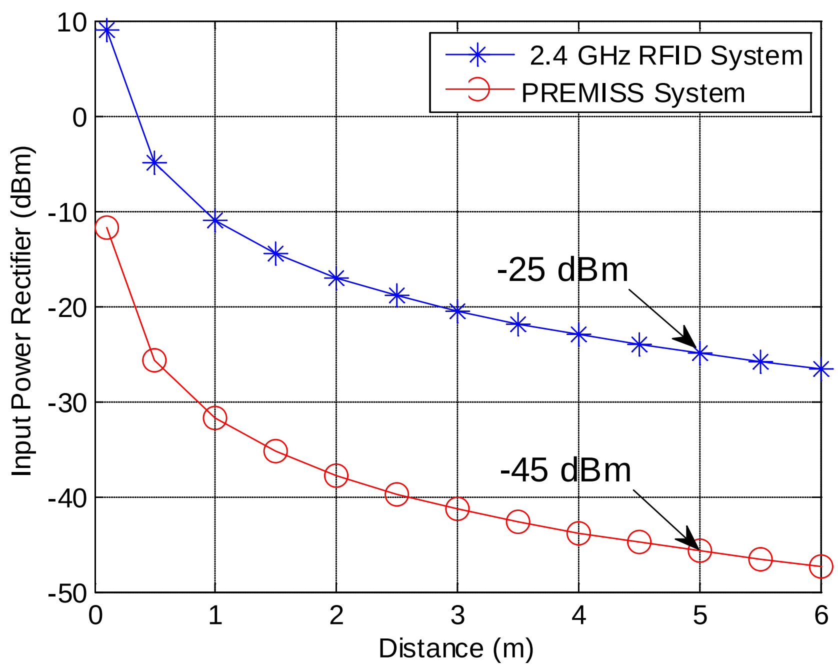
$$P_s = \frac{P_e G_c G_s}{L_p} \eta_a \eta_m \eta_{sw} \eta_{rec}$$

- **We compare the PREMISS system with a typical 2.4 GHz RFID system**

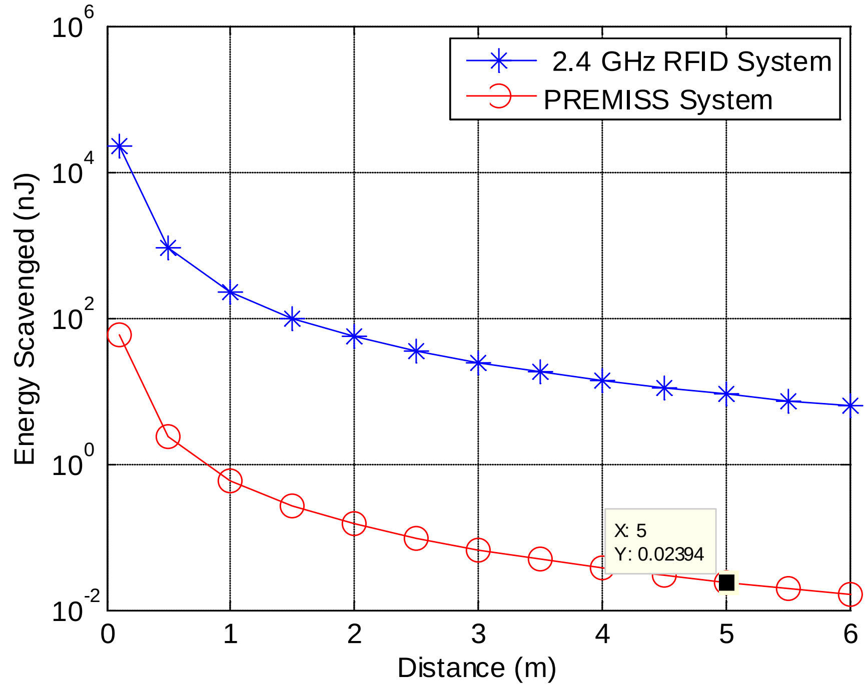
Parameters	PREMISS	2.4 GHz RFID
λ (mm)	5	125
P_e (dBm)	20	20
G_T (dB)	20	11
G_s (dB)	0	0
η_a	0.6	0.9
η_m	0.7	0.75×0.95
η_{sw}	0.9	0.9

Downlink Energy Budget

Power available at Rectifier Input



Energy harvested in 10 *ms*



Key-challenge: achieve a decent rectifier efficiency with low input power.

Uplink transmission has to be very efficient.

Uplink Energy Budget

- **The received signal power in the central controller**

$$P_{\mathrm{c}} = \frac{E_{\mathrm{s}}}{t_{\mathrm{d}}} \frac{G_{\mathrm{s}} G_{\mathrm{c}}}{L_{\mathrm{P}}} \eta_T ,$$

$$= \left(\frac{t_{\mathrm{s}}}{t_{\mathrm{d}}} \right) \left(\frac{P_{\mathrm{e}} G_{\mathrm{c}}^2 G_{\mathrm{s}}^2}{L_{\mathrm{p}}^2} \right) \left(\eta_{\mathrm{a}} \eta_{\mathrm{m}} \eta_{\mathrm{rec}} \eta_{\mathrm{sw}} \eta_{\mathrm{T}} \right).$$

- **For an RFID system using reflective transmission**

$$P_{\mathrm{c}} = \left(\frac{1}{4} | \Gamma_1 - \Gamma_2 |^2 \right) \left(\frac{P_{\mathrm{e}} G_{\mathrm{c}}^2 G_{\mathrm{s}}^2}{L_{\mathrm{p}}^2} \right) \left(\eta_{\mathrm{a}} \eta_{\mathrm{m}} \eta_{\mathrm{rec}} \eta_{\mathrm{sw}} \right).$$

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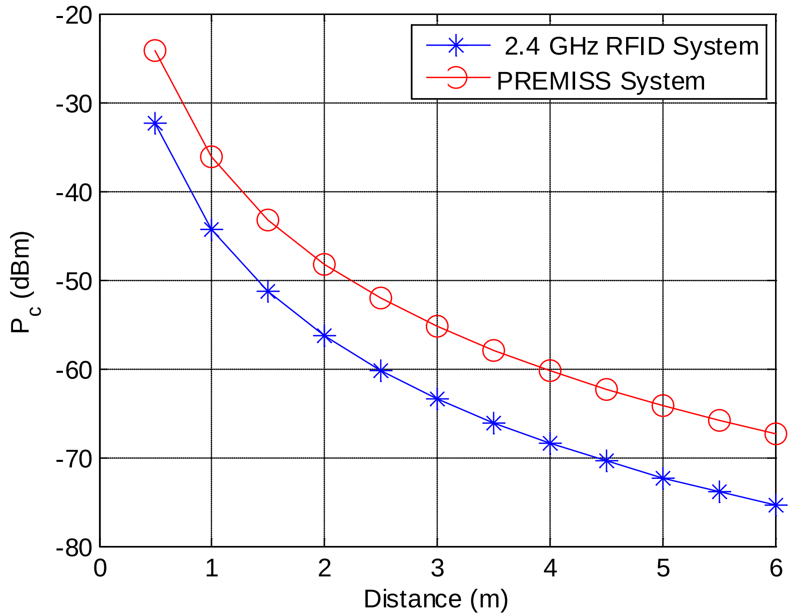
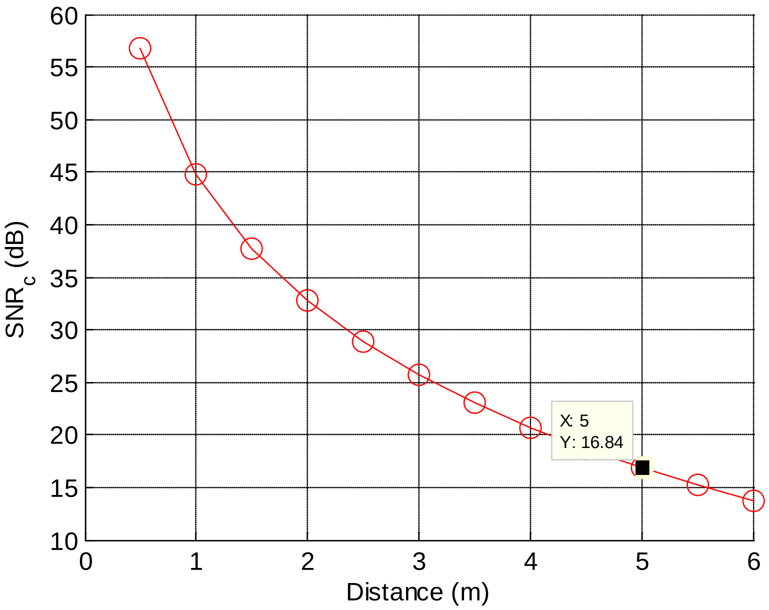
Uplink Energy Budget

Power received at the central controller





An SNR of 17 dB can be achieved at a distance of 5*m* for the PREMISS system.

Remarks

- **More detailed modeling is being considered for various building blocks of the system (on-chip antenna, rectifier, uplink transmission...)**
- **Many activities in millimeter RFID systems. However, the range is below 1*m.***
- **We consider implicit sensing schemes for energy saving in the sensor node**
  - **e.g. temperature dependency of oscillator frequency**

Conclusions

- The PREMISS system:
  - 60 GHz
  - Wireless-powered
  - Fully monolithic
- Preliminary system study shows an SNR of 17 dB can be achieved at the central controller at 5 *m*.
- Rectifier design is challenging.

Thank you