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Opportunistic electromagnetic energy harvesting enabled IEEE 802.15.4 MAC protocols employing multi-channel scheduled channel polling

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Outline

- Double Stage Random Access in Decentralized Single Radio Cognitive Networks IEEE 802.15.4 MAC
- Proposal of an Opportunistic electromagnetic RF Energy harvesting MAC protocol for CR networks
- Multi-Channel-Scheduled Channel Polling (MC-SCP-MAC) Protocol
- Pursuing the Experimental Characterization of Wearable Antennas and Circuits for RF Energy Harvesting in WBANs
  - Proposal of an hybrid energy storage system (HESS) based on super-capacitor and rechargeable battery.
  - Future Enhancements to the RF energy Harvesting Device
  - List of commercially available DC/DC charger/converter
  - HESS Design Issues
  - Criteria Example for the choice of DC/DC charger/converters
- Conclusions

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A Two-stage Decentralized MAC Protocol

- This work presents a MAC protocol for the SUs which uses a double stage mechanism to schedule each SU's transmission:
  - 1st stage - used to reduce the number of competing SUs in order to decrease the number of collisions;
  - 2nd stage - used to schedule the SUs competing for the medium, eliminating the situations of underutilization of idle frames from SUs.

A Two-stage Decentralized MAC Protocol

- 1st stage of contention:
  - Assuming that *n* SUs compete for the medium in the 1st stage, the number of SUs selected to compete in the 2nd stage is reduced to n_2:

$$n_2 = max\left(1, \sum_{k=1}^{n} k \binom{n}{k} \tau_1^k (1-\tau_1)^{(n-k)}\right)$$

Explanation: if a node listens an idle mini-slot before transmitting its mini-packet, it knows that it should compete in the second stage.

- 2nd stage of contention:
  - The information about the mini-slots found busy is then used to reserve the future idle frames to the nodes that have manifested their intention on accessing the channel during the cw_2 mini-slots

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A Two-stage Decentralized MAC Protocol

- Throughput
  - Since n_2 compete in the 2nd stage, the expected number of mini-slots found idle in the 2nd stage is: $\Gamma_{idle} = cw_2(1-\tau_2)^{n_2}$
  - The expected number of idle frames reserved for SUs access during the cw_2 mini-slots is given by:

$$\chi_{res} = cw_2 - \Gamma_{idle}$$

  - Finally, the throughput can be approximated by:

$$S_C = n_2\tau_2(1-\tau_2)^{n_2-1}P_{OFF}^{PU}(1-P_{FA})\alpha_s\alpha_C$$

where:

$$\alpha_C = cw_2/(2+\chi_{res})$$

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Opportunistic electromagnetic RF Energy harvesting MAC protocol for CR networks

- Analyze the impact of the electromagnetic RF energy harvesting on the cognitive radio networks
- Apply the developed 5-stage Dickson voltage multiplier jointly with the hybrid energy storage system (HESS) to the CR node developed in the context of CREaTION project;

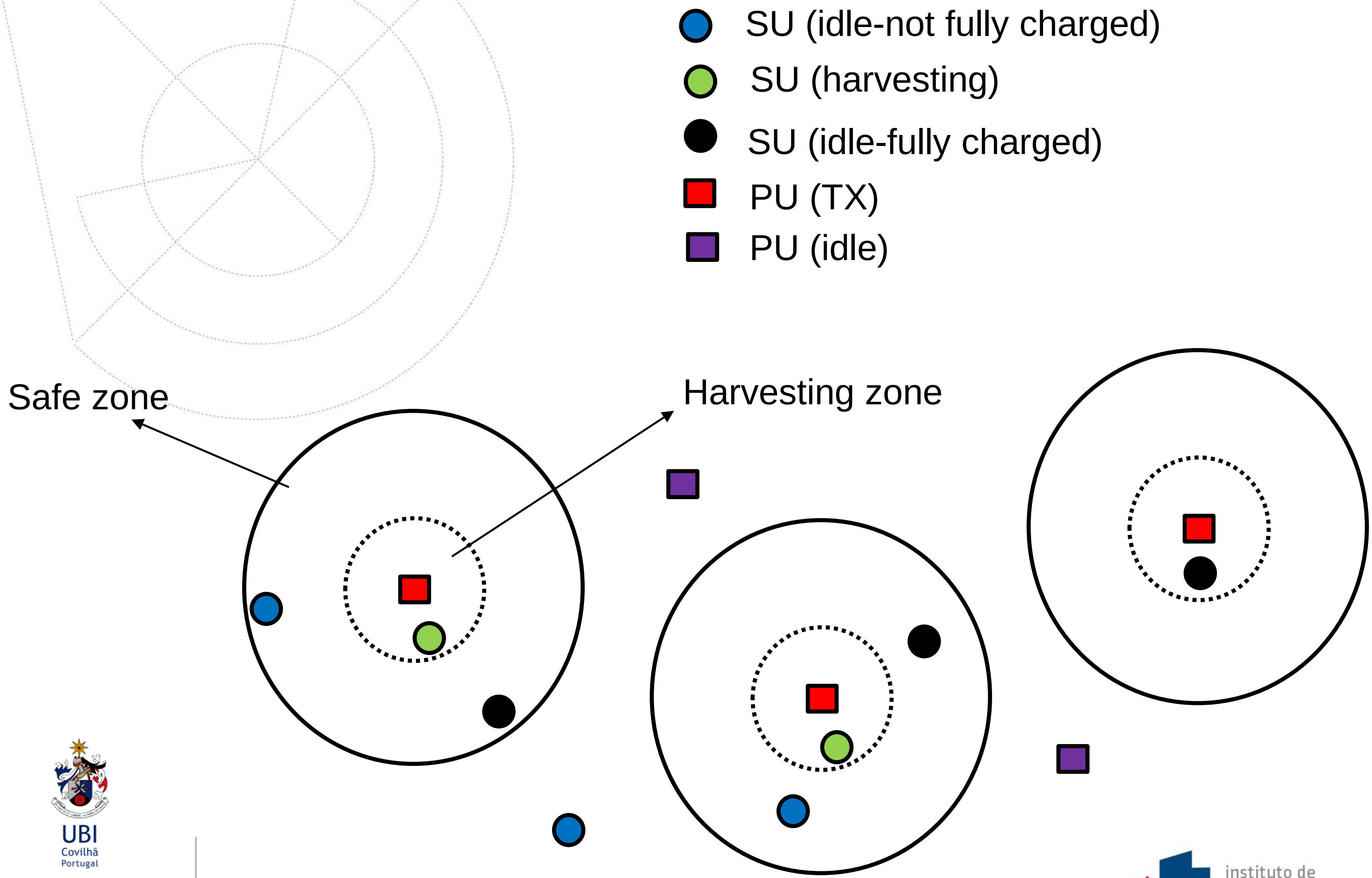
Opportunistic electromagnetic RF Energy harvesting MAC protocol for CR networks

- Propose a MAC protocol for CR networks that considers the already proposed “Two-stage Decentralized MAC protocol” with RF energy harvesting capabilities;
- Propose a novel concept in CR networks that allow the CR to be equipped with our RF energy harvesting prototype (5-stage Dickson voltage multiplier);
- In the CR networks, secondary users (SU’s) coexist with primary users (PU’s);
- The SU’s are capable of sensing the gaps that are available in the spectrum utilized by the PU’s and use it opportunistically to send their data without interfering with the PU transmissions;
- Additionally, in this concept, CR nodes are capable of taking advantage of the spectrum sensing period to opportunistically harvest RF energy from transmissions by nearby PU’s.

Opportunistic electromagnetic RF Energy harvesting MAC protocol for CR networks

- SU's store energy in the HESS and employ the available energy in the CR device transmission when the storage system is fully charged;
- During the idle time of SU's due to the presence of PU, they can take such an opportunity to harvest RF energy from PU transmissions;
- The envisaged scenario considers PU's and SU's over an area with:
  - **Safe zone**: to protect the PU transmissions, SU inside a safe zone is not allowed to transmit to avoid interfering with the PU;
  - **Harvesting zone**: is inside the safe zone. Su harvests energy from a nearby PU if it is inside its harvesting zone.
- Three modes of the CR device can be considered:
  - **Harvesting**: if it is inside the harvesting zone of an active PU and not fully charged;
  - **Transmitting/receiving**: if it is fully charged and outside the safe zone of all active PU's;
  - **Idle**: if it is fully charged but inside any of the safe zones, or neither fully charged nor inside any of the harvesting zones.

Envisaged Scenario



Multi-Channel-Scheduled Channel Polling (MC-SCP-MAC) Protocol

- MC-SCP-MAC explores the advantages of multi-channel features jointly with Enhanced Two-Phase Contention Window Mechanism;
- It employs the Influential Range (IR) concept: reduces delay and packet redundancy;
- It considers cognitive-based capabilities: Channel degradation sensing and Denial Channel List for opportunistic channel selection;
- It employs an *Extra Resolution Phase Decision* algorithm to reduce the delay, increase the packet delivery, whilst reducing energy consumption;
- It considers a predictive channel based wake-up mechanism to choose the channel based on a Linear Congruential Generator.

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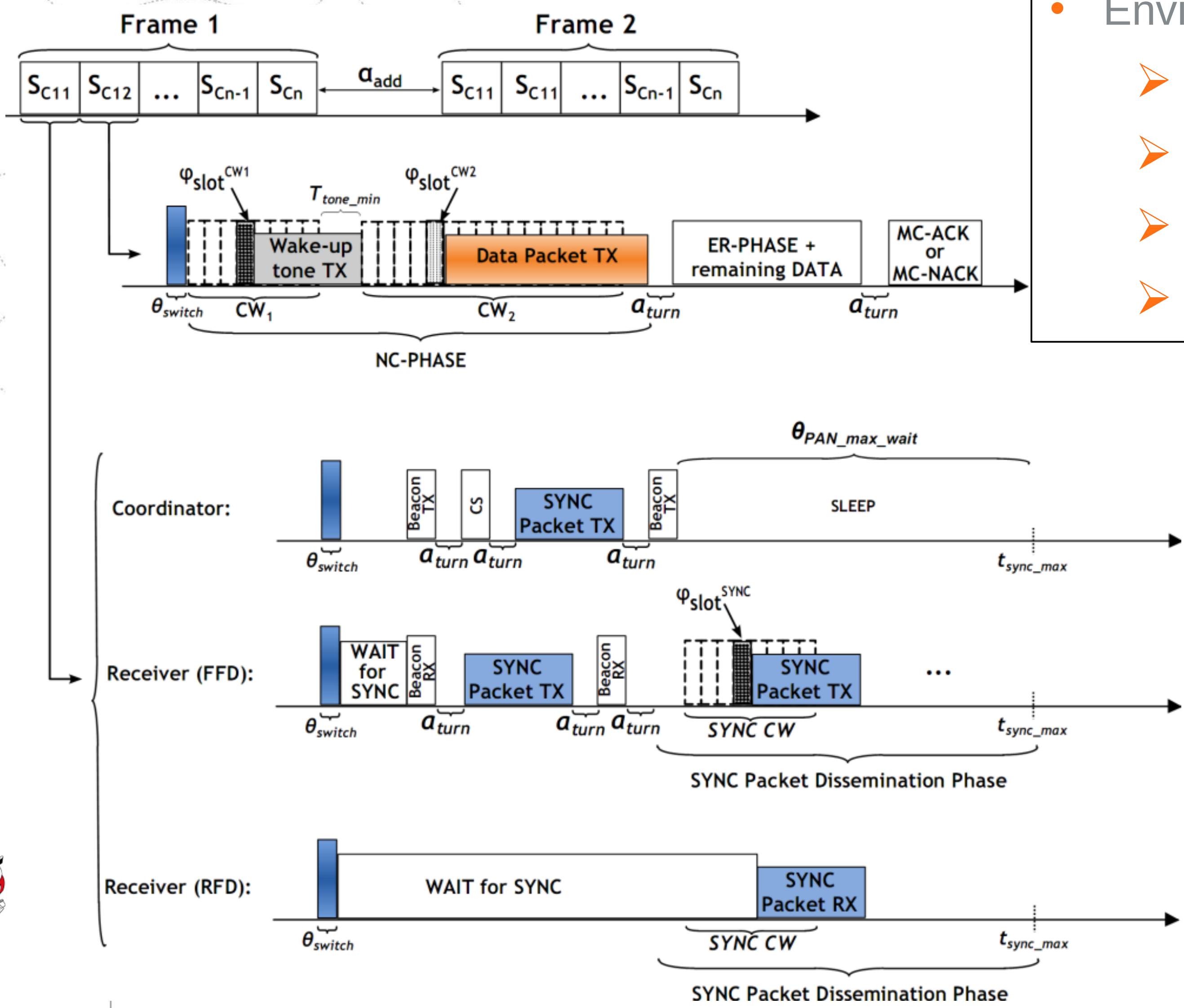
Fundamental of the Protocol-Enhanced-Two Phase Contention Window Mechanism



- Envisaged scenarios:
  - Tree
  - Single-hop
  - Multi-hop
  - Cluster

Predictive Wake-up Mechanism

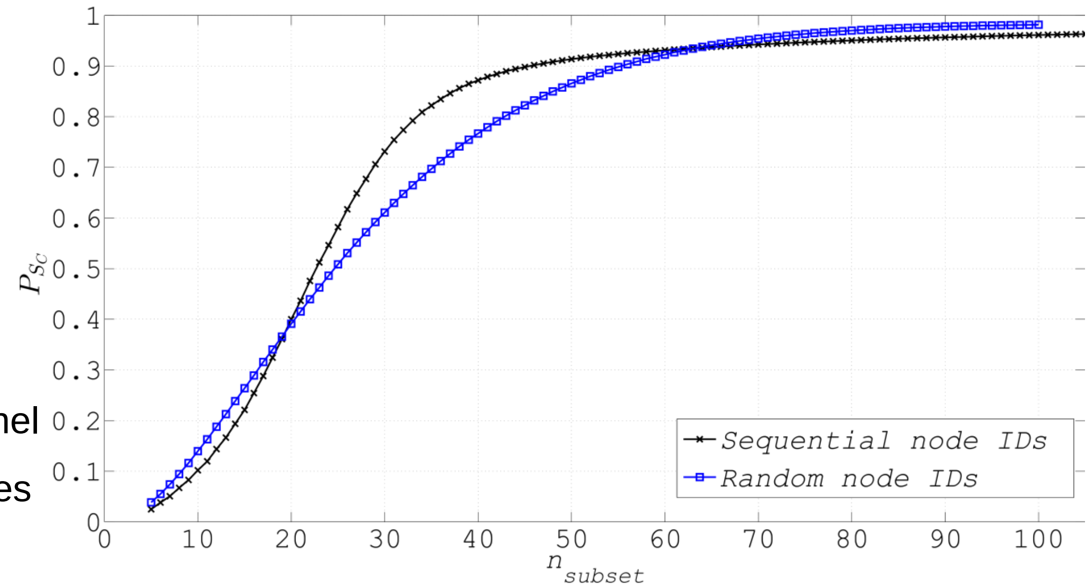
- Consider the Linear Congruential Generator (LCG) due to computation efficiency;
- The channel of the physical layer is defined as a slot channel;
- General formula from the LCG:

$$X_{n+1} = (aX_n + c_+)\ mod(m_{lcg})$$

$m_{lcg} = 65536$ $a = 16807$ $c_+ = 0$

- Map de X_{n+1} value to one of 15 available channels (minus control channel):

$$\varphi_{ch} = 12 + X_{n+1} \cdot mod(15)$$



- Convert into a wake-up time:

$$\psi_{wake-up} = \sigma_{current} + (\varphi_{ch} - 11) \times \Delta t_{SC} + \alpha_{add} - \theta_{switch}$$

$\sigma_{current}$ – Current “time” of the node

Δ_{tSC} – Time duration in each slot channel

α_{add} – Time between consecutive frames

θ_{switch} – Time to switch within channels

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Fundamental of the Protocol- Influential Range (IR)

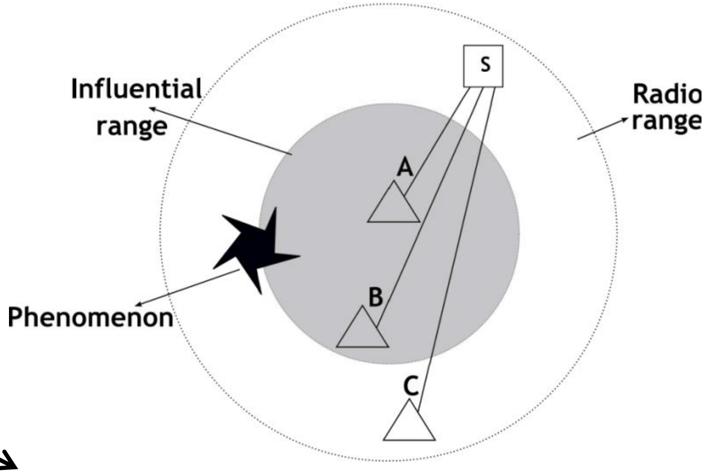
- Influential Range (IR) Concept: mitigate the overhearing problem
- Steps to apply IR:
  - Overhears packet: receives and decodes packet;
  - Check if it is in the IR: compares the packets' RSSI and IR threshold (Π_{irmax});

$RSSI_{pkt} \geq \Pi_{irmax}$ ⟶ is in same IR

$RSSI_{pkt} < \Pi_{irmax}$ ⟶ is not in same IR

  - Overheard packet has the same parent node?
  - If is in same IR and has same parent node

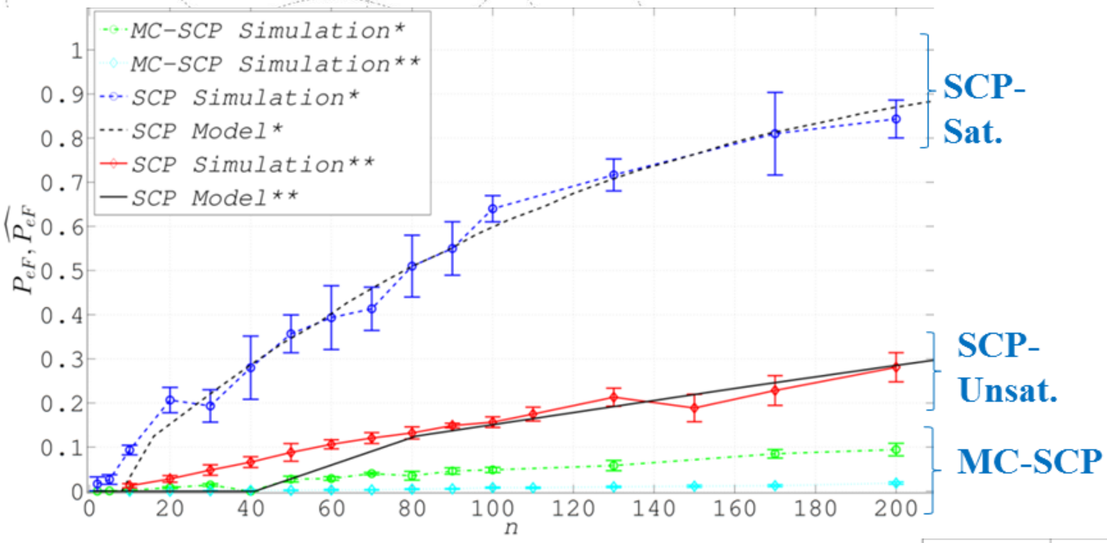
Information of packets ==
Information of overheard packets?



Discards the redundant ones

- Π_{irmax} depends on the density of network;
- $\Pi_{irmax} \in$ {-90;-80; -70; -60] dBm

Collision Probabilities for MC-SCP-MAC



Fixed number of slot channels

$CW_1^{max} = CW_2^{max} = 8$

$N_{ch} = 15$ (MC-SCP-MAC)

$N_{ch} = 1$ (SCP-MAC)

$A = 50 \times 50\ m^2$

$\lambda = 1/2\ s^{-1}$

* → Saturated regime

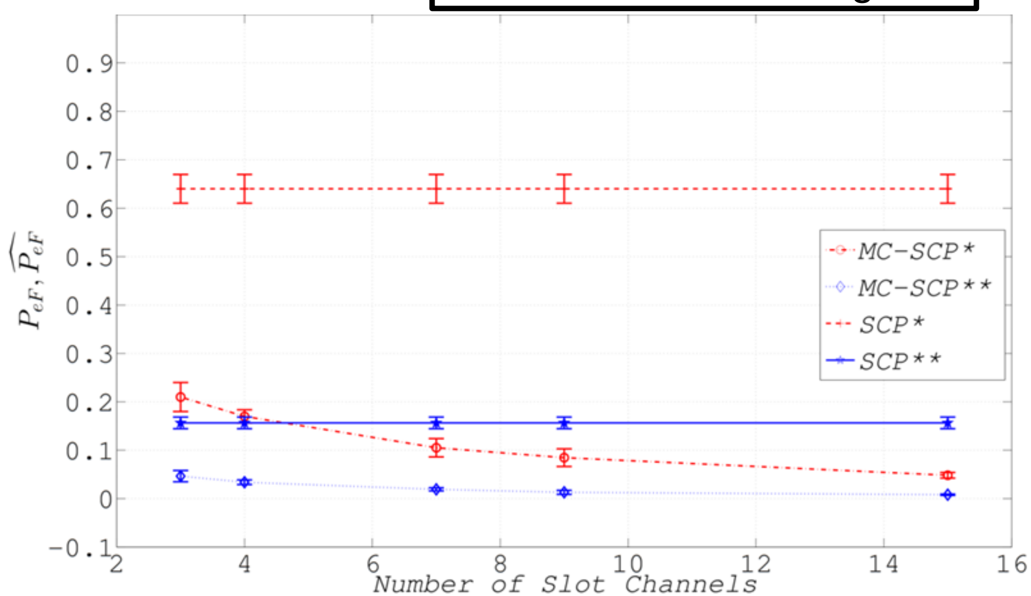
** → Unsaturated regime

Variable number of slot channels

$t_F = 1\ s$

$n = 99\ nodes$

$\Delta t_{SC} = t_F/(Nch + 1)$



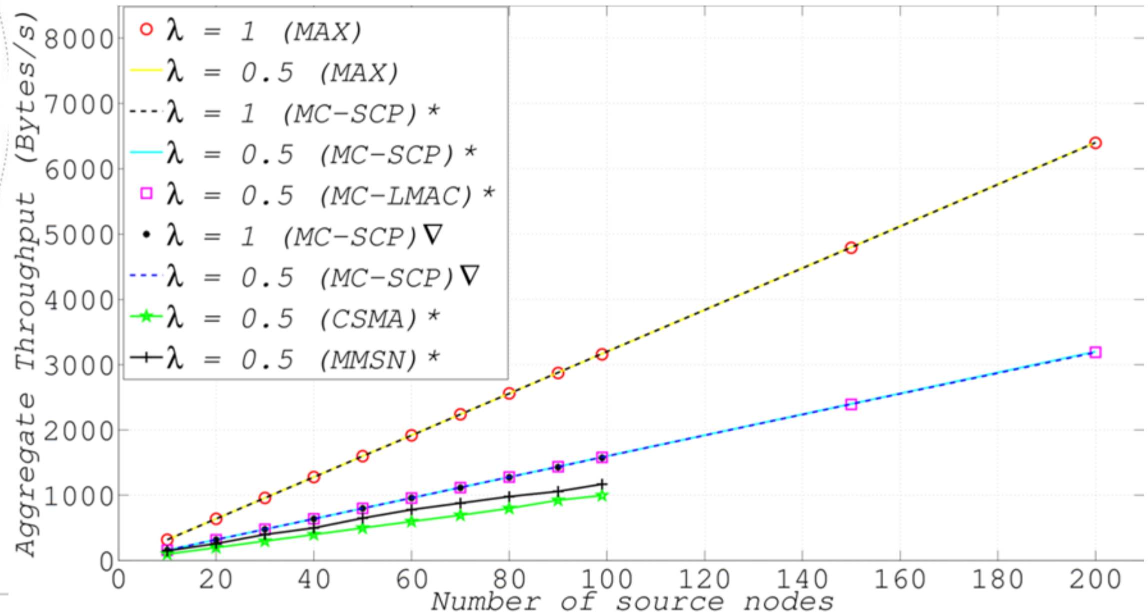
Impact of Traffic Periodic and Exponential Patterns in the Overall Performance (High Density of Nodes)

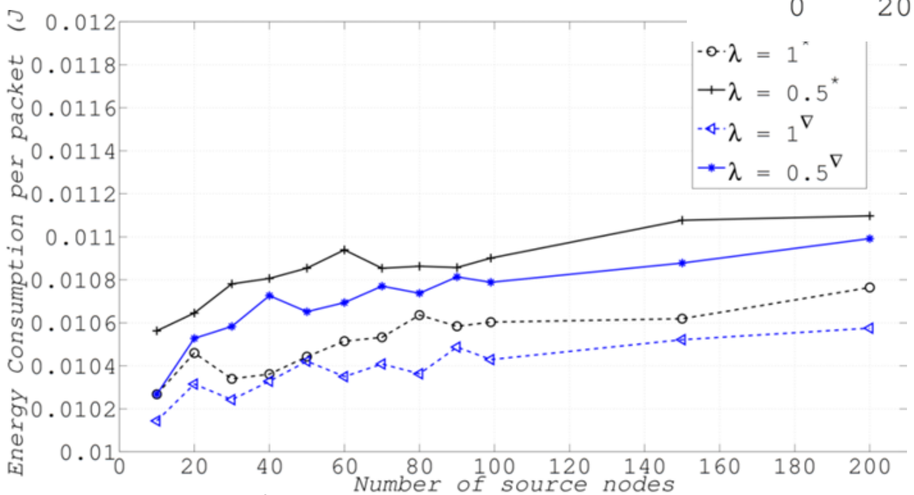
$CW_1^{max} = CW_2^{max} = 80$

$A = 150 \times 150\, m^2$

decrease

$A = 50 \times 50\, m^2$

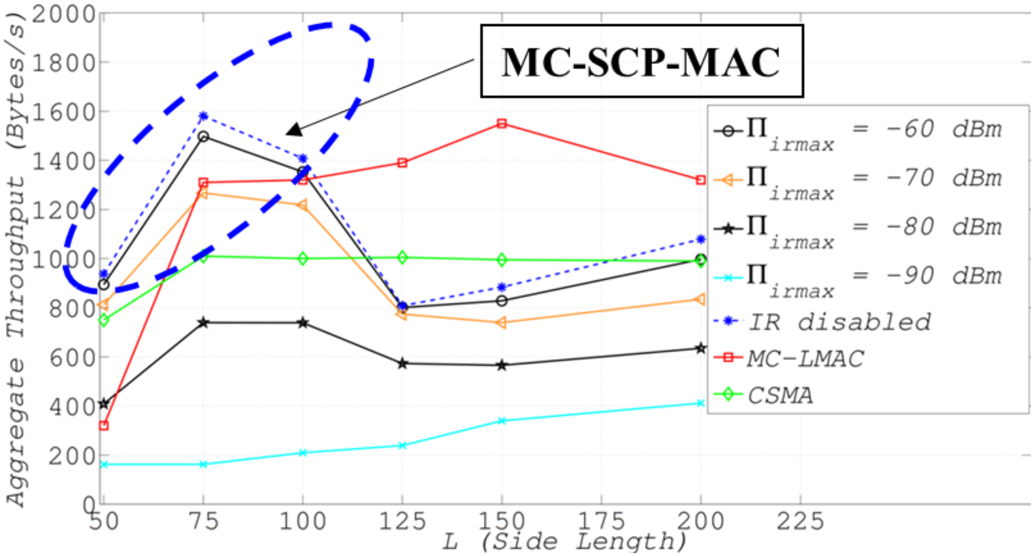




* → Periodic traffic

∇ → Exponential traffic

Impact of Node Density in MC-SCP-MAC



$n = 99 \; nodes$

$N_{ch} =$ 1 (CSMA)

$N_{ch} =$ 8 (remaining ones)

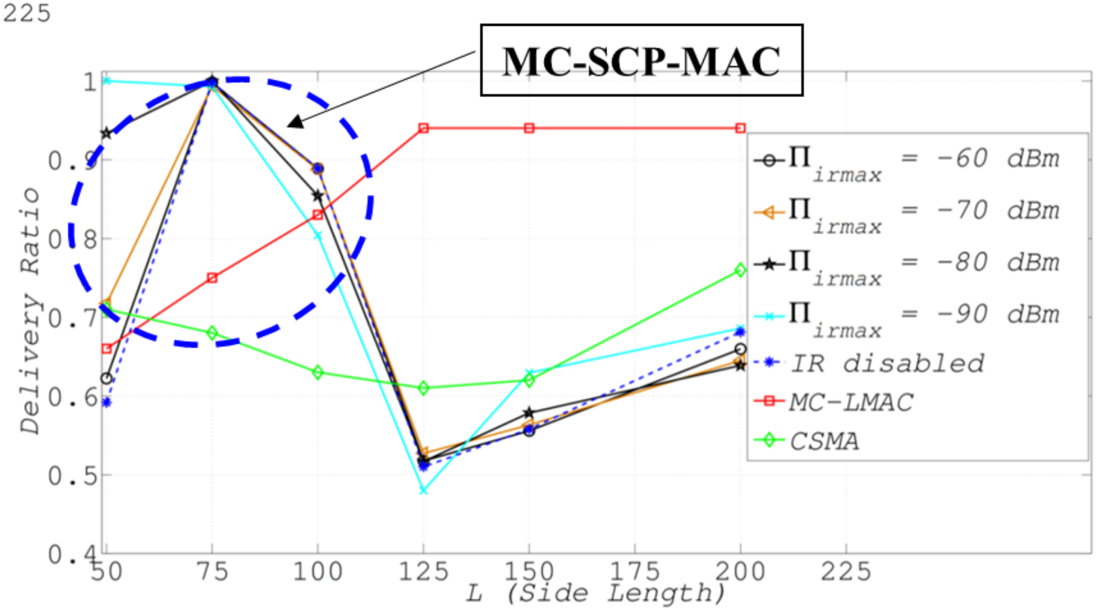
$CW_1^{max} = CW_2^{max} = 80$

$t_F = 1.57 \; s, \;\; \Delta t_{SC} = 0.17 \; s$ (MC-SCP)

$t_F = 1.6 \; s$ (MC-LMAC)

$\Pi_{irmax} \in \{-90; \; -80; \; -70; \; -60\} \; dBm$

$\lambda = 1/2 \; s^{-1}$



Starting Point and Where to Go

- We take as starting point the developed work "*Development of electromagnetic energy harvesting devices applied to WBANs*" developed and presented by Henrique Saraiva;
- In this work the spectrum opportunities for radio frequency (RF) energy harvesting through power density measurements from 350 MHz to 3 GHz were identified;
- Based on the identification of the most promising opportunities, a dual-band band printed antenna operating at GSM bands (900/1800) is proposed, with gains of the order 1.8-2.06 dBi and efficiency 77.6-84%;
- Prototypes of a 5-stage Dickson voltage multiplier were project, developed and tested, in which good results were attained.

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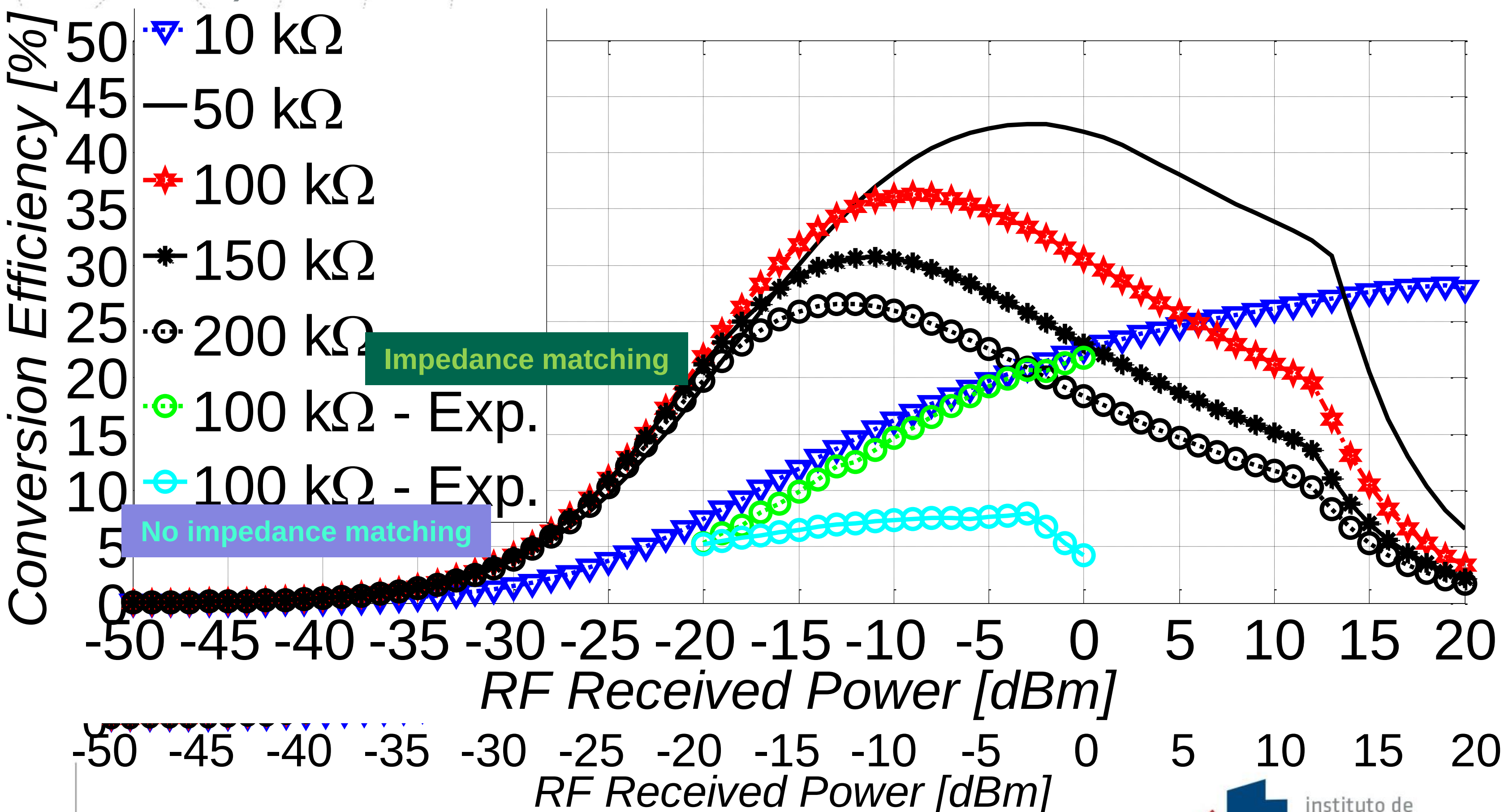
RF Energy Harvesting Circuits

- Verification of the conversion efficiency with the RF received power for the 5-stage Dickson voltage multiplier (load 100kΩ).



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Future Enhancements to the RF energy Harvesting Device

- Implementation of an Hybrid Energy Storage System (HESS) composed by a rechargeable battery and a supercapacitor;

- Perform real tests with the two new prototypes developed with a RF dedicated substrate;

- Project a 5-stage Dickson voltage multiplier along with the impedance matching circuit for other loads and frequencies.

- Tuning and tweaking the matching impedance circuit for the 5-stage Dickson circuit.

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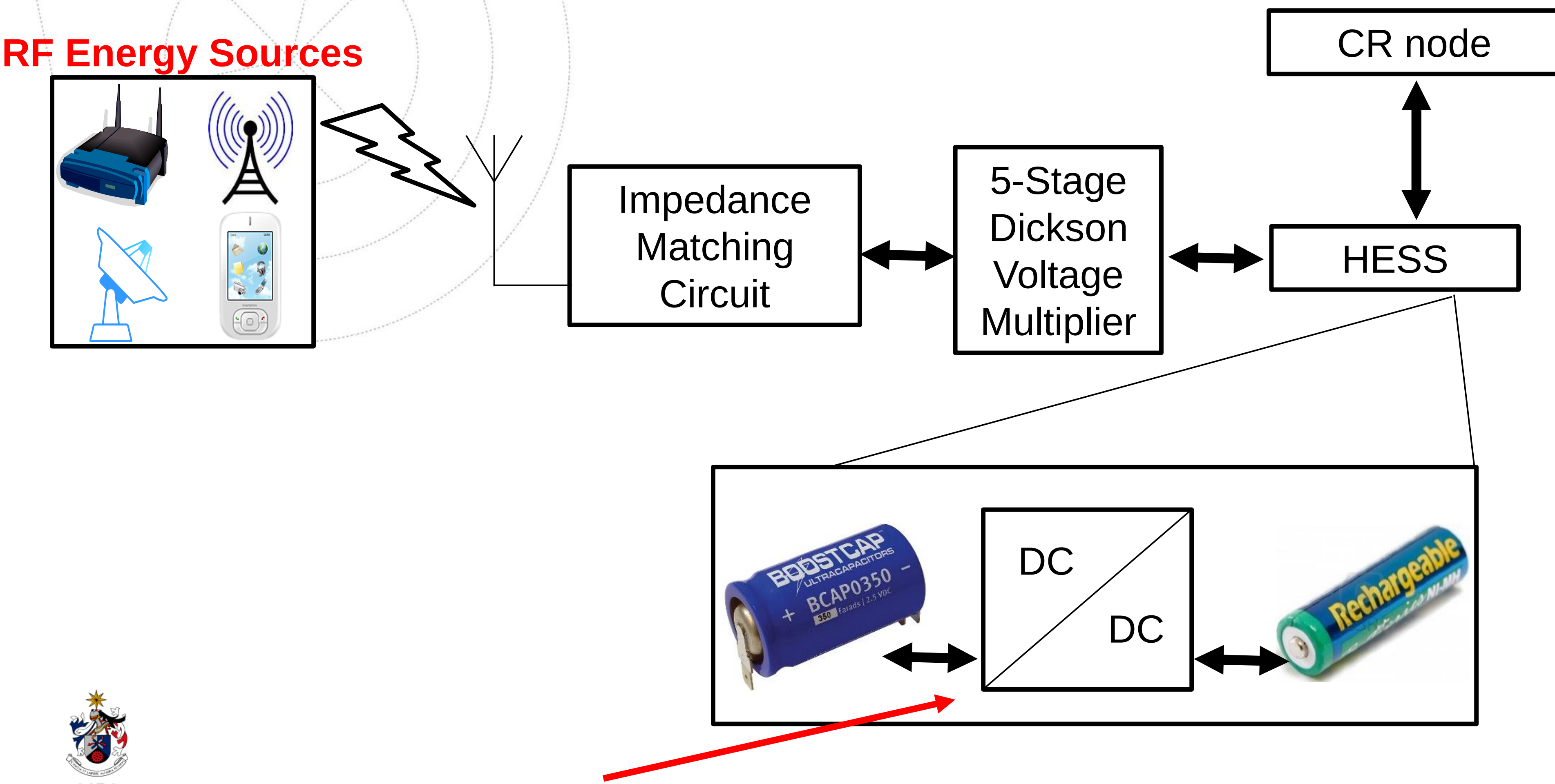
HESS for the RF Energy Harvesting device



DC/DC converter/charger/booster

HESS for the RF Energy Harvesting device

- The HESS relies on the extended capacity of a battery for normal operations and on the rapid charge/discharge characteristics of supercapacitors for power ride-through during peak load periods;
- Decide if we should use:
  - HESS with bidirectional converter between the battery and supercapacitor;
  - HESS with two bidirectional converters between battery-supercapacitor and load.
- The choice of the DC/DC charger that charges the supercapacitor-battery set, must be carefully performed;
- We should met the input requirements (e.g., <u>minimum input current</u>, <u>minimum input voltage</u>) of different DC/DC converters/devices commercially available:
  - Available from Linear Technology, Microchip Technology, Seiko Instruments, Texas Instruments and others.

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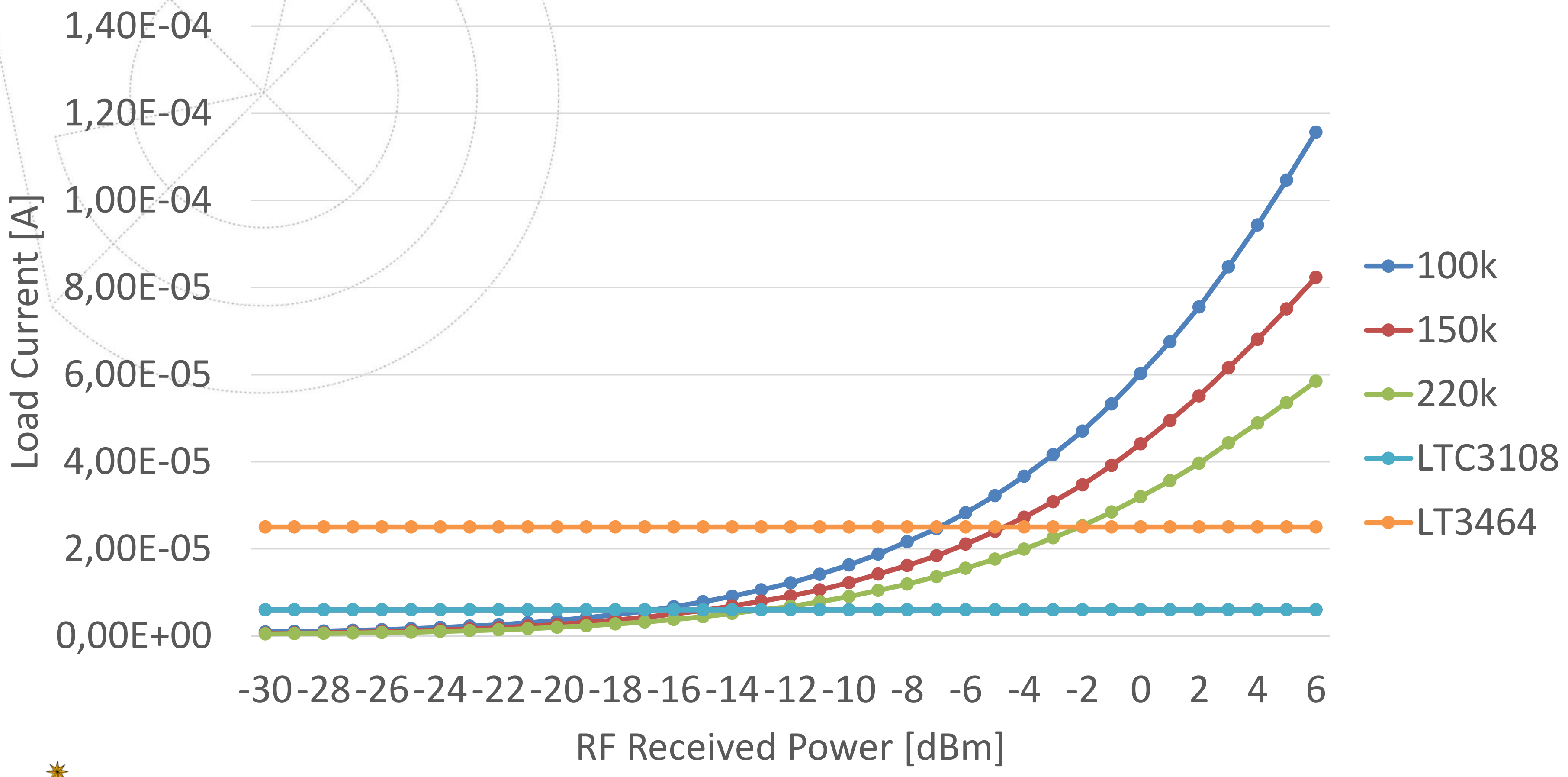
HESS for the RF Energy Harvesting device - List

- **Linear Technology LTC3108**
  - Step-up DC-DC converter that operates at input voltages as low as 20 mV;
  - Offers multiple regulated power outputs;
  - A primary output programmable to four fixed voltages and an output for charging a supercapacitor or battery.
- **Texas Instruments TPS6120x series**
  - Operates with input voltages as low as 0.3 V (0.5 V startup into full load);
  - Low power consumption with a quiescent current of 55 µA and leakage current of 0.01 µA;
  - Requires a higher startup voltage than needed during nominal operation.
- **Seiko Instruments S-882Z series**
  - Supports input voltage as low as 0.3 V;

HESS for the RF Energy Harvesting device - List

- **Microchip Technology MCP1640 family**
  - Less than 1 μA (no load) current drain from the storage device;
- **Microchip MAX17710**
  - For charge storage and protection in energy-harvesting designs operating at a minimum source input voltage of 0.7 V;
- **Specific when using supercapacitors**
  - A supercapacitor appears as an infinite load when it nears depletion, so conventional approaches using feedback regulation will cause the converter to reduce the current substantially, resulting in an extended charge-time for the supercapacitor;
  - Examples:
    - Texas Instruments BQ33100 Super Capacitor Manager;
    - Linear Technology LTC3225 Supercapacitor Charger.

Criteria Example for the choice of DC/DC charger/converters



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HESS for the RF Energy Harvesting device - Design Issues

- The problem is less about the availability of suitable devices than the tradeoff between the increased efficiency available with alternative devices and the increased power consumption of more sophisticated devices.
- Leakage current and standby power consumption are critical performance characteristics for these applications;
- We need to ensure that startup requirements remain within the power budget or the most efficient circuit will not be able to function at all;
- Propose a leakage-aware duty cycle algorithm to find the optimal duty cycle of the energy harvesting and charge of the supercapacitor-battery to mitigate the leakage problem.

HESS for the RF Energy Harvesting device - Design Issues

- Choose the appropriate supercapacitor:
  - Advantages:
    - Efficient charge and discharge performance
    - Infinite recharge cycles
  - Disadvantages:
    - Leakage problem
    - Reduced energy density, compared to batteries.
- Therefore, we will combine supercapacitor and battery;
- Choose a simulation program for supercapacitor modelling, in order to simulate our scenario before building a HESS prototype;

HESS for the RF Energy Harvesting device - Design Issues

- Simulation programs for supercapacitor modelling:
  - Simulink;
  - SimPowerSystems;
  - OrCAD Capture;
  - PSCAD;
  - Saber;
  - PLECS
  - Dymola.

- Perform a comparison of advantages and disadvantages for the program alternatives to assess which alternative suits better for our scenario.

Conclusions

- Proposed the initial guidelines and envisaged scenario for opportunistic electromagnetic RF Energy harvesting MAC protocol for CR networks;
- The proposal of a MAC protocol, based on the SCP, which envisages multi-channel features: **Multi-Channel-Scheduled Channel Polling** (MC-SCP-MAC). It outperforms the other MAC protocols in high density scenarios;
- Proposed an hybrid energy storage system (HESS) based on super-capacitor and rechargeable battery.;
- Future enhancements to the RF energy Harvesting Device;
- List of commercially available DC/DC charger/converters;
- HESS Design Issues;
- Criteria example for the choice of DC/DC charger/converters.

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Thank you,
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