

A Framework for Optimizing the Process of Energy Harvesting from Ambient RF Sources

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Article Info

Article history:

Received Jun 19, 2017

Revised Dec 20, 2017

Accepted Jan 4, 2018

Keyword:

Ambient RF

Energy harvesting

Linear optimization

Mobile device

ABSTRACT

Energy harvesting has been an active research topic in the past half a decade with respect to wireless networks. We reviewed some of the recent techniques towards improving energy harvesting performance to find that there is a large scope of improvement in terms of optimization and addressing problems pertaining to low-powered communicating mobile nodes. Therefore, we present a framework for identifying available RF sources of energy and constructing a robust link between the energy source and the mobile device. We apply linear optimization approach to enhance the performance of energy harvesting. Probability theory is used for identification of event loss in the presence of different number of nodes as well as node distances. The objective of the proposed system is to offer better availability of RF signals as well as better probability of energy harvesting for mobile devices. The proposed technique is also found to be computationally cost effective.

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1. INTRODUCTION

With the evolution of cloud computing, there is a sense of pervasiveness in existing applications, be it a small scale or large scale. Such form of pervasive products and services offer significant saving of time and enhances productivity. To access such forms of products or services, normally smart computing devices are used. Preferences are given for mobile devices e.g. laptops, smart phones, sensors, etc. All these devices are equipped with standard hardware circuitry design depending upon various applications that control its communication operation and processing operation [1], [2]. Power module in such hardware acts as a bridge between communication and computation and hence energy modeling is so important in networking [3]. Energy is one of the essential assets as resource for every communicating device globally and affects directly the communication performance [4]. Energy is directly proportional to communication performance, which means more energy to ensure better networking services. But it should be also known that energy is also one of the limited resources within such communication nodes. Energy is required for every essential communication process e.g. transmitting/receiving data, amplifying signal, data aggregation etc. It is also required for internal processing within the communicating nodes. Till date, the biggest challenge is to determine the points where the depletion rate of the energy is faster. Presence of interference, scattering, and fading degrades the channel and potentially affects the node performance too. In such error-prone networks, a node will be required to expend extra amount of energy to participate in the data delivery process. Therefore, traffic engineering significantly affects the energy dissipation of a wireless node to a very large extent and

modeling a traffic is with full of uncertainty and till date there has been no much advancement in this. As the intensity of the traffic is always unpredictable, it is not sure how long such communicating devices last. Nowadays, we use power banks to charge our communicating devices.

Out of all communicating devices, energy requirement is more in cellular phones as compared to other communicating devices. The prime reason behind this is that a cellular phone is equipped with more than 5 different forms of antenna which are 24/7 in listening mode. However, other communicating devices do not have these many numbers of antennae. Energy harvesting believes in extracting ambient Radio Frequencies (RF) as the source of power and use it as the direct source of power supply to the mobile device depleting energy. Half a decade ago, such research talks were initiated and several prototypes have also been built. Unfortunately, we do not see them in commercial use. This is the direct indication that probably there is certain challenges or trade-offs in this field. We reviewed all the standard research techniques to find that existing techniques are all simulation based carried out in Multisim software, ADS software, USRP software radio reader, Agilent Momentum, PSpice. Some of them have also investigated using hardware prototypes. The sources of energy being investigated are RF Broadcasting, Rectenna, Piezoelectric material, sound, etc. Discussion of all this information can be found in [5]. There is less work being carried out towards exploiting RF signals as the source of energy and perform optimization towards it. Moreover, existing techniques are also not found to be benchmarked which is another reason for less progress in this field. Research towards such direction can not only harness the electromagnetic RF waves but also use them to ensure network longevity. Therefore, this paper investigates some of the recently reported literatures to find that still there is an enough scope for enhancing the performance of energy optimization exclusively in the case of low powered mobile communicating devices. Section 1.1. discusses about the existing literature where different techniques are discussed for energy harvesting followed by discussion of problem identification in Section 1.2. Section 1.3. briefs about the proposed contribution to address research problems. Section 2 elaborates the algorithm implementation followed by result discussion in Section 3. Finally, summary of the paper is presented in Section 4.

1.1. Background

There are various schemes presented by different researchers pertaining to energy harvesting in wireless communication devices. This section discusses only the recent and most frequently used techniques of research published between the years 2010-to till date. Most recently, Hraishawi et al. [6] have presented a study on energy harvesting considering a case of Multiple-Input Multiple Output (MIMO) and cognitive networks. Mao et al. [7] have investigated energy harvesting related to mobile edge computing and introduced a unique offloading scheme. Biazon and Zorzi [8] have addressed the problem of throughput optimization considering energy constraints of the wireless devices. Chandra et al. [9] have discussed the scenario where the importance of offloading is addressed in association with energy effectiveness of harvesting performance of a mobile device. Chang et al. [10] have presented a technique for addressing distributed traffic related problems associated with mobile cloud in collaborative networks and its impact on the principle of harvesting. Addressing the problem of optimizing throughput, He et al. [11] have presented a technique using waterfilling approach over the constraint of power of the communication device in MIMO. Kapoor and Pillai [12] have introduced a framework that uses multiple access channels for enhancing the energy harvesting performance of the communicating devices. The authors have basically used a recursive mechanism for constructing policies to control power dissipation. Khuzani et al. [13] have presented a strategy for energy harvesting considering the case study of fading channels. Tan and Yin [14] have introduced a technique that performs provisioning of specific task to upgrade the energy harvesting performance in embedded system. The authors have considered frequency as well as dynamic voltage for this purpose. Explicit energy model, task model, resource model are designed over voltage and frequency where the study outcome is assessed using overhead and varied forms of duration.

Tran and Chung [15] have developed a harvester node using photovoltaic, sensor node, and a mechanism to track maximum power. It also uses fuzzy logic for obtaining the maximum possible power point of the system. Yuan et al. [16] have performed optimization of the energy harvesting performance considering additive white noise and fading channel. Castagnetti et al. [17] have presented a model that performs energy harvesting for sensor nodes using online power management techniques. Similar line of work is carried out in presence of the sensor node by Koulali et al. [18] using hardware's (photovoltaic cells, sensor nodes, etc). Jabbar et al. [19] have presented an energy harvesting technique over electrical circuits using enhanced version of CMOS design of communicating nodes and Schottky diodes. The study outcome shows high power output. Hence, there are various types of recent research techniques focusing on energy harvesting mechanism. The next section briefs about the problems identified in the existing system of the energy harvesting followed by proposed solution to address it.

1.2. Problem Identification

This section briefs about the open research issues in the line of energy harvesting particularly relating to the mobile device. The identified problems in the existing system are as follows:

- a. Majority of the existing techniques focuses on the energy harvesting from hardware viewpoint on different forms of communicating devices except cellular phones or smart phones. Majority of the studies are concentrated towards wireless sensor nodes or other forms of mobile devices.
- b. At present, there is no such work that explores the ambient RF sources of energy and performs harvesting on it. Existing techniques are more inclined towards predefined energy sources.
- c. Studies towards optimization are very less found in existing literatures. Moreover, usage of iterative mechanism is more in existing system.
- d. There are very few research attempts toward ensuring testifying and minimizing computational complexity about the presented mechanism of energy harvesting.

Hence, the above mentioned problems are yet unsolved and there is a definitive need to formulate a system that can address such problem, the next section brief proposed system addressing such issues.

1.3. Proposed Solution

The proposed system is a continuation of our prior study [20] towards energy harvesting. The present work focuses mainly on optimization and offers two different forms of algorithm as a solution towards research problems. Figure 1 highlights the architecture of proposed system.

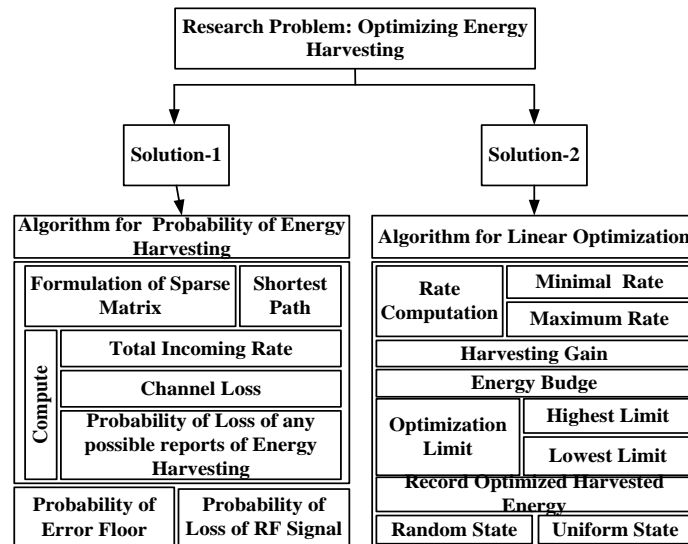


Figure 1. Proposed architecture of energy harvesting

The contributions of the proposed system are a) to introduce a novel algorithm that is capable of computing probability of energy harvesting and b) to incorporate linear optimization that can ensure highest extent of RF source availability either in uniform (or deterministic) state or in any random state. The algorithm also introduces the concept of exploring RF signals in both sparse and dense networks and instantly accomplishes a highly established link between the node and RF sources. In order to maintain realistic scenario, we also consider energy budget as a constraint towards modeling harvesting in mobile device as well as control the limit of optimization (that can be fine-tuned based on different capability of the harvested devices). The complete assessment is carried out using analytic research methodology while the outcome is evaluated using probability factor event loss and energy harvesting.

2. ALGORITHM IMPLEMENTATION

This section discusses about the core algorithm responsible for energy harvesting for mobile devices. The proposed system is equipped with two core algorithms viz. a) Algorithm for computing probability of energy harvesting and b) Algorithm for Linear optimization. Elaborate discussions of these algorithms are as follows.

2.1. Algorithm for Computing Probability of Energy Harvesting

This algorithm is mainly responsible for computing the probability of the amount of energy to be harvested for a standard mobile phone. Finding the source of RF is challenging task which itself requires certain amount of energy to be consumed by the device. Hence, it is essential to develop a model that considers the scarce resources of RFs and applies probability to compute the amount of the energy possibly harvested. The algorithm takes the input of two links generated from a source node and destination node. It also takes input of total number of nodes and upon processing it yields the outcome of event rate arriving on all nodes, Probability of Loss, and Probability of Error Floor. The steps involved in the algorithm are as follows:

Algorithm for Computing Probability of Event Loss during Energy Harvesting

Input: L_1, L_2, S, D, n

Output: θ, P_{loss}, P_{ef}

Start

1. init L_1, L_2, S, D, n .
2. $A \leftarrow \phi(L_1, L_2, arb(size(L_1)))$;
3. $A \leftarrow G(A)$
4. [dist path pred] $\rightarrow sp(A, S, D)$
5. $R_{met} \leftarrow 1/L_1$.
6. $T_{ir} = \sum R_{met} + D_{rep}$ where $D_{rep} = arb(n)$
7. $T_{or} = \sum R_{met}$
8. $\gamma_{cl} \leftarrow T_{or} * T_{ir}$
9. $P = I(n) * arb(n)$
10. $\theta = [\Delta(I)^{-1} - \alpha]^{-1} * T_{ir}$
11. $P_{loss} = 1 - \theta/T_{ir}$.
12. $P_{ef} = 1 - [\Delta(I)^{-1} - \beta]^{-1}$

End

The algorithm initially selects a source node and destination node and formulates a sparse matrix ϕ with it (Line-2). The prime reason for making sparse matrix is to perform investigation of RF node (destination node) availability considering the fact that they are very less in number. Exploring the performance of energy to be harvested from the scarce RF sources will give better optimal solution. The next step is to use a graphical object G , where all the positive entries of the sparse matrix A as well as its non-diagonal elements will present mobile devices with established connectivity (Line-3). A shortest path (sp) will be selected on the basis of graph G , source S and destination D (Line-4). We convert the sparse matrix to the full matrix ϕ in order to extract more information from it as well as to construct rate matrix R_{met} . The computation of the rate matrix R_{met} is given as $1/\text{size}$ of elements in R_{met} (Line-5). An adjacency matrix is formulated only for the condition if $R_{met} > 0$. The algorithm then computes total incoming rate at every node as the summation of the rate matrix itself R_{met} as well as it also computes delayed reports corresponding to arbitrary number of nodes (Line-6). Finally, channel loss γ_{cl} is computed as product of total rate of outgoing energy and total incoming rate (Line-8). The algorithm then computes the probability of loss of any possible reports of energy harvesting for every mobile device (Line-9) using product of identity matrix and arbitrary values with number of nodes. The proposed system considers θ as an empirical expression for the rate of an event arriving over all the mobile devices (Line-10). The formulation of this empirical expression uses diagonal elements of identity matrix constructed with number of mobile devices ΔI . The variable α corresponds to $(1-c) * R_{met} * (1-P)$, where c corresponds to $1 - arb(n)$. It then computes probability of loss of RF signal (Line-11) and probability of error floor which acts as minimal limit of RF signal loss probability. (Line-12). The variable β empirically corresponds to $(1-c) * R_{met}$. Therefore, the outcome will show proper statistics of availability of RF sources even in scarce network condition for energy harvesting.

2.2. Algorithm for Linear Optimization

The above algorithm assists in exploring the best feasible condition of an event that is responsible for direct sourcing of the RF as the source of energy harvesting on a mobile device. This following algorithm will be to ensure that, for a condition of given scarcity of the RF signals, the mobile device could perform energy harvesting to higher level. A linear optimization technique is used for this purpose where the algorithm takes the input of rate, energy budget, which upon processing will lead to optimized energy that can be harvested. The steps involved in the algorithm of optimization are as follows:

Algorithm for Linear Optimization

```

Input: Ebud, Hgain, nTx, nr
Output: mat, matuni
Start
1. for i=1:size(rate), where rate=1:10
2. Ebud←init
3. Hgain←nr(init(nTx))
4. q←sort(2rate-1)/Hgain
5. While (aup-a1)>e
6.   pa=(aup+a1)/2
7.   If (g(pa, pa-e+1, rate)<f((pa-e+1), rate) && g((pa),(pa+e), rate)>f((pa+e), rate))
8.     a1=pa
9.   else
10.    aup=pa
11. End of If
12. End of While
13. B=pa
14. If Ebud>B*∑q
15. for k=1:10
16.   Eopt=[qk/∑q]*Ebud
17. end of for
18. mat=mat/iter && matuni=matuni/iter
19. End of for
End

```

Figure 2 shows the table of symbol used.

Symbol	Meaning
L_1/L_2	Link-1/Link-2
S/D	Source/Destination
n	Number of Nodes
ϕ	Sparse matrix
G	Graph object
R _{met}	Rate Metric
T _{ir}	Total incoming rate
D _{rep}	Delayed Report
T _{or}	Total Outgoing Rate
γ_{cl}	rate of channel loss
P	Probability
I	identity Matrix
θ	event rate arriving on all node
P _{loss}	Probability of Loss
P _{ef}	Probability of Error Floor
E _{bud}	Energy budget
H _{gain}	harvesting gain
n _{Tx}	number of transmitter
nr	normal random number
e	Error
a ₁ /a _{up}	Lower optimization limit/Higher optimization limit
p _a	probability of optimization
E _{opt}	Optimized harvested energy
mat/mat _{uni}	matrix to record optimized harvested energy in random state/uniform state

Figure 2. Table of symbol used

The process of linear optimization initiates with defining the rate with minimum and maximum rate. A matrix *mat* is constructed using the dimension equivalent to the size of the rate matrix R_{met} (Line-1) followed by initialization of the energy budget E_{bud} (Line-2). A new variable of harvesting gain H_{gain} is formulated using normal random number corresponding to the specific number of transmitters (Line-3). The proposed study chooses 10 transmitters. Harvesting coefficient q is computed using rate metric R_{met} and power gain H_{gain} (Line-4). Lower optimization limit a₁ and higher optimization limit a_{up} are formulated and difference between the two is checked and compared with the possible test-error e (Line-5). If the difference is found higher than the error e than probability of optimization p_a is computed as the mean of higher and lower limit i.e. a_{up} and a₁ (Line-6). A gain function g is used to construct a logical condition with function f of

random values of size of rate matrix (Line-7). If the practical gain is found more than the rate matrix than lower limit a_1 is initialized with probability of optimization i.e. p_a (Line-8) otherwise p_a is assigned to higher limit a_{up} (Line-10). The default condition will allocate p_a to B (Line-13). If the energy budget is found more than the product of B and summation of q (Line-14) than the algorithm computes energy that can be optimized as shown in Line-16 under all possible rates of all 10 transmitters. These steps of the algorithm are quite helpful for computing the outage probability of harvesting just on the basis of available rates. Line-18 shows the matrix recording optimized energy values as well as uniform energy values with respect to user-defined iterations. The matrix *mat* can be computed on the basis of optimal energy E_{opt} that could be harvested using Line-16. The direct empirical interpretation of *mat* and *mat_uni* could be given as product of E_{opt} and probability of identical energy harvesting corresponding to each rate value for random and uniform states of energy, respectively.

3. RESULT ANALYSIS

This part of the paper discusses about the results being accomplished from the proposed study. The framework initiates with selection of source and destination node considering power for active harvesting in mobile device be in range of 1-3 mW while power for passive harvesting be 0mW. We also consider presence of 10 transmitters and define an initialized utility function of value 0.005. It is assumed that the proposed system runs over any conventional mobile application on any mobile operating system and does not require any special resource for this. While in the process of evaluation, the complete focus was to check mainly two parameters: (a) probability of event loss and (b) probability of energy harvesting. As the study towards optimizing energy harvesting on any mobile device is quite less, we choose to apply probability theory in the algorithm testing to perform statistical inferences of the outcome being received. Our first performance parameter probability of event loss is measured with respect to node position and distance from dominant RF sources. For this purpose, we iterate the simulation for certain rounds and capture total event and event losses recorded at particular instances of simulation. Similarly, our second performance parameter probability of energy harvesting is computed with respect to increasing noise levels to find how dominant is the process of acquisition of energy from the available RF sources in the presence of noise. We consider noise as the availability of RF sources is high in high-density area which is always covered by noises and other channel problems.

For effective analysis of the accomplished outcome, we compare our work with that of Yuan et al. [16]. The reason for selecting Yuan et al. [16] work is about the strongest correlation with the research agenda that is, optimizing energy harvesting targeting for mobile devices. It is one of the most recent implementations of energy harvesting where authors have used a specific architecture for energy harvesting in the presence of standard noisy and fading channels. A unique offline strategy of power allocation was implemented by Yuan et al. [16] and its outcome was assessed using battery level. We did certain amendments in Yuan's implementation process by changing initialization values. We substituted the original values used in Yuan's algorithm by proposed environmental data in order to retain similar test-bed for comparative analysis. The study outcome shows that proposed system is witnessed with lesser proportion of probability of event loss as compared to existing approach as shown in Figure 3(a) and Figure 3(b) with respect to node position and distance from RF sources, respectively.

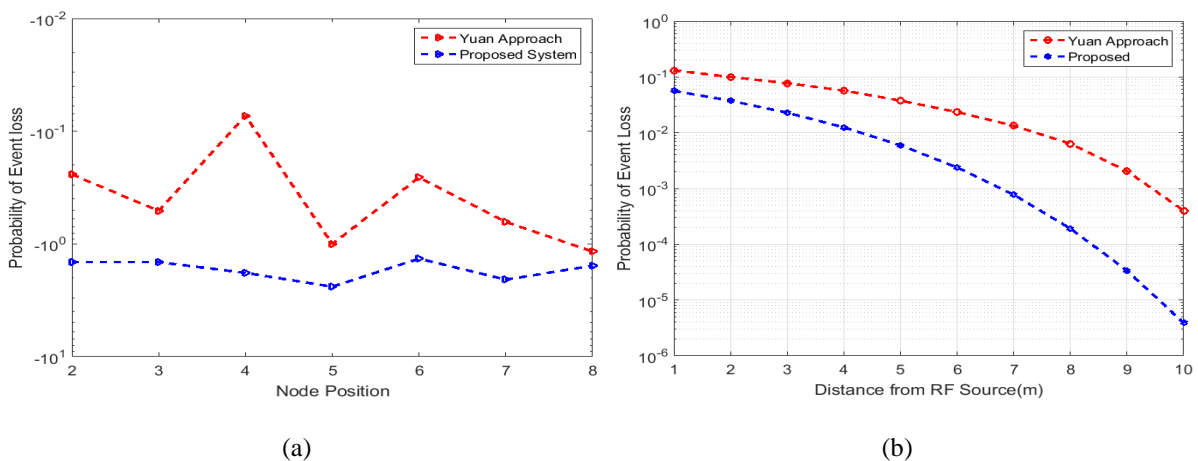


Figure 3. Probability of event loss

The prime reason behind this is Yuan's approach [16] has mainly used hard-coded threshold scheme that only restricts the exploration of any event only in its adjacent nodes. Moreover in the presence of fading and noisy channel, the probability score highly fluctuates. Similarly, if the distance from the RF sources is increased along with the presence of the noisy channel, we find that Yuan's approach is not able to track more number of events in contrast to proposed system. This outcome in Figure 3(b) directly represents that proposed system offer better reliability of event tracking which offer comprehensive connectivity of the mobile devices with the available RF sources. Therefore, a robust supportability of dynamic topology can also be observed as, irrespective of the node's distance from RF sources, there is a seamless connectivity with the RF sources to a large extent.

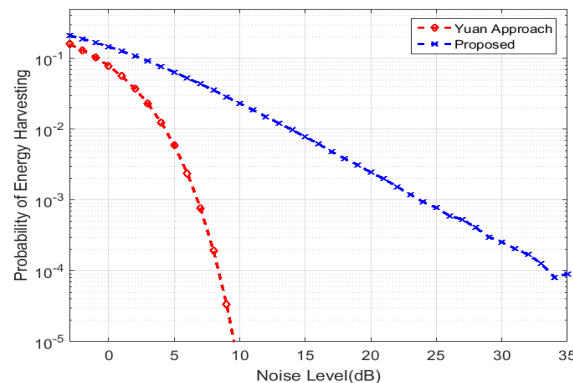


Figure 4 Probability of energy harvesting

Finally, we assess the probability of energy harvesting in the presence of increasing noise level. We consider that the area with high density has increasing noise level while area with high sparsity has lower noise level. Well, both cases are not good for RF energy harvesting. The case of sparsity is direct representation of Figure 4 while in dense area, we see that the proposed system can highly discrete the RF signal sources and establish a robust connectivity unaffected much by increasing level of noise.

The overall processing time is found to be 0.23315 seconds while the algorithm doesn't store any forms of intermediate results in buffer thereby does not affect much on storage. Therefore, the proposed system can be concluded that it offers a cost effective strategy to ensure well establish link with RF sources after exploring it ; mainly higher energy harvesting.

4. CONCLUSION

This paper emphasizes on ambient RF signals and constructs a framework considering different forms of traffic definition in terms of dense and sparse networks. Probability theory is applied for modeling the event of RF source availability which is instantly followed by seamless energy banking process. We also model the principle of uncertainty of RF sources of energy by incorporating near real-life constraints that is energy budget and applied linear optimization principle for this purpose. Our findings suggest that this model is totally capable of performing energy harvesting even in the presence of less number of RF sources.

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