RF Energy Harvesting in Cognitive Radio: Towards Green Communication

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Abstract: There has been a continuous emphasis on an energy efficient communication system design. With the advent of 5G communication technologies, along with a faster and reliable data transfer mechanisms, energy management and conservation is gaining more attention and is becoming a major and indispensable part of communication research. This papers highlights the contemporary technological developments in the field of RF energy harvesting in a cognitive and high data rate network. It has been observed that an efficient RF energy harvesting technology in a cognitive platform definitely leads towards a greener communication paradigm.

Keywords: Cognitive Radio, Energy Harvesting, simultaneous wireless information and power transfer (SWIPT)

1 Introduction

Energy harvesting technology is an important aspect which needs to be embedded in a wireless network to serve the basic purpose of self sustainability and virtual operation. With the increase in network lifetime by harvesting radio frequency (RF) and other ambient energy, it paves the way to make the wireless sensor network (WSN)s feasible in the hard to reach locations viz. remote rural areas, inside concrete structures and human body. Hence apart from other contemporary communications, energy harvesting can become a promising candidate in medical and surveillance applications [1][2].

Apart from RF energy there happens to be several natural and manmade sources available for harvesting energy. As there are diversified sources from where energy can be harvested as well as transferred from one node to the other, the harvesting technology must be of different capabilities and efficiencies. It is seen that though the emphasis to have an efficient energy harvester from the circuit improvement as well as device improvement is being carried out over the years but the approach to get a signal processing based integrated scheme for the network is not very old. Hence it adds a new dimension to the wireless communication system design and also opens a new realm of wireless energy transfer [1][3].

The Cognitive Radio (CR) technology is one of the most important communication technology to enhance the spectrum efficiency with a dynamic and opportunistic channel allocation mechanism. Hence a spectrum sensing mechanism to detect a spectrum hole is an integral part of CR. To devise an integrated mechanism of spectrum sensing and energy harvesting is quite essential as the sensing energy loss can be compensated by the harvested energy and thereby a good throughput can be achieved. This papers highlights the contemporary technological developments in the field of RF energy harvesting in a cognitive and high data rate network. It has been observed that an efficient RF energy harvesting technology in a cognitive platform definitely leads towards a greener communication paradigm.

2 DIFFERENT ASPECTS AND CONSIDERATION OF Energy Harvesting

Energy harvesting in wireless networks is a technology by which RF and ambient energy is exploited and used, making a self-sufficient wireless network. CR is an opportunistic communication framework where spectrum sensing mechanism continuously tries to find energy holes and allowing a secondary user to use the bandwidth. Allowing a secondary user depends on the spectrum policy so as to comply with license issue. But CR is a promising candidate to deal with spectrum efficiency. CR is an indispensable element of present and upcoming RF networks and is likely to gain more acceptance in 5G wireless systems. Therefore the importance of energy conservation and harvesting in CR systems are considered to be integral element of next generation wireless network. The block diagram in figure 1 shows a basic CR framework enabled with energy harvesting and simultaneous wireless information and power transfer (SWIPT).

For a simplistic depiction we can consider an additive white Gaussian channel (AWGN) model. Let us assume A and B be the input and output and N be the Gaussian noise with zero mean and unity variance. Hence the output can be expressed as B=A+N. As the channel

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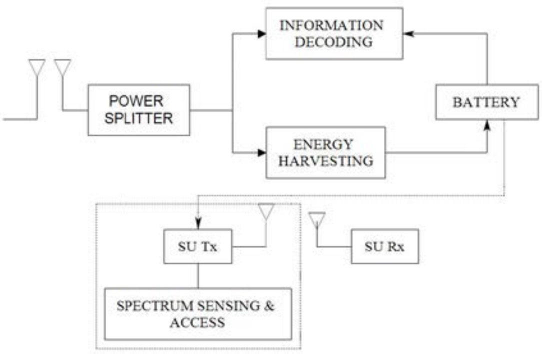

Figure 1: Basic block diagram of a CR with energy harvesting

capacity is C=1/2 log (1+P), we will have a power constraint [4]

$$1/n \sum_{i=1}^{n} A_i^2 \leq P \quad (1)$$

where A_i is an element of the codeword and P is the signal power. If the energy harvesting is considered to be a stationary and ergodic random process E_i with the average recharge rate E $[E_i]$ = P, the energy being harvested and used at every channel use will be directly related. For one channel A_i^2 units of energy will be depleted and E_i units shall get recharged. Hence we must have a causality constraint

$$\sum_{i=1}^{k} X_i^2 \leq \sum_{i=1}^{k} E_I, \ k=1,\ldots\ldots,n \quad (2)$$

The energy utilised at every channel use cannot exceed the cumulative energy harvested. That is why there can multiple forms of constraints in relation to the codeword and the energy depending on the energy harvesting scenario and the nature of the storage/battery being implemented. The capacity of the channel with infinitely large battery, zero battery and unit-sized battery will be different and needs to be explored. Also different techniques needs to be adopted to achieve such schemes [5][6].

2.1. Channel Capacity with Different Natures of Storage

2.1.1 Infinitely Large Battery

If the constraint shown in equation (2) is satisfied by a codeword, it implies automatic satisfaction of the equation (1) as $\frac{1}{n}\sum_{i=1}^{k} E_I \rightarrow P$. Hence the energy harvesting system will have an upper bound which is essentially equals the recharge rate. Broadly two schemes are reported [7].

In the first scheme the energy is saved in the first h(n) channel uses and no transmission is done in this case. Then the remaining n-h(n) uses are for transmission with the use previously retained energy where a pre-designed codebook with independent and identically distributed Gaussian samples having power equal to the recharge rate is used. This scheme is called save-and-transmit. In the second scheme known as best-effort-transmit, there is no separate saving and transmit phase, both occurs simultaneously. Hence the power assigned to each sample has to be less than the recharge rate, otherwise it will create mismatch and zero symbol will result. There has been several alterations to these schemes to deal with different shortcomings. A pictorial depiction of this scenario is presented in figure 2.

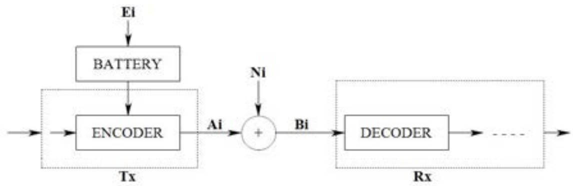

Figure 2:The scenario with infinitely large battery

2.1.2 Zero Battery

Since in this scheme there is no battery to store, hence the codewords are constrained by the instantaneous amplitude and this constraint is purely time-varying and stochastic and hence needs to be determined. The transmitter must have the causal information about the arrival profile and needs to choose the codeword in accordance with the observed energy [8]. It is reported that the capacity of the channel with infinite battery is far better than that of the zero battery. The scenario with zero battery is presented in figure 3.

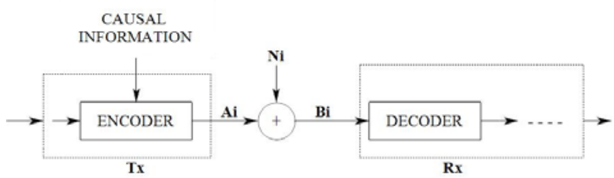

Figure 3: The scenario with no battery

2.1.3 Unit-sized Battery

In the previous section it is understood that the channel inputs are i.i.d. stochastic amplitude-constrained and the optimum inputs are discrete. But tracking the dynamics of energy queue resulted with the codebook is very complex. A system with finite battery size is presented in [4] where energy arrivals are presented as multiples of fixed quantity and thereby having a discrete alphabet based representation in terms of physical layer. Higher rate may be achieved in this case in comparison to the previous one with zero battery. The noiseless binary channel can also be modelled as timing channel which in turn helps the transmitter to have a causal knowledge.

3 RECENT ENERGY HARVESTING STRATEGIES IN COGNITIVE RADIO

Several energy harvesting models has been presented to optimise performances and enhance throughput in a cognitive communication platform.

An integrated approach of energy harvesting and spectrum sensing with emphasis on higher throughput and optimal sensing threshold has been presented in [9].

A primary transmitter is designed to serve the purpose of spectrum sensing while a secondary transmitter is used for the purpose of energy harvesting. The average throughput is used to optimise the energy harvesting model and thereby achieving both spectrum and energy efficiency.

A RF energy harvesting mechanism with optimization for a wireless sensor network is presented where the basic emphasis is on the improvement of success probability [10]. Optimization of success probability is considered with different parameters like transmit power of sensors and primary transmitters and spatial density of the primary transmitters where significant improvement of throughput and success probability is reported with algorithmic modification.

An analysis of cognitive network with realistic relay has been presented with two power policies and two bidirectional relaying protocols in [11]. The basic insight in this paper to analyse the degradation of power outage and throughput with relay impairments and also to have an effective analysis on power policies and protocols.

A cooperative spectrum sensing and energy harvesting approach for multichannel cognitive radio is proposed with channel allocation algorithm and optimization algorithm [12]. The frame structure is divided into two sub-channels, one is used for sensing and the other for harvesting. The harvested energy is stored then used to compensate the sensing loss and thereby maintains a good throughput with better sensing-energy efficiency.

A collaborative cluster based energy harvesting cognitive radio network is reported in [13] where enhancement of sensing performance and maximization of the throughput is achieved. They have introduced the concept of fictitious cognitive node and thereby simplifies the problem of local optimal threshold search into an optimal SNR search and thus a general optimization is formulated.

A practical non-linear energy harvesting model for a wideband wireless powered cognitive radio network is presented in [14]. Three optimization parameters viz. energy harvesting time, channel allocation and transmit power are considered to improve the throughput. It is observed that there is always a trade-off between harvested energy and throughput.

A wideband cognitive radio network with simultaneous wireless information and power transfer (SWIPT) is designed for achieving both energy and spectrum efficiency [15]. By considering several constraints on rate, transmit power, interference and sub-channel allocation, the harvested energy was tried to maximize by adopting Lagrangian and Subgradient methods. To deal with the severe fairness issue in the adopted method, they have further proposed a new max-min based algorithm to maximize the energy harvesting even in the worst link.

A decode and forward relaying scheme for a cognitive network with power splitting receiver has been presented in [16]. For choosing the best secondary user both direct and relaying links are considered and the performance evaluation of the DF protocols are done under Rayleigh fading scenario.

As non-orthogonal multiple access in combination with cognitive radio is a promising candidate for the next generation communication to deal with spectrum scarcity, a non-linear energy harvesting model is explored in such a system architecture to achieve both spectrum and energy efficiency [17]. The technology of simultaneous wireless information and power transfer (SWIPT) is adopted. To deal with the multi-object optimization problem a weighted Techebycheff method is applied where the performance of the non-linear model is claimed to be better than that of linear one.

An energy harvesting aided spectrum sensing and data transmission scheme with the combination of individual and cooperative multi-user sensing is proposed [18]. A RF energy harvesting is done by considering a multi objective optimization. Also the multi objective optimization problem is simplified by converting it into a single objective optimization problem.

A power splitting scheme that allows the cognitive sensor transmitter to have a RF energy harvesting is presented in [20]. The cognitive sensor transmitter spits the received signal into two parts; in the first part decode and forward relaying protocol is used and the second part is used for energy harvesting. In the second slot the CST allocates the part of the bandwidth to have decode and forward with the use of harvested energy and thereby saves the rest of the bandwidth to transmit its own signal. The cognitive radio transmission rate is improved by optimizing the bandwidth and power splitting ratio.

A combined sensing and power allocation scheme with energy harvesting is considered for a cognitive radio network [21]. A non-convex optimization problem is formulated with optimal sensing and power allocation and maximized energy efficiency. Using non-linear fractional programming the original non-convex problem is simplified to a convex problem and an energy efficient scheme is formulated.

The physical layer security issue in an energy harvesting relay based network in terms of energy outage is studied in [22]. Decode and forward technique for sending confidential information is used. As the simultaneous transmission of information and jamming signal degrades the performance the secrecy outage probability is investigated. Several factors like interference threshold, energy harvesting time, power allocation, target secrecy rate, target data rate are also evaluated.

A cooperative mechanism for energy harvesting cognitive radio is proposed to have a maximized throughput and higher energy efficiency [23]. To resolve the issues with maximum throughput and energy efficiency a new algorithm known as Quantum Firework Algorithm is proposed. This algorithm along with the cooperative mechanism is proved to have maximum throughput in a new time slot and thereby shows improved performance in comparison to the previously reported non-cooperative schemes.

A cognitive radio sensor network is a generation solution but with the requirement of continuous spectrum sensing and switching high power consumption takes place. This can be addressed by a RF energy harvesting mechanism embedded along with a spectrum sensing mechanism aiming to optimize throughput and energy efficiency [24].

A novel framework of cooperative transmission and energy harvesting in a switch mode multihop cognitive radio network is presented and power allocation and route selection mechanism is explored [25]. Bellman ford algorithm is used to have an optimal route selection which in turn enhance network lifetime and reduces power consumption. The efficacy of the algorithm is evaluated by Dijkstra's algorithm. A gain in the outage probability is observed.

An energy aware multiuser scheduling scheme is proposed to deal with the physical layer security issues in an energy harvesting underlay cognitive network with multiple cognitive users is proposed in [26]. The algorithm considers interference temperature constraint and residual energy level harvested. The interference probability and intercept probability for the proposed scheme over a Rayleigh fading channel is evaluated.

4 ENERGY HARVESTING IN CR NETWORKS: GAME THEORETIC APPROACHES

Application of a game theoretic approach either with cooperative model or non-cooperative model is observed to enhance not only the throughput but also the selection based performances. The Nash equilibrium proposed by John Nash formed the basis of this criteria. A game theoretic model has been presented in an energy harvesting cognitive radio network in [19]. In a energy harvesting CR network, attaining a good spectral efficiency and energy efficiency at the same time is the prime objective. There happens to be two constraints faced; the energy causality constraint which attempts to maintain a balance between harvested and consumed energy and the collision constraint which attempts to keep the detection probability higher than the certain threshold. The basic issue in an energy harvesting CR network is that since the time frame is divided into three non-overlapping parts for energy harvesting, spectrum sensing and data transmission, hence investing more time in spectrum sensing implicates less time for energy harvesting and data transmission. Though larger duration energy harvesting means more harvested energy but it further reduces time for data transmission. To have a balance among these three processes is a major challenge in an energy harvesting CR network. A fictitious node or access point is proposed to have same sensing performance. Though in many of the works all the nodes are considered to be cooperative but in practical scenario it may not be so. A node may not want to sense or deny to cooperate. Game theory based models are the most suitable in the sense that the consideration for cooperative and non-cooperative nodes can be included and further some mechanisms to influence the non-cooperative nodes can also be incorporated. Figure 4 is a diagrammatic representation of a scenario where game theoretic model is applied in 5G CR network.

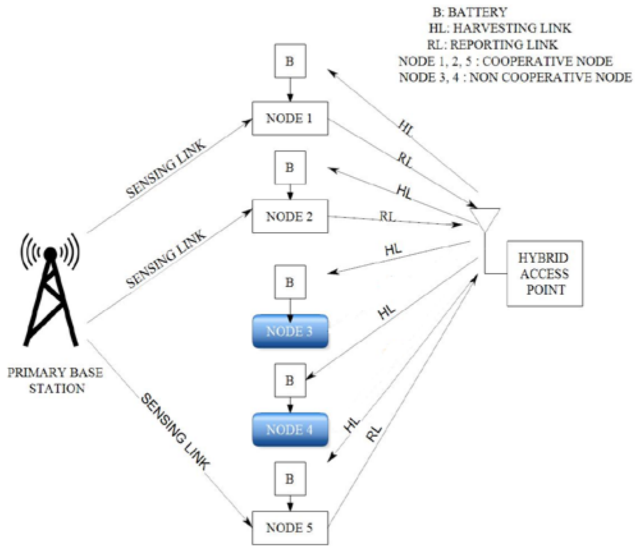

Figure 4: System model with Game theoretic approach

First model is adopted as a cooperative game where the secondary users can choose to participate or deny to participate. The sensed data are processed at the fusion centre to have final decision about the presence of a primary user. In the second phase Stackelberg game is adopted where the fusion centres takes the lead and influences the secondary users to participate and thereby enhancing the performance.

5 CONCLUSION

It has been observed that energy harvesting in cognitive radio plays a very important role and it will be very significant the future generation of technologies. The channel capacity enhancement is an important aspect which has a direct relation with the size of the battery used. Several works has been reported where the main emphasis is to improve the throughput, spectrum efficiency and energy efficiency with different optimization parameters like channel allocation, transmitter power, interference etc. There has been emphasis on the simultaneous wireless information and power transfer (SWIPT) which is surely going to be a revolutionary technological development. Several works have addressed the physical layer security issue and security-reliability trade-off also. Game theoretic approaches are also proposed to have a better selection mechanism. As there are several trade-offs relating to different parameters, hence formulation of a optimization problem and to have a simplified and optimized solution is important.

References

1. S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, and K. Huang, IEEE J. Sel. Areas in Comm., **33**(3), pp-360-381 (2015).
2. S. Sudevalayam and P. Kulkarni., IEEE Comm. Surveys Tutorials, **13**(3), pp-443–461, (2011)
3. J. Rabaey, M. J. Ammer, J. L. Silva, D. Patel, and S. Roundy. Picaradio *IEEE Computer*, **33**,pp-42–48, (July 2000)
4. K. Tutuncuoglu, O. Ozel, A. Yener, and S. Ulukus. IEEE ISIT, (July 2013)
5. V. Anantharam and S. Verdu. IEEE Trans. on Information Theory, **42**(1):4–18, (Jan. 1996)
6. K. Tutuncuoglu, O. Ozel, A Yener, S. Ulukus, IEEE Trans. on Information Theory, 63(7), (July 2017)
7. O. Ozel and S. Ulukus. IEEE Trans. on Information Theory, **58**(10), pp-6471–6483, (October 2012.)
8. O. Ozel and S. Ulukus. *Asilomar Conference*, (November 2011)
9. G. Han, J. Zhang, and X. Mu, IEEE Access, **4**, pp-7212-7222, (2016)
10. M. Ashraf, Adnan Shahid, J. W. Jang, and K. Lee, IEEE Access, **5**, pp-283-294, (2017)
11. D. K. Nguyen, D. N. K. Jayakody, S. Chatzinotas, J. S. Thompson and J. Li, IEEE Access, **5**, pp-21447-21460, (2017)
12. X. Liu, F. Li, and Z. Na, IEEE Access, **5**, pp-3801-3812, (2017)
13. F. Yao, H. W. Y. Chen, Y. Liu, and T. Liang, IEEE Access, **5**, pp-9266-9276, (2017)
14. Y. Wang, Y. Wang, F. Zhou, Y. Wu, and H. Zhou, IEEE Access, **5**, pp-17618-17626, (2017)
15. Z. Hu, N. Wei and Z. Zhang, IEEE Access, **5,** pp-23383-23394, (2017)
16. D. Xie, X. Lai, X. Lei, and L. Fan, IEEE Access, **6**, pp-5596-5606, (2018)
17. Y. Wang, Y. Wu, F. Zhou, Z. Chu, Y. Wu, and F. Yuan, IEEE Access, **6**, pp-12973-12982, (2018)
18. Y. Gao, H. He, Z. Deng, and X. Zhang, IEEE Access, **6**, pp-9081-9090, (2018)
19. O. Elnahas, M. Elsabrouty, O. Muta, and H. Furukawa, IEEE Access, **6**, pp-11086-11100, (2018)
20. W. Lu, T. Nan, Y. Gong, M. Qin, X. Liu, Z. Xu, and Z. Na, IEEE Access, **6**, pp-22480-22488, (2018)
21. K. Lee, C. Yoon, O. Jo, and W. Lee, IEEE Access, **6**, pp-30653-30662, (2018)
22. P. Maji, S. D. Roy, S. Kundu, IET Communications, **12**(11), (2018)
23. G. Hongyuan, D. Yanan, L. Chenwan, IEEE J. of Sys. Engineering and Electronics, **29**(1), pp-18-30, (2018)
24. J. Ren, J. Hu, D. Zhang, H. Guo, Y. Zhang and X. Shen, IEEE Communication Mag., **56**(1), pp-104-110, (2018)
25. A. Banerjee, A. Paul, S. P. Maity, IEEE Trans. on Cognitive Comm. and Networking, **4**(1), pp-82-92, (2018)
26. P. Yan, Y. Zou, J. Zhu, IEEE Trans. on Vehicular Tech., **67**(3), pp-2084-2096, (2018)