

INVESTITURE CEREMONY  
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EXECUTIVE COMMITTEE

Energy Harvesting Wireless  
Communications: A Futuristic Approach  
BY

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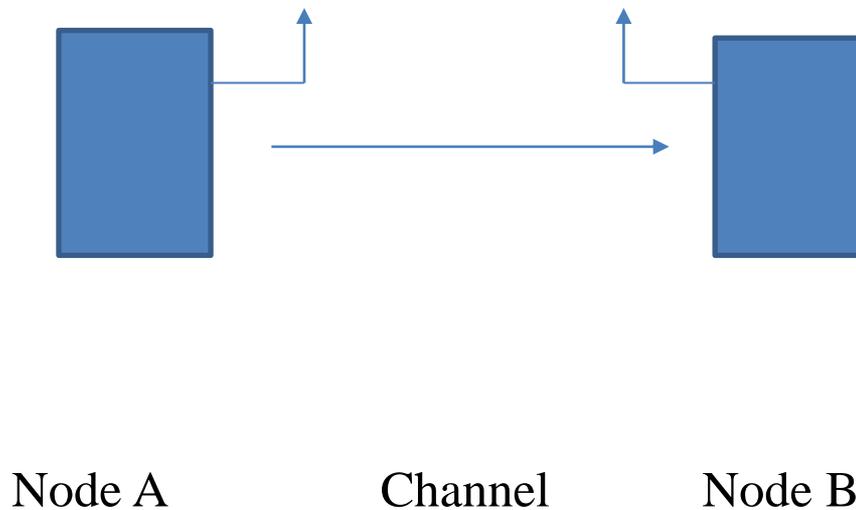
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# Content

- Introduction
- Research Aim
- Research Applications/Contributions
  - Point to point Wireless Communication
  - Secure Full-duplex wireless communication
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# Wireless communication

- Information transmission from point A (Transmitter) to point B (Receiver).
- **Received signal at Node B = Information signal + Noise**
- Nodes have limited power storage capacity
- Thus, communication will be terminated when the wireless node depletes its stored power



## Limitations

- Wireless devices cannot function independently infinitely away from centralized/grid power sources.
- Although the lifetime of wireless nodes can be extended by replacing or recharging the batteries, the replacement or recharging process incurs high cost, hazardous or sometimes impossible
- The continuous operation of wireless devices is mostly constrained by the limited capacity of their power sources.
- Spectral Inefficiency (For Half-duplex communication)

# Introduction to Radio Frequency Energy harvesting

1. Since the continuous operation of wireless devices are mostly constrained by the limited capacity of their power sources, radio frequency (RF) energy harvesting (EH) has been identified as a promising technique to power future wireless devices.
2. Technically, RF signals that carry information can also be used as a vehicle for transporting energy at the same time. For this reason, the study of simultaneous wireless information and power transfer (SWIPT) has attracted huge interest from industrial and academic communities.

## Introduction. contd

3. Effectively, wireless data and energy access can be made available to mobile users through the application of SWIPT, which in turn gives mobile users great convenience.
4. Ambient RF energy is harvested by firstly collecting the surrounding RF waves via highly efficient and high-gain antennas and then converting them into DC voltage via rectifier circuits.
5. RF energy harvesting is a process whereby RF energy emitted by sources that generate high electromagnetic fields such as TV signals, wireless radio networks and cell phone towers, through power generating circuit linked to a receiving antenna, are captured and converted into usable DC voltage.

# RF wireless power transfer 1

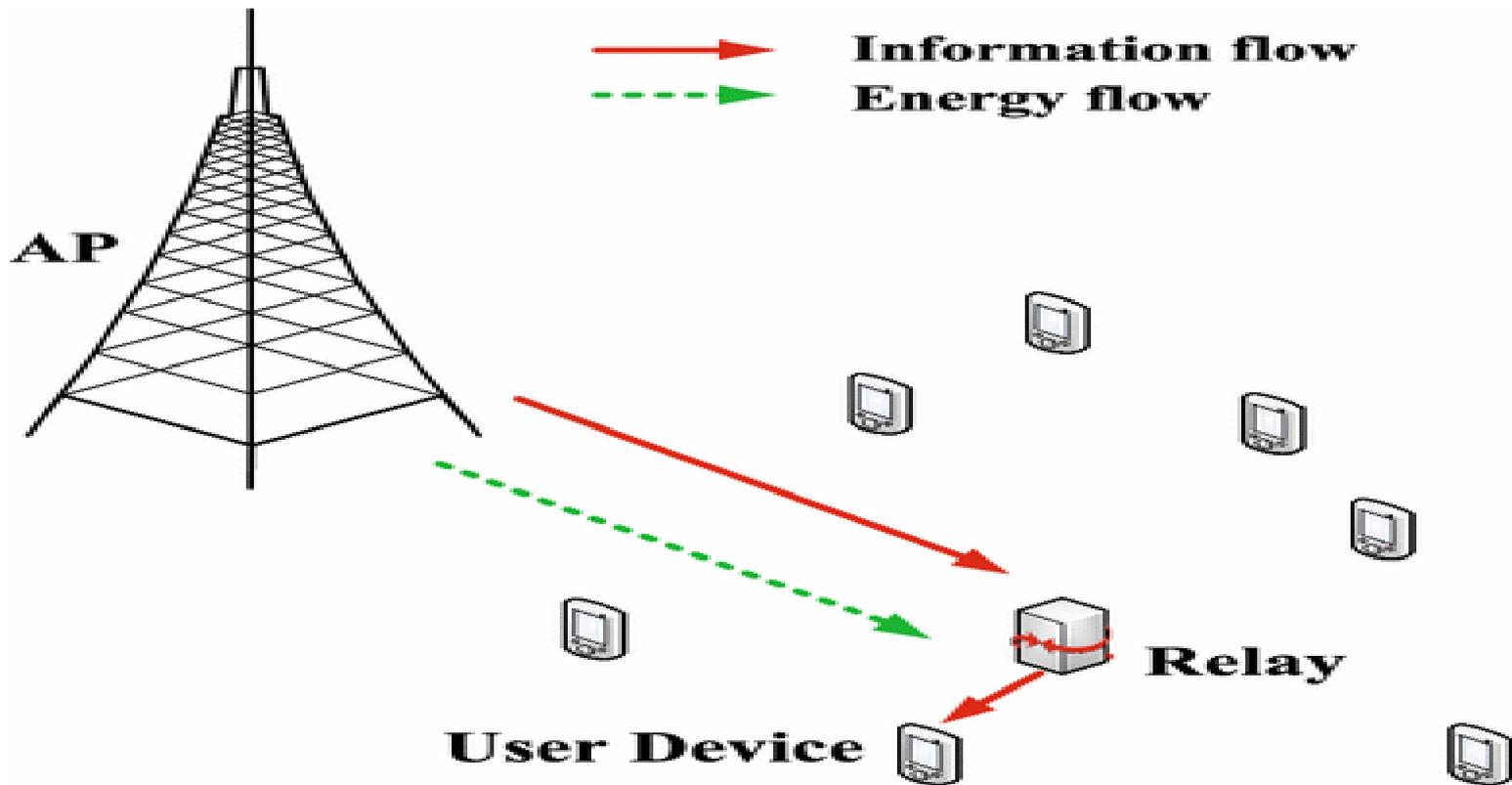


Fig: Wireless information and power transfer

# Wireless Power Transfer 2

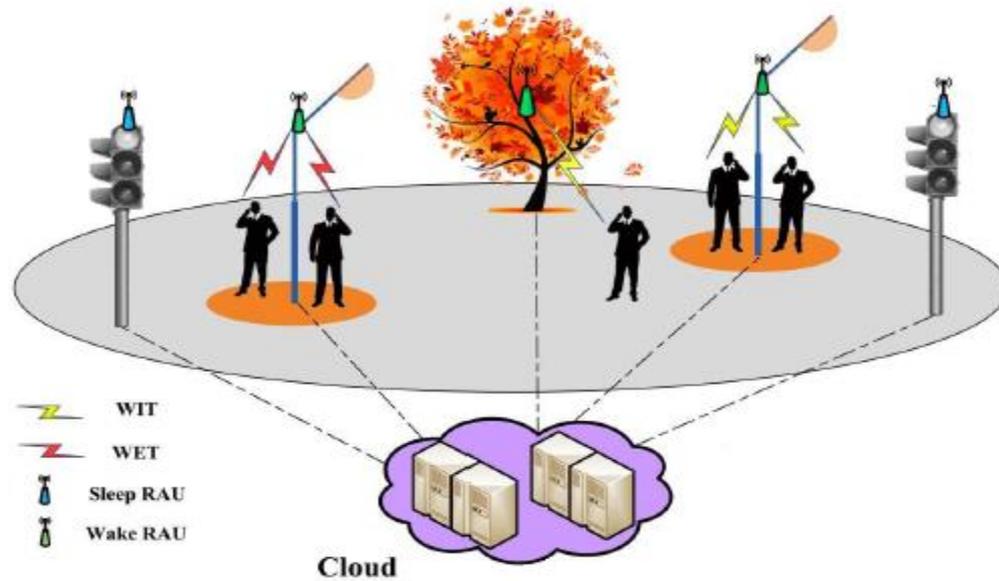


Figure: Joint Information and Energy Transfer in a Wireless Communication Network

# Why Radio Frequency Energy Harvesting?

- Unlimited mobility for wireless devices.
- Reduction in operating cost as energy harvesting is a cheap source of energy.
- Energy harvesting serves as an effective way to implement green communications.
- To increase the lifetime of battery constrained wireless devices.
- To build self-sustainable networks, such as wireless sensor networks in remote human-unfriendly environments.
- In order to eradicate frequent battery replacements for an increasing number of connected devices, to reduce carbon emission and to wipe out the dependence of wireless terminals on the power grid, EH technology is considered as a major component of future wireless networks.

# Wireless Power Transfer 2

- Applications: Wireless sensor networks [1]; Wireless body Networks [2].
- Effective distance: Depends on frequency and sensitivity of RF energy harvester (typically from several meters to several kilometres).
- Efficiency: 0.4%, above 18.2%, and over 50% at -40dBm, -20dBm and -5dBm input power, respectively [3].

- [1] H. Nishimoto, Y. Kawahara, and T. Asami, Prototype implementation of ambient RF energy harvesting wireless sensor networks," in proc. *IEEE Sensors*, kona, HI, Nov. 2010.
- [2] X. Zhang, H. Jiang, L. Zhang, Z. Wang, and Z. Chen, An energy-efficient ASIC for wireless body sensor networks in medical applications," *IEEE Trans. biomedical circuits and Sys.*, vol. 4, no. 1, pp. 11-18, Feb. 2010.
- [3] C. Mikeka and H. Arai, Design issues in radio frequency energy harvesting systems, "*Sustainable energy harvesting- past, present and future*," Dec. 2011.

# Receiver Architecture design for Energy Harvesting

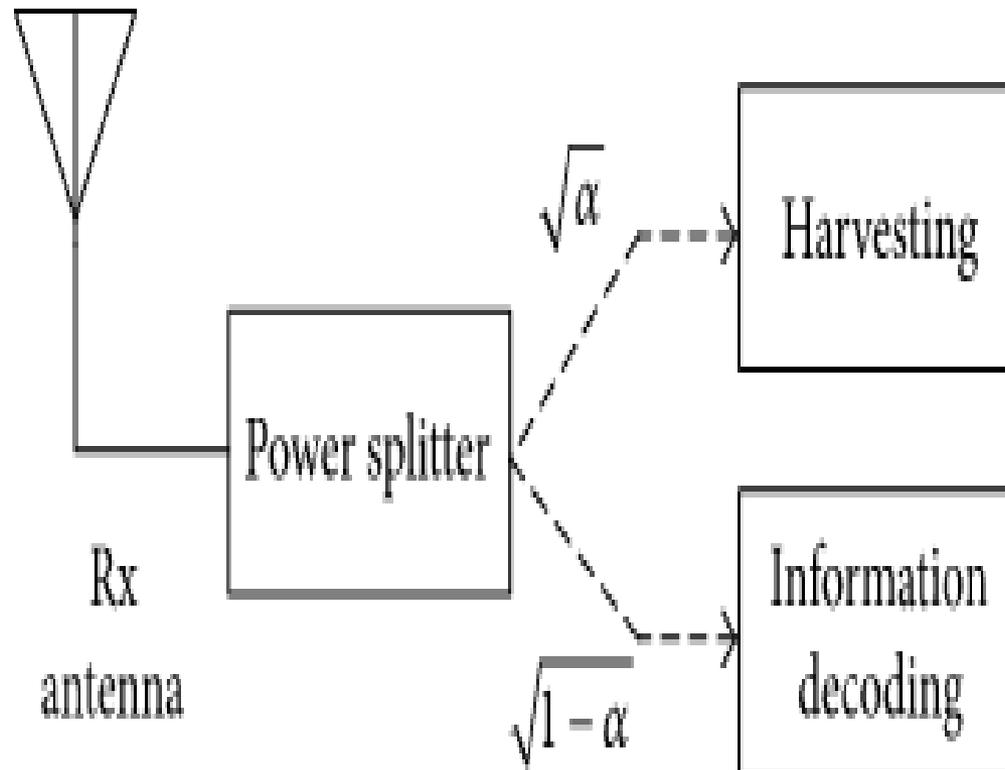
- Currently, practical receiver circuits for harvesting energy from radio signals are not yet able to decode the carried information directly.
- To counter this potential limitation, a practical dynamic power splitting (DPS) scheme is proposed to enable the receiver to harvest energy and decode information from the same received signal at any time  $t$ , by dynamically splitting the received signal into two streams with the power ratio  $\alpha(t) : 1 - \alpha(t)$ , which are used for harvesting energy and decoding information, respectively, where  $0 \leq \alpha(t) \leq 1$ .

Dynamic power splitting is further divided into:

- *Time switching*: when the information receiver is switched to its off mode, all signal power is used for energy harvesting. However, when the information receiver operates in the on-mode, all signal power is used for information decoding i.e.,  $\alpha(t) \in (0,1)$ .
- *Uniform power splitting*: when equal power is split between the information decoder and the energy harvester i.e.,  $\alpha(t) = 1/2$
- *Optimal power splitting*: when the characteristics system conditions determines the optimal values for  $\alpha$ .

## Receiver architecture...contd

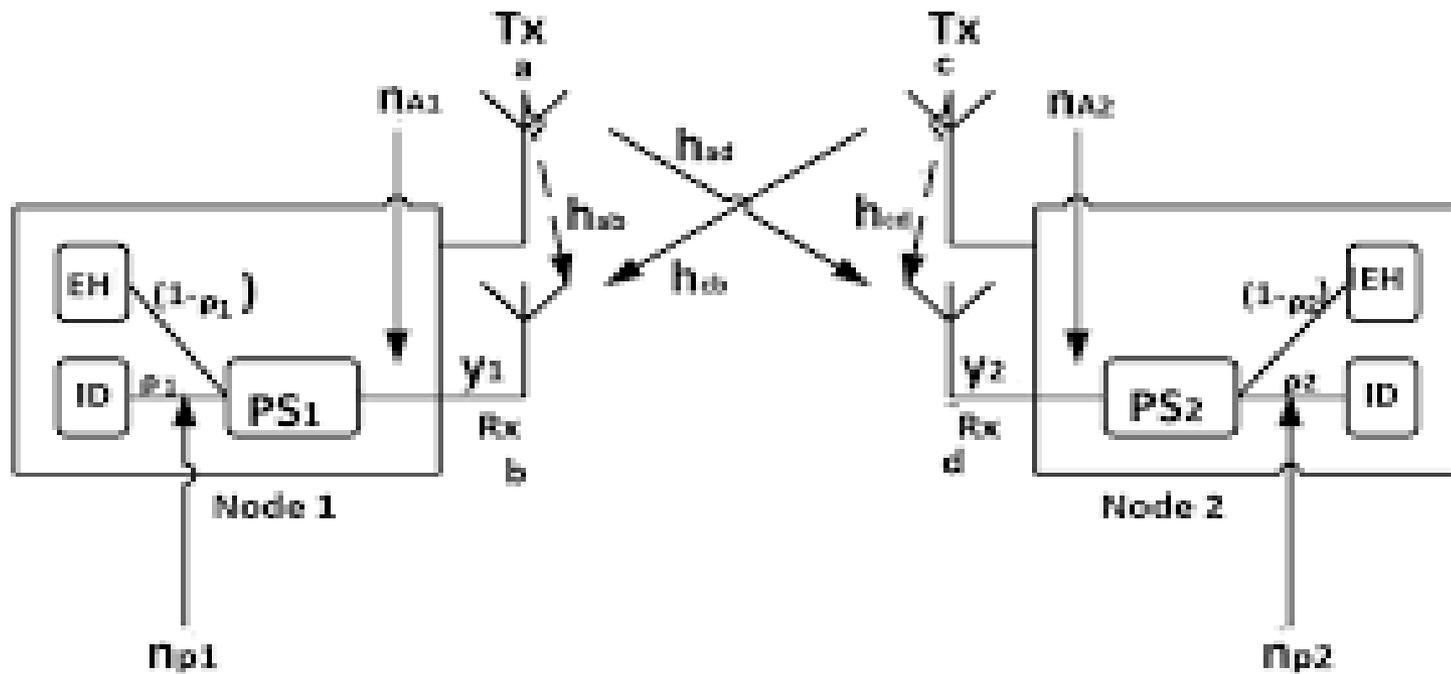
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## HARVESTING ENERGY IN FULL-DUPLEX (FD) COMMUNICATIONS

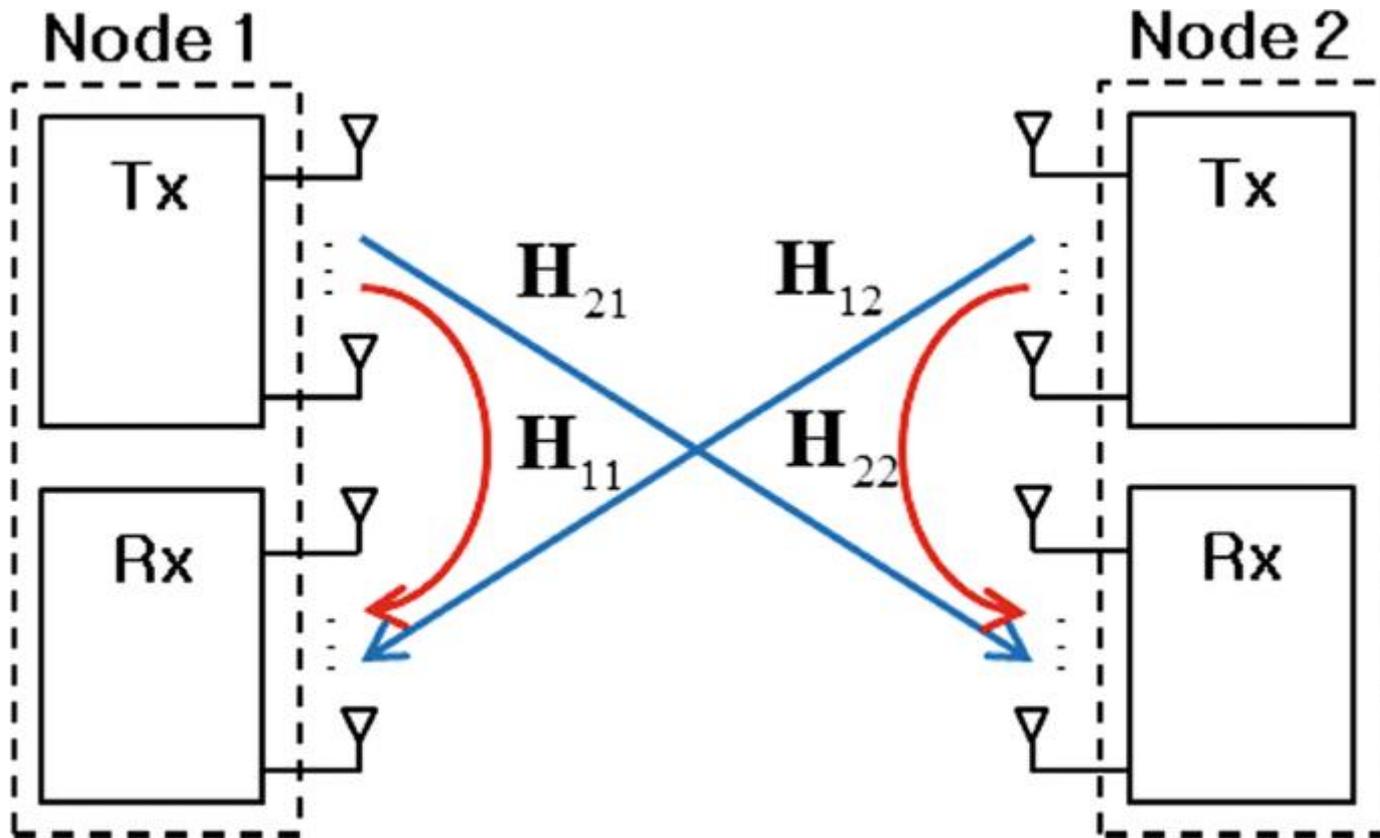
- The exponential development of wireless communication has led to spectral resource gradually becoming a limiting factor.
- It is observed that a higher spectral efficiency in wireless communication is needed in order to save cost and to maximise the use of available resources.
- FD thus emerges as a technique which can be used to achieve optimal utilization of the limited available spectral resource.
- FD can double the spectral efficiency of a wireless communication system.
- However, an improved spectral efficiency is preceded by successful self-interference cancellation

# Energy harvesting full-duplex communication..... contd

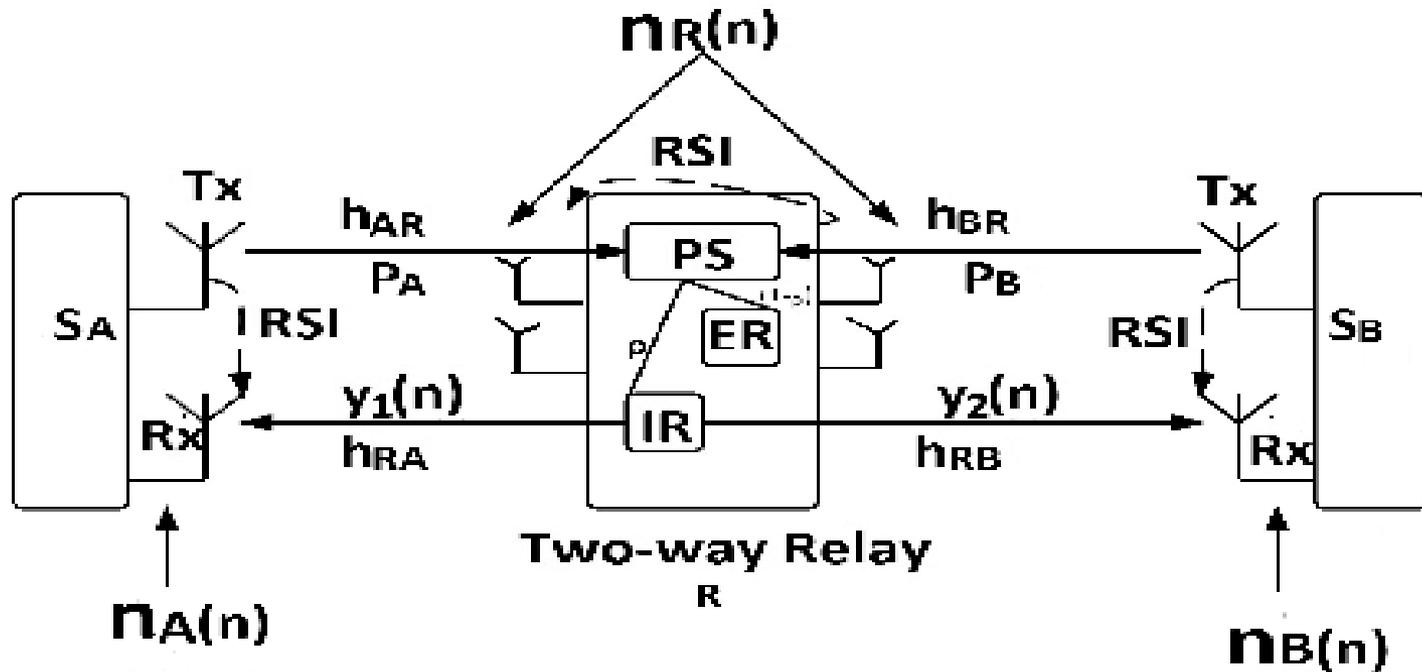


*Fig: Model of a point-to-point Full-Duplex SWIPT system*

# Self-interference



Energy harvesting full-duplex communication..... contd



*Fig: The model of a two-way relay full duplex SWIPT system*

# Research Aim

- The aim of this study is to successfully integrate simultaneous wireless information and power transfer (SWIPT) into full-duplex (FD) wireless communication systems. In particular, this research work investigates the potentials of SWIPT in FD communication systems.
- Accordingly, the contributions highlighted in this presentation are novel and have substantially improved the state of the art as can be seen in the area of practical deployment of wireless sensor networks mounted at remote and difficult-to-access locations, and powered only by a battery with limited operation time. The implementation of SWIPT enables the wireless sensor to recharge its batteries by harvesting energy from the radio frequency signal from the huge amount of electromagnetic energy in the environment.

# SWIPT in FD systems: An Introduction

- Radio frequency (RF) signal that carry information can also be used as a vehicle for transporting energy simultaneously (SWIPT).
- Transmission and reception of signals simultaneously at the same time on the same frequency (Full-Duplex).
- Wireless communication systems that simultaneously transmits and receives information signal and power at the same time on the same frequency (FD SWIPT systems).
- Great potentials for low-powered devices e.g., wireless sensor networks.
- Through SWIPT in FD systems, mobile users are provided with access to both energy and information at the same time together with a higher spectral efficiency which brings great convenience.

# Motivation: Challenges in Full-Duplex SWIPT systems

- Information and energy receivers have very different power sensitivities. e.g., -60dBm for information receiver versus -10dBm for energy receiver. Thus, existing receiver circuit cannot decode information and harvest energy from the same received signal independently.
- Strong self-interference signal imposed by the transmit antenna on the receive antenna within the same transceiver.
- Very low harvested energy.



# Problem Formulation

[To maximise the end-to-end sum-rate for SWIPT in FD systems, we formulate the following problem

$$\begin{aligned} & \max_{\rho_1, \rho_2 \in (0,1), P_1, P_2} R_{sum} \\ & \text{s.t.} \quad \min_{|\Delta h_{ab}| \leq \epsilon_1} Q_{2 \rightarrow 1} \geq \bar{Q}_{2 \rightarrow 1} \\ & \quad \quad \min_{|\Delta h_{cd}| \leq \epsilon_2} Q_{1 \rightarrow 2} \geq \bar{Q}_{1 \rightarrow 2} \\ & \quad \quad 0 \leq P_1 \leq P_{max} \\ & \quad \quad 0 \leq P_2 \leq P_{max} \end{aligned}$$

where  $\bar{Q}_{1 \rightarrow 2}$  and  $\bar{Q}_{2 \rightarrow 1}$  are the minimum amount of harvested energy required to maintain the receivers operation, and  $P_{max}$  is the maximum available transmit power budget at node 1 and node 2, respectively.

# Simulation Result (1)

Here, we investigate the performance of the proposed algorithm versus the transmit power budget for different values of the harvested energy constraint.

- ▶  $\rho$  = receive power splitter value
- ▶  $Q$  = minimum harvested power
- ▶ Joint Opt = joint optimization

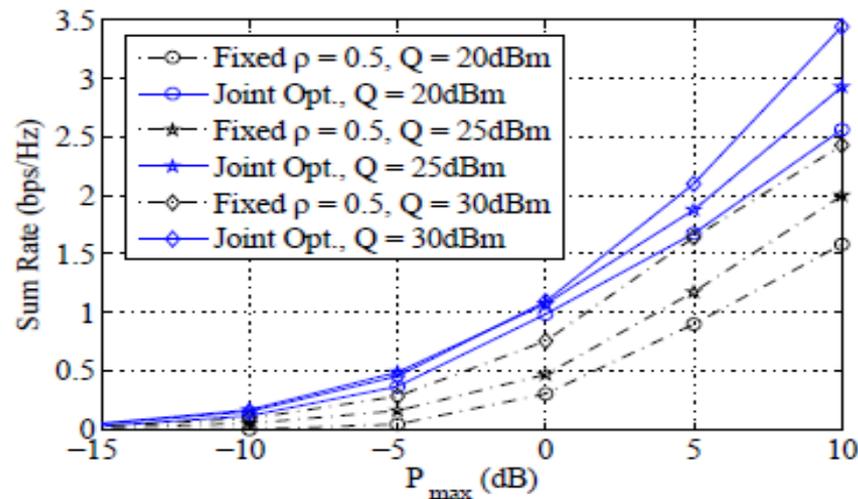


Figure: Sum-rate versus  $P_{\max}$ .

## Simulation Result (2)

In this figure, we analyse the impact of the residual self-interference (RSI) on the achievable sum-rate. Particularly, we investigate the performance of our proposed scheme for both fixed PS and joint optimization versus the RSI.

- $\rho$  = receive power splitter value

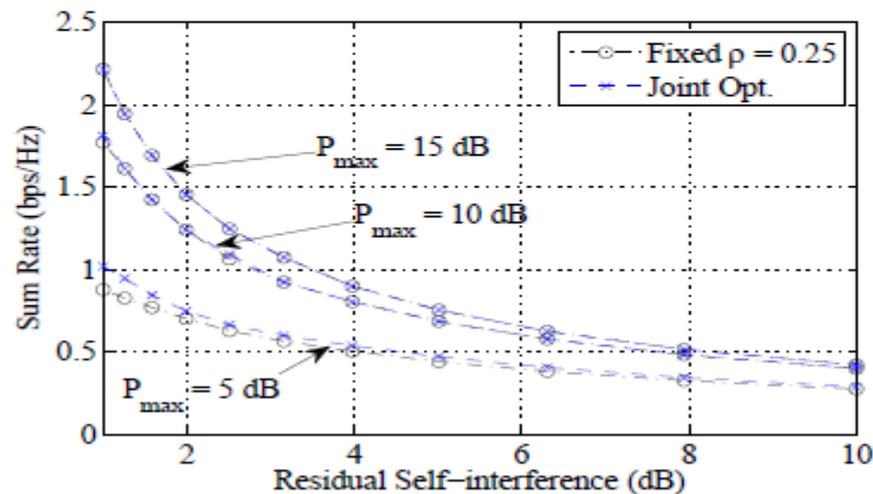
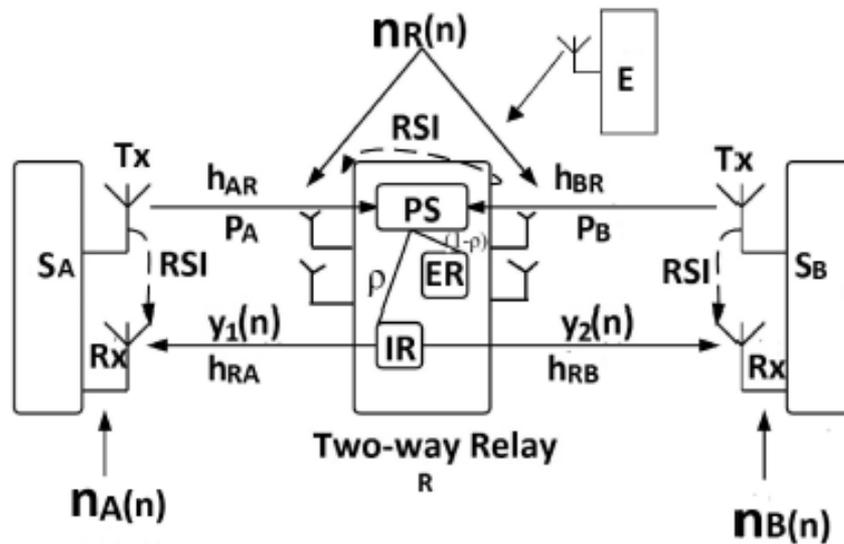


Figure: Sum-rate versus residual self-interference

# Contribution 2: Secure FD two-way relaying for SWIPT



- ▶  $n_A$  = node A;  $n_B$  = node B;  $E$  = eavesdropper
- ▶  $\rho$  = receiver power splitter
- ▶ ER = energy receiver
- ▶ IR = information receiver
- ▶  $y_1$  = received signal at node A
- ▶  $y_2$  = received signal at node B

Figure: Two-way full-duplex SWIPT system with external eavesdropper

# Problem Formulation

To maximise the secrecy sum-rate for SWIPT by ensuring system parameters are optimal, we formulate the problem below

$$\min_{\substack{\rho \in (0,1), \mathbf{W}, \mathbf{Q} \succeq \mathbf{0} \\ 0 < P_A \leq P_{\max}, 0 < P_B \leq P_{\max}}} P_A + P_B + P_R \quad \text{s.t.} \\ \left\{ \begin{array}{l} \Gamma_A \geq \gamma_A; \Gamma_B \geq \gamma_B; \Gamma_E \leq \gamma_E, \\ (1 - \rho)(|\mathbf{h}_{AR}|^2 P_A + |\mathbf{h}_{BR}|^2 P_B + \bar{E} + \sigma_R^2 M_R) \geq \bar{Q}, \\ \mathbf{H}_{RR} \mathbf{W} = \mathbf{0}. \end{array} \right.$$

where  $P_A$ ,  $P_B$  and  $P_R$ , respectively, represents the transmit power at Node A, Node B and the Relay node.  $\gamma_A$ ,  $\gamma_B$ ,  $\gamma_E$ , and  $\bar{Q}$  are respective quality of service threshold;  $\mathbf{W}$  = Relay beamforming matrix;  $\rho$  = receive power splitter;  $\mathbf{Q}$  = Antenna noise.

## Simulation result (3)

Here, we investigate the secrecy sum-rate for SWIPT in FD systems versus the transmit power budget  $P_{\max}$  (dB) for different values of the harvested power constraint.

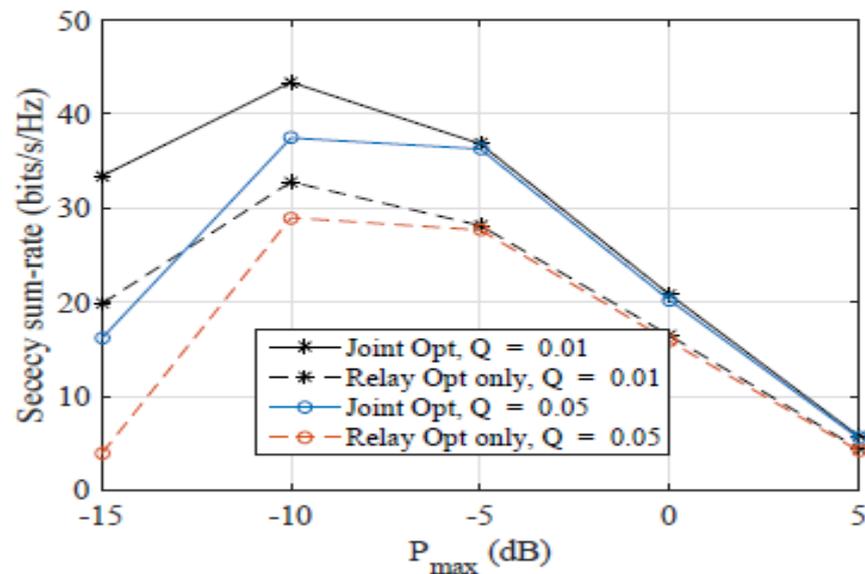


Figure: Secrecy sum-rate versus  $P_{\max}$ .

## Simulation result (4)

In this Fig., we investigate further, the secrecy sum-rate performance against the RSI for different values of the harvested power constraints.

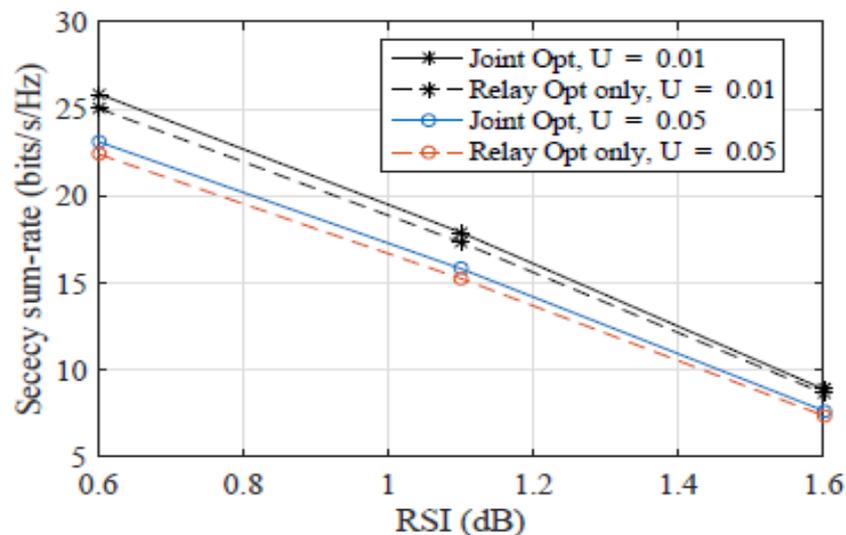


Figure: Secrecy sum-rate versus  $P_{\max}$ .

# Summary

- For contribution 1, we proposed an iterative algorithm that jointly optimises the receive power splitter and the transmit power for SWIPT in a point-to-point FD system.
- Our second contribution proposed a novel integration of SWIPT, FD technology, and physical layer security to jointly maximise the secrecy sum-rate of SWIPT in a MIMO FD two-way relay system. The proposed scheme showed that given the transmit power, harvested energy and SINR constraints for secure SWIPT in FD MIMO relay systems, at low transmit power, the secrecy rate rises while at high transmit power, the secrecy sum-rate drops due to the increase in RSI.

# Questions?



# List of publications in RF Energy Harvesting

1. **Okandeji, A. A.**, Khandaker, M. R. A., and Wong, K-K. Wireless information and power transfer in full-duplex communication systems, in Proc. *IEEE International Conference on Communication*, pp. 1-6, May 23 - May 27 2016, Kuala Lumpur, Malaysia.
2. **Okandeji, A. A.**, Khandaker, M. R. A., and Wong, K-K. "Two-way beamforming optimization for full-duplex SWIPT systems, in Proc. *Special session on full-duplex radio, IEEE 24th European Signal Processing Conference*, pp. 2375-2379, 29 Aug. - 02 Sept. 2016, Budapest, Hungary.
3. **Okandeji, A. A.**, Khandaker, M. R. A., Wong, K-K., and Zheng, Z. Joint Transmit Power and Relay Two-Way Beamforming Optimization for Energy-Harvesting Full- Duplex Communications, in Proc. *IEEE First International Workshop on Full- Duplex Wireless Communications, Globecom*, Washington, USA, pp. 1-6, Dec. 2016

## Publications....contd

4. **Okandeji, A. A.**, Khandaker, M. R. A., Wong, K-K., Zheng, G., Zhang, Y., Zheng, Z. and Ruopeng, L. SWIPT in MISO full-duplex systems. *IEEE Journal of Communications and Networks*, **19**(5), 469-479, Oct. 2017.
5. **Okandeji, A. A.**, Khandaker, M. R. A., Wong, K-K, Zhang, Y., and Zheng, Z. "Secure beamforming design for SWIPT in MISO Full-duplex systems. *ZTE Journal of Communications, Special Issue on Wireless Data and Energy Integrated Communication Networks*, **16**(1), 38-46, Feb. 2018.
6. **Okandeji, A. A.**, Khandaker, M. R. A., Wong, K-K., Zheng, G., Zhang, Y., and Zheng, Z. "Secure Full-Duplex Two-way Relaying for SWIPT. *IEEE Wireless Communications Letters*, **7**(3), 336-339, Jun. 2018.
7. **Okandeji, A. A.** Multicast Beamforming for SWIPT in MISO Full-Duplex Systems. *Nigerian Journal of Technological Research. Faculty of Engineering, Federal University of Technology, Minna, Nigeria*. **16**(1), 26-33, Jan., 2021.