TELKOMNIKA Telecommunication, Computing, Electronics and Control
Vol. 19, No. 5, October 2021, pp. 1466~1474
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v19i5.20413

Dynamic power allocation and scheduling for MIMO RF energy harvesting wireless sensor platforms

Amar Esse, Khaizuran Abdullah, Mohamed Hadi Habaebi, Huda Adibah Mohd Ramli, Ani Liza Asnawi, Md. Rafiqul Islam
Department of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Selangor, Malaysia

Article Info

Article history:

Received Sep 9, 2020
Revised Jul 15, 2021
Accepted Jul 23, 2021

Keywords:

Dynamic power allocation
Power splitting
RF Energy
SWIPT
WSN

ABSTRACT

Radio frequency (RF) energy harvesting systems are enabling new evolution towards charging low energy wireless devices, especially wireless sensor networks (WSN). This evolution is sparked by the development of low-energy micro-controller units (MCU). This article presents a practical multiple input multiple output (MIMO) RF energy-harvesting platform for WSN. The RF energy is sourced from a dedicated access point (AP). The sensor node is equipped with multiple antennas with diverse frequency responses. Moreover, the platform allows for simultaneous information and energy transfer without sacrificing system duplexity, unlike time-switching RF harvesting systems where data is transmitted only for a portion of the total transmission duty cycle, or power-splitting systems where the power difference between the information signal (IS) and energy signal (ES) is neglected. The proposed platform addresses the gap between those two. Furthermore, system simulation and two energy scheduling methods between AP and sensor node (SN) are presented, namely, Continuous power stream (CPS) and intermittent power stream (IPS).

Corresponding Author:

Khaizuran Abdullah
Department of Electrical and Computer Engineering, Kulliyyah of Engineering
International Islamic University Malaysia
Gombak Road, 53100, Selangor, Malaysia
Email: khaizuran@iium.edu.my

1. INTRODUCTION

Radio frequency (RF) power transfer has recently received a great deal of interest in the research arena as a consequence of a massive proliferation in the number of low power connected nodes, especially in wireless sensor networks (WSN) [1]. RF energy harvesting represents a genuine opportunity for replacing huge batteries [2], [3], which are not just expensive to produce and discard but also limit the lifetime of a sensor node [4]. Furthermore, when a sensor is operating in harsh environments, the battery life could be very much less than the expected lifetime due to the limited linear operating range of such batteries [5], [6]. RF power transfer (RF-PT) enables an access point (AP) to send energy wirelessly to a sensor node (SN). An AP has unbounded power, for example, connected to the grid, or has massive, stored energy, for example, harvests energy from the sun or other high-power sources. RF-PT is not a new concept, as Tesla [7] conducted experiments of the earliest wireless energy transfer system almost a century ago [8], with an ambition of realizing global energy to replace the traditional power lines. However, due to the safety concerns of the high transmission power adopted by Tesla [7], the field of RF energy harvesting (EH) had lost interest for quite some time. Until recently, where it gained attention again as a consequence of the development in microcontroller units (MCU)s, such developments make it possible to produce MCUs with high computing power, low energy consumption, and very small size, which enables it to be embedded in almost anything.

In today's grueling competition, businesses encounter evolving needs to improve their operational efficiency. Furthermore, companies need to achieve their financial objectives while complying with the regulatory body's recommendations in terms of environmental regulations. Current automation systems are achieved through wired architectures. However, realizing such automation systems involves costly wire networks, requiring regular maintenance [9]. Hence the implementation of wired automation systems is very limited in industrial plants. Consequently, there is an imperative necessity for wireless automation systems, which are not only cost-effective but also convenient and easy to operate and integrate into larger systems. The realization of low-cost automation solutions by embedding small sensors on the industrial machinery become feasible due to the current advancements in the field of WSN and MCUs. In WSN, small size sensors are embedded in industrial machinery or equipment [10]. These sensors collect critical information related to the operation of this equipment [11], such as temperature, humidity, pressure, voltage, and sometimes radiation levels in nuclear reactors. The collected data are then sent to an access point or a sink for analysis and decision-making on a timely basis [12]. Hence, catastrophic breakdowns of the equipment can be avoided, which may otherwise cause expensive replacement and repair costs, or in worst scenarios, may result in personal injury.

The main advantages of WSN over wired sensor networks in industrial monitoring systems are easy deployments and communication flexibility [13], which allows changing network architecture rapidly. Accordingly, WSN plays an essential role in establishing self-sustaining reliable industrial networks. One of the current main challenges in WSN is sustainability [14]. Due to the increasing number of WSN nodes and their ever-shrinking size, powering them through traditional methods is inherently expensive and infeasible. The solution to the sustainability problem is to enable SNs to harvest energy [15]-[17]. Numerous energy harvesting methods for WSN have been presented in the literature, including: photovoltaic, piezoelectric, and RF energy harvesting [18]. However, considering the indoor nature of industrial plants and critical quality of service (QoS) requirements, only a controllable energy source can be adapted, for instance, an RF power transmitter. In RF power networks, an AP with a relatively unlimited power connection transmits energy and information signal (IS) to the SNs. The energy signal is used to power the SN, while the IS is used to send instructions to the sensor. The SN requires proper scheduling to receive energy and information on the same RF resources simultaneously. Two practical RF-EH scheduling methods have been proposed in the literature, namely, power splitting (PS) and time switching (TS) [19]. However, both methods do not consider the different power requirements of decoding a signal and powering an SN. Moreover, TS is half-duplex.

The contribution of this paper is the proposition of a dynamic switching architecture with multiple input multiple output (MIMO) antenna rack with various spectrum response support, which allows simultaneous information and energy communication over different frequency bands. The proposed architecture considers the massive power gap between the energy signal (ES) and information signal (IS). Furthermore, two scheduling methods are presented,

The rest of the article is arranged as follows: section two, RF energy harvester switching methods. In section three, a MIMO RF energy switching architecture for industrial platforms is presented. In section four, system simulation is presented. In section five, Energy and Information scheduling are presented, and finally, section six concludes the paper.

2. RF ENERGY HARVESTER SWITCHING METHODS

2.1. Power splitting

In power splitting, the received power is split into two streams, one stream for the information decoding and the other for energy harvesting. The signal is divided according to a preselected power ratio ρ for the information decoder and $(1-\rho)$ for the Energy harvester [20], [21], as shown in Figure 1. PS does not require any special circuitry at the transmission side, implying that most of the legacy systems can be used as a transmitter.

The power and information rate can be balanced by varying ρ according to the system requirements. Thus, the performance of the system is determined by the power splitting ratio. The harvested energy at a PS system with transmitting source a and receiver b can be expressed as follows:

$$P_b = \eta P_a |h_{ab}|^2 (1-\rho) \quad (1)$$

where h_{ab} is the channel matrix between transmitter and receiver, and η is the conversion efficiency of the energy harvester. Furthermore, the information rate of the receiver can be expressed as (2).

$$R_b = w\log(1 + \frac{(\rho)P_a|h_{ab}|^2}{\sigma^2}) \quad (2)$$

Where σ^2 is the receiver power noise and w is the physical spectrum. No signal processing noise is considered.

Theoretically, PS offers the best balance between transferred RF energy and information rate [22]. However, PS architecture completely overlooks the difference between information decoding and powering SN in terms of power requirements. For instance, information is usually sent just above the noise threshold of the intended receiver, around -120 dBm [23]. While a modern MCU intended for low power applications such as Texas instruments MSP430F247 MCU requires a minimum power of 0 dBm [24].

2.2. Time switching

A time switching (TS) architecture shares the same spectrum resource between EH and information processing (IP) circuitry. A TS architecture comprises of information decoder, RF energy harvester, and a time switcher to alternate between system states [25]. Thus, at any given point in time, the system can only be at one state, either IP or EH. Moreover, as any system that uses time as a scheduling technique, the TS requires very strict time synchronization to schedule between energy and information. When the receiver b is in EH state, the amount of harvested energy can be expressed as (3).

$$P_b = \eta P_a|h_{ab}|^2 \quad (3)$$

Where η is the EH efficiency of the receiver and, P_a is the transmission power of source a. Likewise, when the receiver is switched to the IP state, the information decoding rate can be computed using the (4) [15].

$$R_b = w\log(1 + \frac{P_a|h_{ab}|^2}{\sigma^2}) \quad (4)$$

Furthermore, the TS sequence and duty cycle of each state can be varied because of changing power constraints and channel statistics. Hence, different optimization objectives depending on the required QoS can be achieved. Despite TS being the simplest form of RF EH switching, the system can only receive information for a portion of the total transmission duty cycle. In other words, TS is a half-duplex system [26]. As shown in Figure 2, the system can only perform Information processing or energy harvesting at any specific point in time.

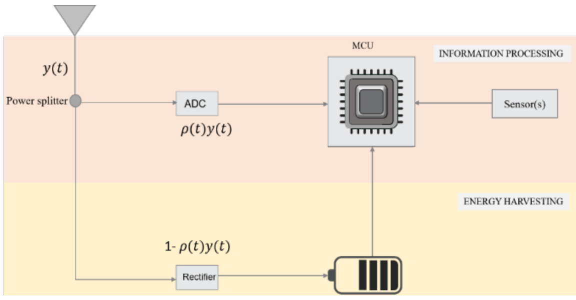


Figure 1. Power splitting receiver architecture

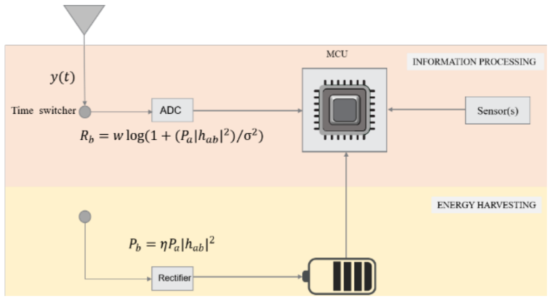


Figure 2. Time switching receiver architecture

3. SYSTEM MODEL

The proposed MIMO RF energy harvesting architecture for WSN platforms, as shown in Figure 3, consists of an AP with dynamic power allocation (DPA), depicted in Figure 4. The output power at the AP is varied depending on whether the transmitted signal is ES or IS. For example, the receiver can sense signals just above the noise level, as low as -120 dBm. So, the transmission power of 20 dBm is enough, especially in an indoor environment where the receiver is less than 100 meters away from the transmitter. While for ES, a transmission power 1000 folds higher is required. On the other hand, the SN node consists of a receiver with multiple antenna components, as depicted in Figure 5. Each component can receive energy or information depending on the exchanged channel state ranking; the details of the system scheduling are discussed in section five.

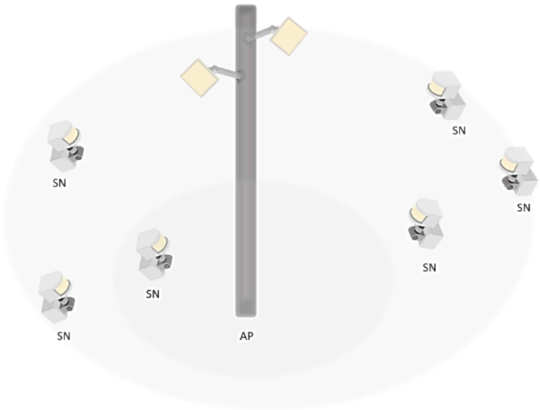


Figure 3. System architecture for EH industrial platform

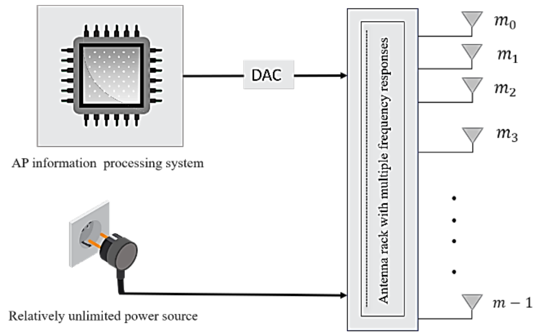


Figure 4. AP transmitter design

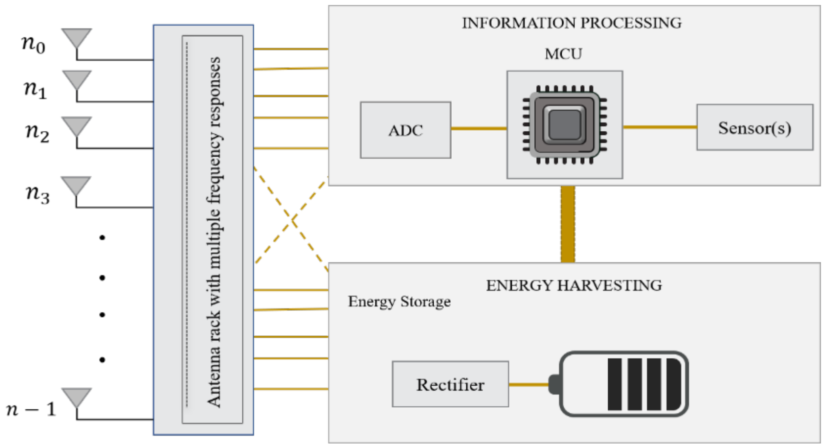


Figure 5. SN receiver design

The system exists in an indoor environment with just outer walls, for example, a manufacturing environment where the AP and SN are stationary or moving in a very limited axis. In such an environment, there exists a continuous line of sight (LOS) between the SN and AP. The received signal at the SN could be expressed as (5) [27].

$$s_{rn} = \sum_{n=1}^{N_t} \int_{-\infty}^{\infty} h_{mn}(\tau, t) s_{tm}(t - \tau) d\tau \quad (5)$$

Where h_{mn} is the channel impulse response between the AP and SN, t the time changing channel, N_t is the number of transmit antennas, τ is the time delay caused by multipath and, s_{tm} is the transmitted signal. Moreover, in a MIMO system, there are two categories of received signal components: LOS component without delay, and multipath components with a varying delay depending on the traveled path. This can be expressed mathematically as (6).

$$s_{rn}(t) = \frac{s_{tm}(t - t_{mn0})}{2\sqrt{\pi}\, r_{mn0}} + \sum_{p=0}^{N_p(m,n)} \frac{s_{tm}(t - \tau_{mnp})\, \Gamma_p(m,n)}{2\sqrt{\pi}\, r_{mnp}} \quad (6)$$

The r_{mnp} stands for path length, Γ_p reflection coefficient, and p stands for the path. Each antenna component at the receiver side has a specific and relatively high stopband attenuation. Thus, the channel matrix only contains the links between the antennas with the same spectrum. Furthermore, providing that all the components have different frequency responses and considering only LOS (due to the short distance between the AP and SN) than, the channel matrix becomes one column vector.

$$H = \begin{bmatrix} h_{11} \\ \vdots \\ h_{mn} \end{bmatrix}$$

The received signal without multipath components can be expressed as (7).

$$\sum_{n=0}^{N_r}\sum_{m=0}^{M_t}\frac{s_{tm}}{2\sqrt{\pi}r_{mn}} \tag{7}$$

A thorough analysis of the capacity of MIMO systems can be found in [28].

4. SYSTEM SIMULATION

A downlink simulation is carried out to evaluate an RF-powered SN using [29]. A transmission power of 100 mW is considered for the IS. While for the power signal, a transmission power of 10 watts is considered, 100 times higher than that of the IS. Moreover, the DPA allocates different power levels to the ES and IS, while PS and TS architectures allocate the same power level to information and power signals as depicted in Figure 6. For PS and TS architectures to achieve equivalent DPA level of power transmission, they have to transmit a high-power modulated wave that occupies a wide bandwidth, which may introduce serious interference to the nearby wireless systems. The rest of the simulation parameters are listed in Table 1. The peak to average power ratio (PAPR) of the signals is depicted in Figure 7, showing a high difference in PAPR levels due to the huge difference in the transmission power. Traditionality, a high PAPR is unwelcomed in wireless communications. However, in the case of sending a power signal, which is not carrying any information, the higher the transmission power, the better. Thus, if one is using multiple carriers, the higher the PAPR, so it is wise to use as few carriers as possible for energy signal. In Figure 8, the BER of the IS is depicted over different SNR values. One hundred points along those SNR values are simulated, and the average BER for 900 frames for each point is shown in the figure. In Figure 9. the throughput for the IS is shown using the simulation values stated in Table 1.

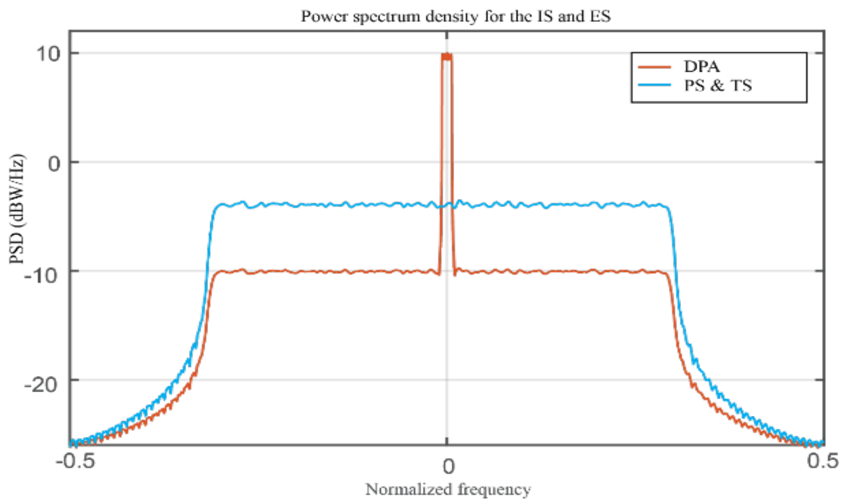


Figure 6. The PSD for IS and ES

Table 1 Simulation parameters

Simulation parameters	Value
Carrier central frequency	2.5Ghz
Number of simulated frames	900
Number symbols per frame	15
Information signal bandwidth	$(15 \times 10^3 \times 60)\ KHz$
Energy signal bandwidth	$(15 \times 10^3 \times 12)\ KHz$
Modulation type	QPSK
Information signal Tx power	$20dBm$
Energy signal Tx power	$40dBm$
Number of AP antennas	2
Number of SN antennas	2
Channel coding	Turbo codes
Decoding algorithm, decoding Iterations	Linear-Log-MAP, 8

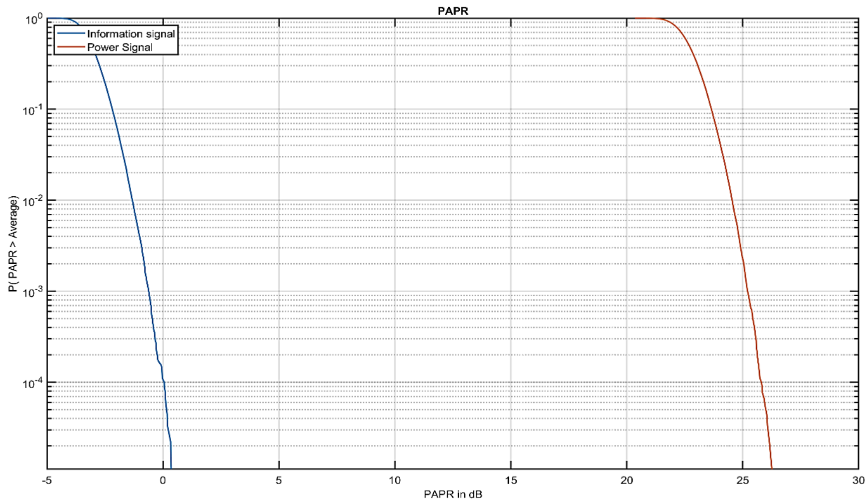


Figure 7. The beak to average ratio of the information signal and power signals

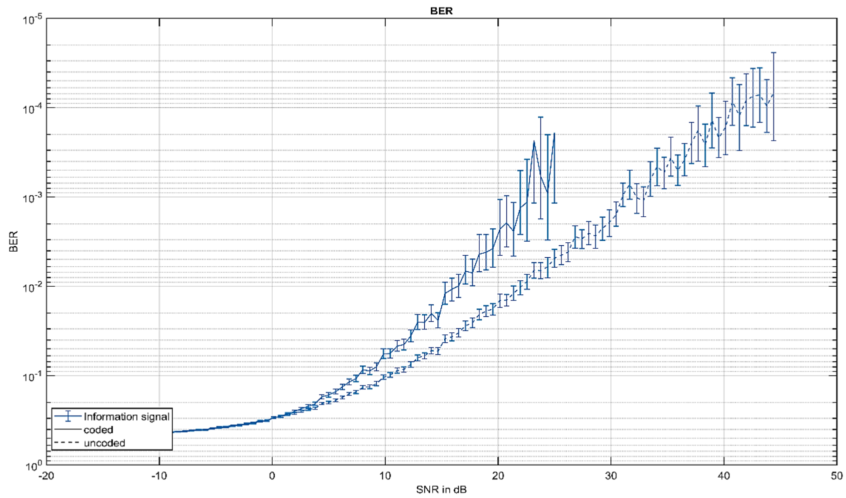


Figure 8. BER of the Information signal

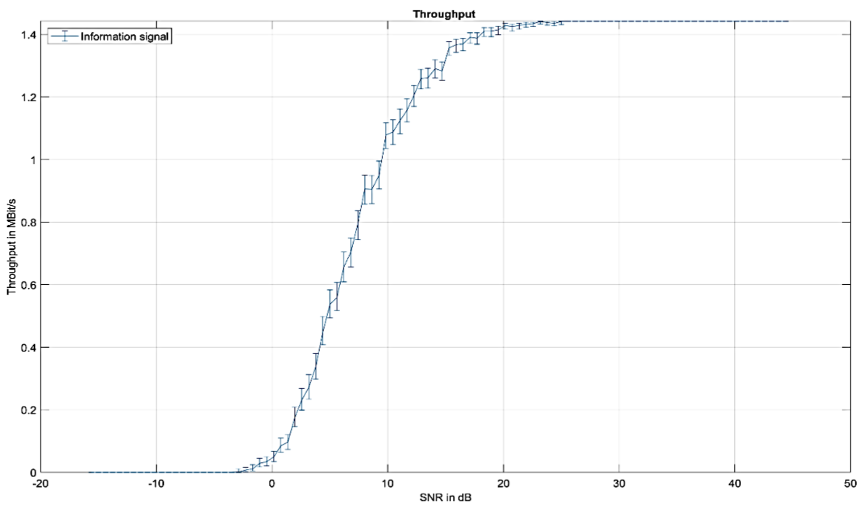


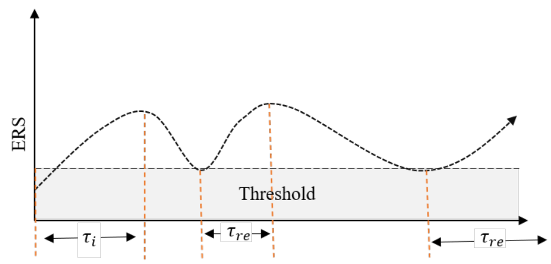
Figure 9. Throughput of the information signal

5. ENERGY AND INFORMATION SCHEDULING

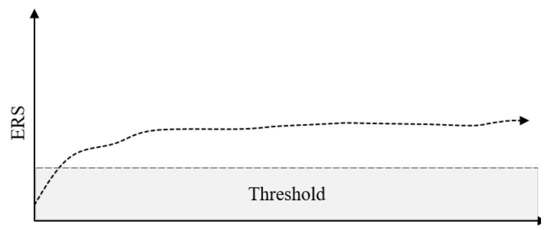
In this section, two scheduling methods are introduced, namely the continuous power stream (CPS) and the intermittent power stream (IPS). In CPS, the AP continuously transmits power; in other words, a constant power flow exists between AP and SN. In this scheduling method, the AP initially sends a broadband signal to the SNs to report their existence. Next, AP sends the spectrum resource allocation for EH and IP to the SN. To perform resource allocation, the AP could rely on a predetermined resource repository, or it may implement a dynamic spectrum database, for example, Google spectrum database.

Furthermore, CPS scheduling is easy to implement and requires stationary AP and SN. The initial broadband signal sent by the AP in CPS is a short unmodulated high-power sinewave. When the SN receives the signal, it will passively modulate it with its medium access address (MAC) and backscatter [30] the modulated signal to the AP. Moreover, the process of adding a new SN to the system could be automatic, meaning AP checks the present SNs following time frame, for example, update every 30 seconds. Alternatively, the SNs can be added physically by triggering the node-addition process manually.

In IPS, the power is sent following an intermittent style; in this case, there is no continuous power stream between AP and SN. the power is sent only based on demand. The process of initiation of the network, as well as the addition of new nodes, is like CPS. After initiation, the AP charges all the new nodes for some instance τ_i. The discrete nature of IPS necessitates having information about the energy level at the SN in order to know when to send or not to send energy. Accordingly, In IPS, the energy reservoir status (ERS) at the SN is obtained in two ways. The first way is by attaching the ERS (A-ERS) to every packet sent from SN to AP. Thus, whenever the ERS is under a specific threshold, the AP starts transmitting power to recharge the SN for a time instance of τ_{re}. The second way is to dedicate a small fraction of the spectrum resource to an energy request flag (ERF). The dedicated ERF (D-ERF) is sent by the SN when the ERS declines under a specific level. Moreover, when the AP receives the ERF signal, it will automatically start transmitting energy to SN again for time instance of τ_{re} as shown in Figure 10. Which IPS method to select is mainly depends on the energy reservoir size and the frequency of information transmission from SN to AP. For example, if the transmission at the SN is very frequent, then adopting A-ERS introduces redundancy which increases with the data rate, in such an event, it is wise to implement D-ERF. The flow graph of both CPS and IPS scheduling methods is illustrated in Figure 11 (see Appendix). Finally, an essential point, which is not covered in this article is overload protection of the SN's IP part. Because of the vast power difference between the IP and EH, it is very crucial to develop a protection solution to prevent overloading, which could damage the SN.



(a)



(b)

Figure 10. Power scheduling methods for (a) IPS, (b) CPS

6. CONCLUSION

RF energy harvesting presents a great opportunity for the future of wireless networks. Mainly WSN, where the number of network nodes is very high, and nodes are diversely scattered in the coverage zone. Providing electricity for such nodes in a conventional way will become prohibitively expensive as the number of nodes increase. A considerable amount of research has been done on ways to harvest RF energy. Different Scheduling algorithms for IP and EH are proposed in the literature. The scheduling methods can be mainly divided into TS and PS. The TS switches between EH and IP temporally, thus, sending information only half of the time. While the PS, in theory, splits the received signal between IP and EH circuitry without considering the different power requirements between the two circuitries. This article presents a MIMO IP and EH system with frequency diversity and dynamic power allocation support. The system allows wireless nodes to receive information and energy at the same time. Furthermore, two scheduling methods for power transmission, from the AP to SN, are discussed, namely CPS and IPS.

APPENDIX

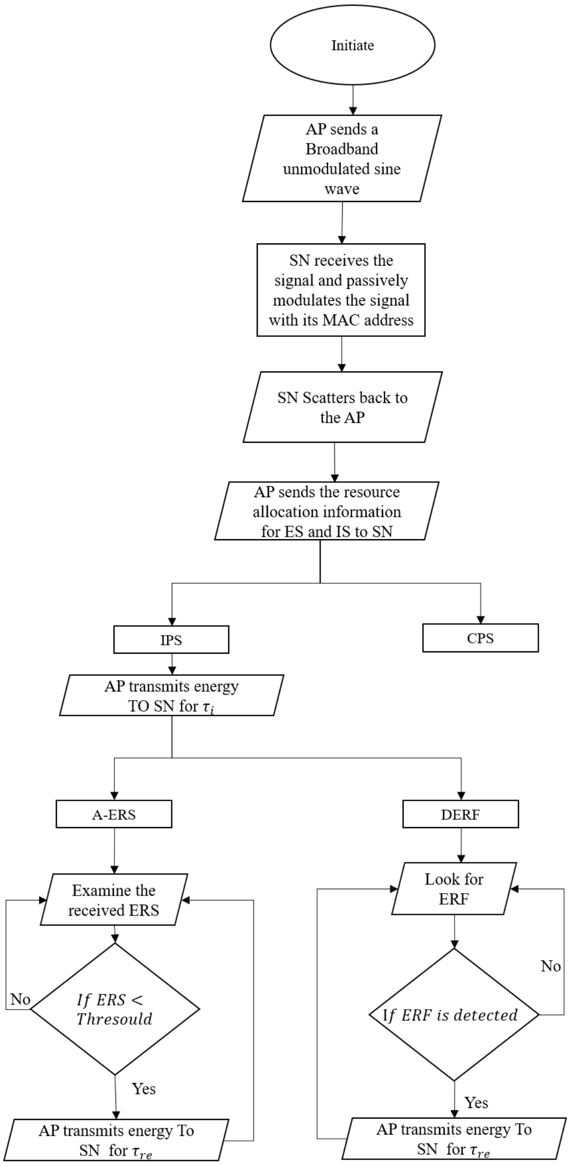


Figure 11. Energy scheduling flowgraph for IPS and CPS

ACKNOWLEDGEMENT

We are very grateful to the Ministry of Higher education Malaysia for supporting this research under grant ID FRGS19-055-0663.

REFERENCES

[1] M. Alfaqawi, M. H. Habaebi, M. R. Islam, and M. U. Siddiqi, "Energy Harvesting Network with Wireless Distributed Computing," *IEEE Syst. J.*, vol. 13, no. 3, pp. 2605–2616, 2019, doi: 10.1109/JSYST.2019.2893248.
[2] M. I. M. Alfaqawi, M. H. Habaebi, M. U. Siddiqi, M. R. Islam, A. Zyoud, and M. Al-Shibly, "Survey on energy harvesting cognitive radio network," *ARPN J. Eng. Appl. Sci.*, vol. 10, no. 23, pp. 17407–17415, 2015.
[3] M. Alfaqawi *et al.*, "POMDP Formulation for Energy Harvesting Network with Wireless Distributed Computing To cite this version : HAL Id : hal-02508299 POMDP Formulation for Energy Harvesting Network with Wireless Distributed Computing," 2020.
[4] H. Yu *et al.*, "Big-Data-Based Power Battery Recycling for New Energy Vehicles: Information Sharing Platform and Intelligent Transportation Optimization," *IEEE Access*, vol. 8, pp. 99605–99623, 2020, doi: 10.1109/ACCESS.2020.2998178.
[5] C. M. Yu, M. Tala'T, C. H. Chiu, and C. Y. Huang, "Joint balanced routing and energy harvesting strategy for

maximizing network lifetime in WSNs," *Energies*, vol. 12, no. 12, pp. 1–20, 2019, doi: 10.3390/en12122336.
[6] J. L. Mathieu and J. A. Taylor, "Controlling nonlinear batteries for power systems: Trading off performance and battery life," *19th Power Syst. Comput. Conf. PSCC 2016*, 2016, doi: 10.1109/PSCC.2016.7540856.
[7] N. Tesla, "Apparatus for transmitting electrical energy," US patent number 1,119,732, Dec. 04, 1914
[8] R. Dana, P. Sardhara, A. Sanghani, and P. Mehta, *A Detailed Survey of Rectenna for Energy Harvesting : Over a Wide Range of Frequency*. Springer Singapore, 2019. doi: 10.1007/978-981-13-6159-3.
[9] V. C. Gungor and G. P. Hancke, "Industrial wireless sensor networks: Challenges, design principles, and technical approaches," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4258–4265, 2009, doi: 10.1109/TIE.2009.2015754.
[10] T. Poongodi, A. Rathee, R. Indrakumari, and P. Suresh, *Iot sensing capabilities: Sensor deployment and node discovery, wearable sensors, wireless body area network (WBAN), data acquisition*, vol. 174. 2019, doi: 10.1007/978-3-030-33596-0_5.
[11] A. Djimli, S. Merniz, and S. Harous, "Energy-efficient MAC protocols for wireless sensor networks: A survey," *TELKOMNIKA Telecommunication Computing Electronics and Control*, vol. 17, no. 5, pp. 2301–2312, 2019, doi: 10.12928/TELKOMNIKA.v17i5.12163.
[12] Y. Luo, L. Pu, G. Wang, and Y. Zhao, "RF energy harvesting wireless communications: Rf environment, device hardware and practical issues," *Sensors (Switzerland)*, vol. 19, no. 13, 2019, doi: 10.3390/s19133010.
[13] D. V. Queiroz, M. S. Alencar, R. D. Gomes, I. E. Fonseca, and C. Benavente-Peces, "Survey and systematic mapping of industrial Wireless Sensor Networks," *J. Netw. Comput. Appl.*, vol. 97, pp. 96–125, 2017, doi: 10.1016/j.jnca.2017.08.019.
[14] D. Imededdin, A. Salih, and H. Medkour, "Design and implementation of low power consumption wireless sensor nodea," *TELKOMNIKA Telecommunication Computing Electronics and Control*, vol. 17, no. 6, pp. 2729–2734, 2019, doi: 10.12928/TELKOMNIKA.v17i6.12047.
[15] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with rf energy harvesting: A contemporary survey," *IEEE Commun. Surv. Tutorials*, vol. 17, no. 2, pp. 757–789, 2015, doi: 10.1109/COMST.2014.2368999.
[16] T. N. Nguyen, V. D. Phan, H. N. Nguyen, M. Tran, and T. T. Trang, "Performance analysis for power-splitting energy harvesting based two-way full-duplex relaying network over Nakagami-m fading channel," *TELKOMNIKA Telecommunication Computing Electronics and Control*, vol. 17, no. 4, pp. 1595–1603, 2019, doi: 10.12928/TELKOMNIKA.v17i4.11191.
[17] S. Suman, S. Kumar, and S. De, "UAV-Assisted RFET: A Novel Framework for Sustainable WSN," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 4, pp. 1117–1131, 2019, doi: 10.1109/TGCN.2019.2938403.
[18] Y. Chen, *Energy Harvesting Communications: Principles and Theories*. 2019. [Online]. Available: https://www.wiley.com/en-bm/Energy+Harvesting+Communications:+Principles+and+Theories-p-9781119383086
[19] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying Protocols for Wireless Energy Harvesting and Information Processing," *IEEE Trans. Wirel. Commun.*, vol. 12, no. 7, pp. 3622–3636, Jul. 2013, doi: 10.1109/TWC.2013.062413.122042.
[20] D. Wing, K. Ng, E. S. Lo, and R. Schober, "Wireless Information and Power Transfer : Energy Efficiency Optimization in OFDMA Systems," vol. 12, no. 12, pp. 6352–6370, 2013.
[21] C. Song, C. Ling, J. Park, and B. Clerckx, "MIMO broadcasting for simultaneous wireless information and power transfer: Weighted MMSE approaches," in *2014 IEEE Globecom Workshops, GC Wkshps 2014*, 2014, pp. 1151–1156. doi: 10.1109/GLOCOMW.2014.7063588.
[22] X. Zhou, R. Zhang, and C. K. Ho, "Wireless Information and Power Transfer: Architecture Design and Rate-Energy Tradeoff," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4754–4767, Nov. 2013, doi: 10.1109/TCOMM.2013.13.120855.
[23] K. W. Choi *et al.*, "Simultaneous Wireless Information and Power Transfer (SWIPT) for Internet of Things: Novel Receiver Design and Experimental Validation," *IEEE Internet Things J.*, vol. 7, no. 4, pp. 2996–3012, 2020, doi: 10.1109/JIOT.2020.2964302.
[24] A. M. Baranov, S. Akbari, D. Spirjakin, A. Bragar, and A. Karelin, "Feasibility of RF energy harvesting for wireless gas sensor nodes," *Sensors Actuators, A Phys.*, vol. 275, no. 2010, pp. 37–43, 2018, doi: 10.1016/j.sna.2018.03.026.
[25] D. Xu and Q. Li, "Joint Power Control and Time Allocation for Wireless Powered Underlay Cognitive Radio Networks," *IEEE Wirel. Commun. Lett.*, vol. 6, no. 3, pp. 294–297, 2017, doi: 10.1109/LWC.2017.2676102.
[26] T. N. Nguyen, T. H. Q. Minh, P. T. Tran, and M. Vozňák, "Energy harvesting over rician fading channel: A performance analysis for half-duplex bidirectional sensor networks under hardware impairments," *Sensors (Switzerland)*, vol. 18, no. 6, 2018, doi: 10.3390/s18061781.
[27] R. L. Haupt, *Wireless Communications Systems: An Introduction*. Wiley-IEEE Press, 2020. [Online]. Available: https://www.wiley.com/en-us/Wireless+Communications+Systems%3A+An+Introduction+-p-9781119419204
[28] P. Varzakas, "Average channel capacity for Rayleigh fading spread spectrum MIMO systems," *Int. J. Commun. Syst.*, vol. 19, no. 10, pp. 1081–1087, 2006, doi: 10.1002/dac.784.
[29] S. Pratschner *et al.*, "Versatile mobile communications simulation: the Vienna 5G Link Level Simulator," *EURASIP J. Wirel. Commun. Netw.*, vol. 2018, no. 1, p. 226, Dec. 2018, doi: 10.1186/s13638-018-1239-6.
[30] W. Liu, K. Huang, X. Zhou, and S. Durrani, "Next generation backscatter communication: systems, techniques, and applications," *Eurasip J. Wirel. Commun. Netw.*, vol. 2019, no. 1, 2019, doi: 10.1186/s13638-019-1391-7.