Resource Allocation for Wireless Networks with Energy Harvesting Constraints Over Fading Channels

Mohammed Baljon and Lian Zhao

Abstract—This research work considers the utilization of energy harvesters, instead of conventional time-invariant energy sources, in wireless communication. For the purpose of exposition, we study the traditional two-hop communication system for delay limited (DL) and delay tolerant (DT) relaying networks over fading channels, in which the source node transmits with power drawn from energy harvesting (EH) sources and the relay transmits with conventional non-EH sources. We address the throughput maximization problem for the proposed system model for DL and DT cases. We find that the optimal power allocation algorithm for the single-hop communication system with EH constraints, namely, recursive geometric water-filling (RGWF), can be utilized as a guideline for the design of the two-hop system. We first introduce RGWF algorithm and we show the advantages of the geometric approach in eliminating the complexity of the Karush-Kuhn-Tucker (KKT) condition as well as providing a closed-form and exact solutions to the proposed problem. Based on the RGWF algorithm, we propose offline joint power allocation and transmission time scheduling schemes for DL relaying network and DT relaying network. We also propose efficient online resource allocation schemes for both relays' cases. The performance of the proposed schemes is evaluated via simulation and the results demonstrate that a network with delay tolerant ability provides better performance in terms of throughput.

Index Terms—energy harvesting technology, delay limited networks, delay tolerant networks, fading channels, optimization, relay networks (telecommunication), resource allocation, telecommunication power management, telecommunication scheduling.

1. Introduction

With increasing demand and explosion growth in wireless communication in recent years, energy conservation becomes more desirable to save the world’s energy consumption. Today’s number of communication devices, such as smartphones and sensor nodes will be doubled or tripled by 2050 [1]. According to International Energy Agency [1], due to huge demand of energy on all fields by 2050, investments on energy preservation could decrease the waste of energy by one-third. Green communication is the key solution of many problems related to the wasting energy due to radio transmissions [2]. Green Radio (GR) basically can be represented as the relationship between energy harvested from the environment along with efficient techniques to utilize the energy wisely. As a matter of fact, scavenging ambient energy and utilizing the available energy wisely lead to maximizing the throughput [3], [4].

Another advantage of utilizing green communication is to maximize the radio communication tasks’ lifetime. Operation of traditional communication systems can not surpass battery size or power constraint of the power supply. In contrast, nodes with energy harvesting capability in wireless communication systems are able to harvest energy from the environment, such as sun, wind, vibration etc. Therefore, we can say, EH nodes are a potential technique that defeats the limitation of network longevity by recharging the nodes with the sufficient power opportunistically from nature as shown in [5]–[7].

Although the lifetime of communication systems will be prolonged due to the energy replenishment from nature, optimizing the resource allocation and design parameters are mandatory. Along with this motivation, designing an algorithm that provides optimum allocated power for green wireless communication is significant. Resource allocation in green wireless communication has been studied under various system models with various performance metrics. Several optimal transmission policies have been presented for a single-hop transmission and many other transmission types with EH constraints in recent open literature.

Transmission policies for EH communication systems to maximize throughput have been well investigated recently. Throughput maximization problem for a single-hop with EH constraints over a fading channel has been investigated in [8] and [9]. Authors in [10] revisit the problem in [8], [9] and a novel approach: a Recursive Geometric Water-Filling (RGWF) algorithm, is proposed as an optimal transmission policy.
On the other hand, multi-hop transmission is used in order to expand the network size geographically using relays, thereby increasing the communication transmission range. Besides, multi-hop transmission is utilized to enhance the energy efficiency of the network. Many researchers have proposed new algorithms and transmission policy in order to gain an efficient energy wireless-relaying system. Two-hop communication systems with EH constraints have been studied recently, but only for some special cases. Authors in [11] propose an optimal transmission policy for the two-hop system model in case of multiple EH packets arriving at the relay. In [12], throughput maximization problem for the two-hop communication system in case of an EH source with two energy arrivals has been solved using cumulative curve algorithm. In [13], a Recursive Geometric Water-Filling (RGWF) algorithm, which is used to obtain optimum power allocation for a single-hop transmission, was adopted to gain an efficient transmission policy for a two-hop communication with EH Source (EH-S) and conventional Non-EH Relay (NEH-R) over a fading channel for a delay-limited network.

In this paper, we investigate optimal and sub-optimal transmission policy of the same system model in [13] for DL relaying network as well as DT relaying network under deterministic (offline) and online setting based on RGWF algorithm. By comparing our work with the existing results, the contributions of this work are summarized as follows:

- We present novel solutions to tackle the throughput maximization problem for the system model with EH-S and half-duplex NEH-R network over a fading channel, which has not been considered in the literature.
- The low-complexity RGWF algorithm is modified and extended into a two-hop network scenario in such that optimize the off-line resource allocation that maximizes the end-to-end system throughput for DL and DT relaying networks.
- For DL and DT cases, we propose several online low-complexity approaches that provide reasonable performance.

The remainder of this paper is organized as follows. General tools and background work are presented in Section II and III, respectively. Section IV presents the system model and introduces the transmission policy adopted in this paper. In Section V, we formulate the throughput maximization problem and we propose the developed algorithms for the DL case. The formulation of the throughput maximization problem and the proposed algorithms for the DL case are discussed in Section IV, followed by numerical results and conclusions in Sections V and VI, respectively.

2. General Tools

EH communication is an advanced wireless communication technique that has attracted enormous research attention. Radio resources, such as power and bandwidth, have to be well utilized and it can be classified as a Radio Resource Management (RRM) problem. Recently, various tools are accomplished and established for solving RRM problems. Water-Filling (WF) is a well-known information theory technique and it is a useful tool for RRM problem in wireless communication systems. Specifically, WF is widely utilized to determine power allocation strategy that maximizes point-to-point channel capacity by assigning more power to the channel with higher gains. As a result, the overall channel capacity is maximized. In the following, we introduce the water-filling problem, which can be formulated into the following problem: given $P > 0$, as the total power or volume of the water, find that

$$\max_{\{p_i\}_{i=1}^K} \sum_{i=1}^K L_i \cdot \log(1 + h_ip_i)$$

subject to:

$$0 \leq p_i, \forall i,$$

$$\sum_{i=1}^K p_i = P$$

where $K$ is the total number of channels. Let $L_i$, $h_i$ and $p_i$ denote the time duration, the channel fading gain and the transmission power of the $i$th channel, respectively. Since the constraints are that (i) the allocated power to be nonnegative, and (ii) the sum of the power equals $P$, the problem (1) is called the water-filling (problem) with sum power constraint.

By interpreting the observed properties of the optimal power allocation scheme as a water-filling scheme, $p_i$ units of water is filled into a rectangle container with bottom width as $\frac{L_i}{h_i}$, ($i=1, \ldots, K$). For unifying parameter notation, through a change of variables, we can obtain an equivalent target problem as follows:

$$\max_{\{p_i\}_{i=1}^K} \sum_{i=1}^K \tau_i \cdot \log(1 + h_ip_i)$$

subject to:

$$0 \leq p_i, \forall i,$$

$$\sum_{i=1}^K p_i = P$$

where $\tau_i \leftarrow \frac{L_i}{h_i}$, $h_i \leftarrow \frac{h_i}{L_i}$ and $p_i \leftarrow L_ip_i$. Note that the symbol $\leftarrow$ is the assignment operator.

In this section, two water-filling approaches are presented that solve the water-filling (problem) with sum power constraint. One is the conventional water-filling (CWF); another is the proposed geometric water-filling (GWF). The main principle of WF approaches is that determining the optimum water level that maximizes the overall network throughput. Nevertheless, CWF and GWF algorithms are developed to solve this constrained optimization problem using different optimization approaches.

2.1. Conventional Water-Filling (CWF)

CWF is an approach of a wide WF algorithm umbrella that solves a power allocation problem with a sum power constraint under non-negative individual powers. Because of the non-linear equation and the inequality equation as shown in the problem (2), the resulting proposed system is non-linear. In CWF algorithm, Karush-Kuhn-Tucker (KKT) conditions are utilized to find the solution of the proposed problem. KKT conditions can be considered, on the other hand, as a group of the optimality conditions. Below is the derived
solution after applying the KKT conditions,
\[
\begin{align*}
    p_i &= \left( \mu - \frac{1}{h_i} \right)^+, \forall i, \\
    \sum_{i=1}^{K} p_i &= P, \\
    \mu &\geq 0,
\end{align*}
\]
where \((z)^+ = \max\{0, z\}\). \(\mu\) is the water level chosen to satisfy the power sum constraint with equality \(\sum_{i=1}^{K} p_i = P\). Eqn. (3) is referred as a solution of the CWF problem (2).

2.2. Geometric Water-Filling (GWF)

The GWF approach can be seen as a functional block that solves the same CWF RRM problem in Eqn.(2). GWF approach simplifies the CWF algorithm by eliminating the complexity of solving the non-linear system using KKT conditions into a geometric approach that provides explicit solutions and helpful insights to the problem and the solution. In conventional water-filling algorithm, the optimum water level will have to be determined first, and then, the power allocation task is solved. In GWF, on the other hand, the highest channel under water (\(i'\)), is aimed to be obtained instead, which is an integer number. The water volume above the \(i\)th channel \(P_2(i)\) can be determined based on the height of the \(i\)th fading channel \(d_i = \frac{1}{h_i \tau_i}\) and the channel width \(\tau_i\) as shown below,
\[
P_2(i) = \left[ P - \sum_{k=1}^{K-1} (d_i - d_k) \tau_k \right], \text{ for } i = l, \ldots, K. \tag{4}
\]

The main purpose of determining \(P_2(i)\) is to find the maximal channel index (\(i'\)) that makes \(P_2(i)\) positive. Hence, \(i'\) can be obtained using the following formula
\[
i' = \max\{i\} P_2(i) > 0, \ 1 \leq i \leq K\} \tag{5}
\]
Consequently, the allocated power of the \(i\)th channel \((i = 1, 2, \ldots, K)\) is determined as follows:
\[
\begin{align*}
p_i &= \left[ \frac{p_{i'}}{\tau_{i'}} + (d_{i'} - d_i) \right] \tau_i, \quad l < i \leq i' \\
p_i &= 0, \quad i' < i \leq K,
\end{align*}
\]
where the power level of the \(i'\) channel is obtained as follows:
\[
p_{i'} = \frac{\tau_{i'}}{\sum_{k=1}^{i'} \tau_k} P_2(i') \tag{7}
\]
On the other hand, GWF algorithm occupies less computational resource compared to CWF. The worst-case computational complexity of GWF approach is \((8K + 3)\) fundamental arithmetical whereas CWF approach has \(O(K^2)\) fundamental arithmetic [14]. More detailed of GWF algorithm can be found in [14].


Authors in [10] presented the RGWF algorithm that solves the optimum power allocation problem for a point-to-point data transmission with EH transmitter over a fading channel, as shown in Fig. 1, based on GWF approach. Shannon capacity is adopted to achieve the maximum link capacity by determining the rate versus power relationship of the channel, given by:
\[
R[p_i] = \log[1 + h_ip_i] \tag{8}
\]
where \(h_i\) and \(p_i\) are the channel fading gain and the transmission power at the \(i\)th slot, respectively. The total transmitted bits for a given link in the \(i\)th time slot with duration \(\tau_i\), is given by:
\[
D(i, \tau) = \sum_{i} \tau_i \cdot R(p_i) \tag{9}
\]

3.1. Problem and Algorithm

In [10], throughput maximization problem for a single-hop system with EH constraints over fading channels is investigated. The non-negative transmission powers of EH node is defined as \(p_i\) with non-negative transmission durations \(\tau_i\) for \((i = 1, 2, \ldots, K)\), respectively. Moreover, \(\sum_{j=1}^{i} E_{j}^{EH}\) is cumulative harvested energy on the transmitter. When the input power is subject to energy causality constraint, it means that the energy harvested can only be used in the current time or in the future, but not in the past. In addition, total consumed energy cannot be more than the total available energy, and an energy causality constraint can be stated as follows
\[
\sum_{j=1}^{i} \tau_j \cdot p_j \leq \sum_{j=1}^{i} E_{j-1}^{EH}, \forall i. \tag{10}
\]
In other words, by replacing the sum power constraint in Eqn.(2) into the EH causality constraint, the target problem can be defined as a water-filling problem with EH constraints. As a results, other approaches were utilized to solve this problem, and they are namely called directional water-filling (DWF) [8] and recursive geometric water-filling (RGWF) [10], which are extensions of CWF and GWF approaches, respectively. Hence, the throughput maximization problem can be formulated as follows,
\[
\max_{\{p_i\}_{i=1}^{K}} \sum_{i=1}^{K} \tau_i \cdot \log(1 + h_ip_i)
\]
subject to:
\[
\sum_{j=1}^{i} \tau_j \cdot p_j \leq \sum_{j=1}^{i} E_{j-1}^{EH}, \forall i, 0 \leq p_i, 0 \leq \tau_i. \tag{11}
\]
Consequently, the objective function of this problem will be based on the total amount of data that energy harvesting transmitter can forward to the destination over a given number of transmission time slot \(K\).

3.2. Recursive Geometric Water-Filling (RGWF)

Problem (11) has been solved based on GWF scheme, which eliminates the complexity of employing the KKT multipliers. The RGWF algorithm, on the other hand, is an recursive version of the geometric water-filling algorithm that is used to allocate optimum transmission power and maximize the throughput of a single-hop transmission with EH constraint, while taking into account that channel condition and harvested energy vary in time. In RGWF, GWF can be represented as a functional block that is recursively applied to sequentially solve the power allocation problem for energy harvesting transmission over fading channels. Exact optimal allocated power can be determined to provide insights into the given profile and the solution.

In the following, a description of the RGWF algorithm is presented.
1) Assuming $K$ is an integer that represents the total number of slots in a given transmission time ($T$), the assigned arrival harvested energy can be represented as $\{1, K, \{E^{EH}_{i}\}_{i=1}^{K}\}$.

2) RGWF sequentially processes for the ($K$) slots starting from the second time slot.

3) Assuming ($L$) is the index of current processing slot, the power levels are updated for slot ($L$) and its previous ($L-n$) slots. Hence, a processing window is established.

4) GWF algorithm is applied to this window to obtain optimal power allocation for the slots that are assigned to this window by solving (4) - (7). The common water level is then found, consequently.

5) Comparing the water level of the current processing window with the previous slot, and then, if the non-decreasing water level condition being satisfied, the allocated powers for the corresponding ($L$) slots are obtained. Consequently, a new processing window will be created by moving to the next time slot. Otherwise, the current processing window will be extended with one slot in the left side and the same above steps are applied.

In this way, the completed optimum power allocation $\{p_i\}_{i=1}^K$ for the $i^{th}$ time slot ($i = 1, \ldots, K$) are determined within finite loops. That is to say, RGWF can be written as a formal expression:

$$\{p_i\}_{i=1}^K = RGWF(1, K, \{\tau_i\}_{i=1}^K, \{h_i\}_{i=1}^K, \{E^{EH}_{i}\}_{i=1}^K).$$ (12)

In the following, we use this mapping as a first step to solve the two-hop communication system with EH constraints.

4. Two-hop EH Communication Systems

4.1. System Model

In this section, we adopt the system model in [15], which consists of a two-hop communication system with an EH-S and a half-duplex NEH-R over a fading channel, as shown in Fig. 1. The direct transmission between source and destination is negligible because of deep fading. For convenience, we consider that the given total transmission time period is from [0, $T$] including $K$ epochs. Each epoch is represented as either arriving new harvest energy or changing in the channel fading gain or both of them. The time difference between epochs’ instants $(t_{i-1})^{th}$ and $(t_i)^{th}$ is called the $i^{th}$ epoch, which is defined as $\tau_i = t_i - t_{i-1}$, for $i = 1, 2, \ldots, K$. Moreover, $E_i$ is the corresponding amount of harvested energy and $\{h_i\}$ is the fading level in the $i^{th}$ interval, for $i = 1, 2, \ldots, K$. Without loss of generality, we assume $t_0 = 0$ and $t_K = T$. The terms epoch and interval are used interchangeably in this paper. We assume the channel between the source-relay link ($h_1$) experiences fading whereas ($h_i$) is the AWGN channel on the relay-destination link for the $i^{th}$ interval, ($i = 1, 2, \ldots, K$). In addition, the available energy is utilized only for transmission purposes. Thus, Shannon capacity is adopted to achieve the maximum link capacity by determining the rate versus power relationship of the channel.

![Fig. 1: System model, $K=7$ epochs in [0,$T$] with (a) EH source, i.e., random energy arrivals ($E_{i,n}$), has time-variant channel, and (b) non-EH relay, i.e., relay is powered by battery, experiences AWGN channel.](image)

In this paper, we propose resource allocation schemes for a two-hop wireless communication with EH constraints over fading channels for delay limited and delay tolerant networks. In the following subsection, we discuss the advantage of RGWF-EH profile in maximizing the network throughput and the transmission policy for both delay networks’ types.

4.2. RGWF-EH Profile

RGWF algorithm has been shown to provide optimal power allocation for a single-hop over a fading channel [10]; as it is illustrated in Fig.(2-a), where the plain areas represent the fading gain and the shadowed areas represent the allocated power for the epochs. According to Fig.(2-a), it is easy to notice that more power is allocated to the epoch with less fading whereas less power is allocated to high fading epoch, which leads to maximum throughput. Now, by only plotting the allocated power, we obtain RGWF-EH profile as shown in Fig.(2-b). This profile can be used as a guideline for designing an efficient scheduling scheme that maximizes the network throughput for a two-hop communication system. On the other hand, a harvested energy arrival profile at the source node and a bit arrival profile at the destination are strongly related to each other. Since the source can transmit no data until energy being physically available, the EH profile at the source controls the number of the transmitted bits to the relay. Moreover, the bit arrival profile at the relay will be shaped based on the number of bits that have already been transmitted by the source. In addition, according to the energy causality constraints, the total power assigned up to the $i^{th}$ epoch cannot be greater than the total harvested energy up to the same epoch. Consequently, EH profile forms the domain of the harvested energy usage, and all the feasible transmission policies will be narrowed to this domain.
throughput. Therefore, to obtain optimal transmission policy for a single-hop transmission plays the core role of designing a two-hop communication system, the objective function for the two-hop transmission is dissimilar. Particularly, the objective function in single-hop transmission is to maximize the throughput in (T), whereas two-hop system has the same overview except the transmission has to be through a relay node. It means that the transmission scheduled time has to be divided between source-relay and relay-destination sessions. Therefore, to obtain optimal transmission policy for two-hop transmission, source and relay power allocation as well as transmission scheduling need to be well planned in order to maximize the network throughput.

In addition, the transmission policy for the EH two-hop communication system is investigated based on both DT and DL cases. In a delay tolerant network, the source node keeps transmitting as long as it has a good channel condition and sufficient energy to transmit. The relay node, on the other hand, will start forwarding the received bits once the source pauses its transmission due to deteriorated channel condition. In contrast, an example of non-delay tolerant networks is real-time applications that impose strict restrictions on packet delays in such that relay has to forward received packets as soon as they arrive. Whereas data buffer at NEH-R is neglected in a delay limited network, we assume that the data buffer in a delay tolerance network has infinite capacity at the relay node as well as EH-S has data all the time.

In the following sections, we will show how we can take advantage of the obtained RGWF-EH profile to maximize network throughput. The ordinary RGWF algorithm is only valid for a single-hop power allocation problem. In order to extend RGWF to two-hop transmission, a modified version of RGWF is proposed. For throughput maximization problem with a source having RGWF-EH profile, the transmission policy of a two-hop communication has the following properties:

1. The transmission rate/power of a node is constant within the ith interval, for $i = 1, 2, ..., K$:
   \[ p^s(t) = \begin{cases} p^s_i, & t \in L^s_i \setminus L^r_i \, \forall i, \\ 0, & t \in L^r_i \, \forall i \end{cases} \]
   \[ p^r(t) = \begin{cases} p^r_i, & t \in L^r_i \, \forall i, \\ 0, & t \in L^r_i \, \forall i \end{cases} \]
   where $L^s_i$ (or $L^r_i$) is the set of the source (or relay) transmission sets in the given time $[0, T]$.

2. Emptying both source energy and the relay data buffer at the end of the given transmission time ($T$) where $l^s_i$ and $l^r_i$ are the scheduled time for source and relay, respectively.
   \[ \sum_{i=1}^K l^s_i \cdot \log(1 + h^r_{ip^r_i}) = \sum_{i=1}^K l^r_i \cdot \log(1 + h^s_{ip^s_i}), \quad (13) \]
   \[ \sum_{j=1}^K l^s_j \cdot p^s_j = \sum_{j=1}^K E^s_{j-1}, \quad (14) \]

Based on the above discussed properties, we conclude that a joint source and relay power allocation along with their scheduled time has to be optimized in such that a source transmits first and then it is followed by the relay at its allocated scheduling time. On the other hand, the total number of transmitted bits that are delivered from the source to the destination must satisfy (13) by a deadline of $K$ time slots.

5. Throughput Maximization Problem for the DL case

In this section, we aim to maximize network throughput of a two-hop system with EH constraints for the DL network under offline and online knowledge of energy state information (ESI) and channel state information (CSI). EH-S and NEH-R are sharing the same epoch for the DL case. All received bits once the source pauses its transmission set in the given time.

subject to:
   \[ \sum_{i=1}^K l^s_i \cdot p^s_i \leq E^R, \, \forall i, \]
   \[ \sum_{j=1}^i l^s_j \cdot p^s_j \leq \sum_{j=1}^i E^s_{j-1}, \, \forall i, \]
   \[ l^r_i \cdot \log(1 + h^s_{ip^s_i}) \leq l^r_i \cdot \log(1 + h^r_{ip^r_i}), \, \forall i, \]
   \[ l^r_i + p^r_i = \tau_i, \, \forall i, \]
   \[ 0 \leq p^r_i, 0 \leq l^r_i, 0 \leq l^s_i, \, \forall i, \]

where $\sum_{j=1}^i E^s_{j-1}$ and $E^R$ are cumulative harvested energy on the source and the total available energy on the relay, respectively. Consequently, the objective function of this problem will be based on the total amount of data that NEH-R can transmit to the destination for the given total number of epochs $K$. The first and the second conditions are due to the energy causality constraints at the source and the relay, respectively, whereas the fourth constraint represents the half-duplex at the relay. Since small end-to-end delay is required, Eqn.(13) can be further relaxed into the above third constraint, which shows the equality of transmitted bits by both nodes at
each time instant. Hence, the problem can be rewritten as following:

\[
\begin{align*}
\text{max} & \quad \sum_{i=1}^{K} L_i^s \cdot \log(1 + p_i^s) \\
\text{subject to:} & \quad \sum_{i=1}^{K} L_i^r \cdot p_i^r \leq E^R, \forall i, \\
& \quad \sum_{j=1}^{J} (\tau_j - L_i^s) \cdot p_j^s \leq \sum_{j=1}^{J} E_j^{EH}, \forall i, \\
& \quad L_i^s \cdot \log(1 + p_i^s) \leq (\tau_i - L_i^r) \cdot \log(1 + h_{sr,i} P_i^s), \forall i, \\
& \quad 0 \leq p_i^s, 0 \leq L_i^r, \forall i.
\end{align*}
\]

It is noticeable that the above property reduced the problem (16) into a convex optimization problem and it can be optimally solved using any conventional convex optimization techniques [16]. In the following, optimal and suboptimal methods that solve the throughput maximization problem for a DL network will be discussed.

5.1. Optimal Resource Allocation

One of the most recent advanced methods that provide the global optimal solutions for both convex and non-convex optimization problems is the Interior-Point OPeration Timizer (IPOPT) algorithm [17]. Interior-point method provides optimal solution for Non-Linear Programming (NLP) problems with enormous inequality constraints. The global convergence of the IPOPT method, which involves the primal-dual interior point algorithm, is proposed by Fletcher and Leyffer [18] utilizing a filter line search method. Specifically, the search direction is found by applying Newton’s method into modified Karush-Kuhn-Tucker (KKT) equations. On the other hand, the filter term is referred as a set of values that guarantee the objective and constraint functions never return. A trial point is acceptable only if it achieves considerable progress towards the optimization goal as well as it is not a member of the filter.

5.2. Sub-optimal Resource Allocation

In the optimal transmission policy for the proposed problem without delay tolerant, there is a single source-relay stage pair in each epoch. Particularly, source and relay stages for the \(i\)th RGWF interval \((i = 1, 2, ..., K)\) are defined as \(L_i^s = [t_{i-1}, t_{i-1} + t_i^s]\), \(L_i^r = [t_{i-1} + t_i^r, t_i]\) respectively, where the time instants, \(t_{i-1}\), \(t_i\), and \(t_i^s\) are the beginning, the ending of the \(i\)th epoch, and the time when transmission is switched to the relay, respectively. The transmit powers of the \(i\)th RGWF interval \((i = 1, 2, ..., K)\) for the EH-S and NEH-R are \(P_i^s = P_i^{EH}\), \(P_i^r = P_i^{R}\) respectively, where \(P_i^{EH}\) is the allocated power that is obtained based on applying RGWF algorithm considering only the source-relay link, and \(P_i^{R}\) is the relay power, which is given and fixed. Consequently, by applying Eqn. (17), the initial scheduled time is obtained for the \(i\)th epoch \((i = 1, 2, ..., K)\)

\[
t_i^s = \frac{\tau_i \cdot \log(1 + P_i^{R})}{\log(1 + P_i^{R}) + \log(1 + h_{sr,i} P_i^{EH})}.
\]

Remark 1. In the case of ordinary RGWF, where a single-hop is only involved in the transmission, the power is allocated on the whole \(i\)th interval, which include source and relay transmission period. In this system model, the relay shares the interval with the source and therefore, RGWF algorithm has to be modified in order to guarantee that power allocation algorithm is exactly applied on the length of source stage. Otherwise, the allocated power on the relay stage, which is a result of applying RGWF on the whole epoch (\(\tau_i\)), will be considered as wasted power. To overcome the potential problem of assigning source power on the relay transmission period, the source transmit power is re-allocated for the \(i\)th epoch \((i = 1, 2, ..., K)\) as follows:

\[
P_i^s = P_i^{EH} \cdot \frac{\tau_i}{t_i^s}.
\]

The optimum time scheduling will be re-determined based on the optimum source transmit power \(P_i^s\), and subsequently, on the initial scheduled time \(t_i^s\). Hence, the optimum scheduled time for the \(i\)th epoch \((i = 1, 2, ..., K)\), is determined as follows:

\[
t_i^r = \frac{\tau_i \cdot \log(1 + P_i^{R})}{\log(1 + P_i^{R}) + \log(1 + h_{sr,i} P_i^{EH})}.
\]

5.3. Pre-Defined Data Rates (PDDR) Based

In this subsection, we propose suboptimal performance considering the same problem set-up with only causal knowledge of CSI and ESI. We adapt the pre-defined multi-rate wireless technology in order to support the two-hop DL network with EH constraints. The rate adaptation techniques comprise of scheduling algorithms based on instantaneous information of source SNR (\(\gamma^s\)). We assume the fixed relay SNR (\(\gamma^r\)) is the only parameter that has to be known in advance. Since relay node is powered by a fixed energy source, relay SNR is assumed to be higher than any instantaneous SNR of source node. Hence, resource allocation is obtained based on \(\gamma^s\) only, where it is computed as follows:

\[
\gamma^s = h^s_i \cdot \frac{2E_i^{EH}}{\tau_i}.
\]

The algorithm is proposed as follows. The maximum number of bits that the link can afford \((B_{max})\) is determined as follows:

\[
B_{max}= \frac{\tau_i}{2} \log(1 + (\gamma^r)).
\]

Then, \((L)\) pre-defined multi-rate is computed by dividing \((B_{max})\) into \((\frac{1}{2})\) scale factors for \((n=1, \ldots, L)\) where \((B_{max}(n))\) is the highest possible transmitable bits and \((B_{max}(L))\) is the lowest possible transmitable bits that source can transmit in its scheduled time. On the other hand, the corresponding relay scheduled time that relay needs to re-transmit \((B_{max}(n))\) is determined as follows:

\[
t_{\max} = \frac{B_{max}(n)}{rate(\gamma^s)}.
\]

Finally, the source scheduled time for \(i\)th epoch \((t_i^s) = \frac{B_{max}(n)}{rate(\gamma^s)} \) is computed. If \(t_i^r \leq B_{max}(n)\), then, \(B_{max}(n)\) is the maximum number of bits that can be transmitted for epoch \((i)\). Otherwise, \((n)\) increases by
that solve this problem under offline and online settings.

have been proposed to solve this type of the problem.

δ of this problem will be based on the total amount of

the number of transmitted data by the relay at any

was transmitted by EH-S is higher than or equal to

which shows the data causality, the amount of data

the relay, respectively. According to the third constraint,

energy on the source and the total available energy on

maximization problem for the delay tolerance network

identical by the end of the

K

\[ K \]

Algorithm 1 Pseudocode for PDDR

1: Input: \( \gamma^\dagger_t \);
2: Calculate \( B_{\max}(n) \) and \( t_{\max}(n) \) using (21) and (22), respectively.
3: Let integer \((L > 1)\), divide \( B_{\max}(n) \) and its corresponding \( t_{\max}(n) \) into \((L)\) pre-defined thresholds.
4: for \( i = 1 \) to \( K \) do
5: Calculate \( t^*_i = \frac{B_{\max}(n)}{\text{rate}(\gamma^\dagger_t)} \).
6: while \( t^*_i > (\tau - t_{\max}(n)) \) do
7: \( n \leftarrow n + 1 \)
8: end while
9: output: \( B_{\max}(n) \) is the maximum number of transmitted bits for epoch (i).
10: end for
11: Output: \( \{B_{\max(i,n)}\}_{i=1}^K \).

6. Throughput Maximization Problem for the DT Case

In this section, we consider maximization the number of bits delivered of the two-hop system with EH constraints by a deadline \( T \) for DT network. A delay tolerance network is desirable when the network has no constraint on the end-to-end delay. Unlike to the delay limited network, epoch is never being shared between nodes, however, it is either being allocated to the EH-S or NEH-R for the \( i \)th interval \((i = 1, 2, \ldots, K)\) in such that the total transmitted bits by both nodes have to be identical by the end of the \( K \) time slots. The throughput maximization problem for the delay tolerance network can be formulated as follows:

\[
\begin{align*}
\text{max} & \quad \sum_{i=1}^{K} \delta_i \cdot \tau_i \cdot \log (1 + h_i^E p_i^\star) \\
\text{subject to:} & \quad \sum_{i=1}^{K} \delta_i \cdot \tau_i \cdot p_i \leq E^R, \forall i, \\
& \quad \sum_{j=1}^{i} (1 - \delta_i) \cdot \tau_i \cdot p_i^\star \leq \sum_{j=1}^{i} E_{s,j-1}^{EH}, \forall i, \\
& \quad \sum_{i=1}^{K} \delta_i \cdot \tau_i \cdot \log (1 + h_i^E p_i^\star) \\
& \quad \leq \sum_{i=1}^{K} (1 - \delta_i) \cdot \tau_i \cdot \log (1 + h_i^E p_i^\star), \forall i, \\
& \quad \delta_i \cdot (1 - \delta_i) = 0, \forall i, \\
& \quad p_i^\star \geq 0, p_i^\star \geq 0, \tau_i \geq 0, \delta_i \in \{0, 1\}, \forall i,
\end{align*}
\]

where \( \sum_{j=1}^{i} E_{s,j-1}^{EH} \) and \( E^R \) are cumulative harvested energy on the source and the total available energy on the relay, respectively. According to the third constraint, which shows the data causality, the amount of data was transmitted by EH-S is higher than or equal to the number of transmitted data by the relay at any instant of time. Consequently, the objective function of this problem will be based on the total amount of data that NEH-R can transmit to the destination for the given total number of epochs \( K \). The above problem is convex Mixed Integer Non-Linear Program (MINLP) since the integer variable \( \delta_i \) is either (1) or (0); i.e., \( \delta_i \in \{0, 1\} \) and many advanced algorithms recently have been proposed to solve this type of the problem optimally. In this paper, we propose several schemes that solve this problem under offline and online setting.

6.1. Optimal Resource Allocation

Besides IPOPT algorithm is the most recent advance method that provides the global optimal solution for NLP optimization problems, Advanced Process Optimizer (APOPT) algorithm is approved to solve many large-scale optimization problems, such as NLP, MILP and MINLP problems. APOPT is an open source software solver that provides global optimal solutions for convex MINLP problems [19].

On the other hand, problem in (23) can be simply solved using exhaustive search algorithm by giving \( \delta_i \) for the \( i \)th interval \((i = 1, 2, \ldots, K)\). Hence, the only variables that need to be optimized are \( (p_i^\star, p_i^\prime) \) for all possible combinations of \( \delta_i \), for the \( i \)th interval \((i = 1, 2, \ldots, K)\), and only a \( \delta_i \)'s combination that maximizes the overall throughput will be chosen. Because of the complexity of exhaustive search algorithm especially for large number of time slots, the exhaustive search approach will not be applied in this paper.

6.2. Sub-Optimal Resource Allocation

To solve the problem (23) heuristically, the whole epoch will be either allocated to the source node or the relay node based on \( (\gamma_i^\dagger) \) for the \( i \)th interval \((i = 1, 2, \ldots, K)\). First, RGFV approach will be applied into the source-relay link for the \( i \)th RGFV interval \((i = 1, 2, \ldots, K)\). Hence, the transmit powers of the \( i \)th RGFV interval \((i = 1, 2, \ldots, K)\) for the EH-S and NEH-R are \( p_i^\prime = p_i^{EH} \), \( p_i^\star = p_i^B \) respectively. The threshold average capacity \( (\theta_\varepsilon) \) for \((K \rightarrow \infty)\) can be formulated as

\[
\theta_\varepsilon = \frac{\sum_{i=1}^{K} \gamma_i^\dagger}{K} = \frac{\sum_{i=1}^{K} h_i^E p_i^{EH}}{K}
\]

That is all, the whole interval is assigned to the source set \( (L^\prime_i) \) if \( (\gamma_i^\dagger \geq \theta_\varepsilon) \) or it is allocated to the relay set \( (L^\gamma_i) \), otherwise. Moreover, the first interval is allocated to the source set whereas the last epoch to the relay. Eventually, RGFV algorithm is utilized again and it will be only applied on the intervals that are assigned to the source node \( (\gamma_i^\dagger) \). To avoid a vital problem that results in \( p_i^\star \neq 0 \) even when the relay node does not have data to send, our proposed algorithm solves that potential problem as it is shown in (2). The “for” loop (line 15 to 23) ensures that the bit arrival profile at the relay will be shaped based on the number of bits that have been transmitted by the source and the relay node only transmits if it has stored data in the buffer. The proposed algorithm is referred as Relay In Demand using Average Capacity (RID-AC). Algorithm 2 shows the pseudo-code for this scheme.

6.3. Relay In Demand using Average Fading (RID-AF) Based

It is well-known that only causal information of channel status and harvested energy is available for real scenario of resource allocation in wireless communication. This is to say, we proposed an efficient low-complexity scheme that solves (23) with knowledge of CSI only. Similar to the sub-optimal performance of offline transmission policy using average capacity as a threshold, the whole epoch will be either allocated to source node or relay...
Algorithm 2 Pseudocode for RID-AC

1. Input: \( \{\tau_{i}^{h}\}_{i=1}^{K-1}, \{h_{i}^{s}\}_{i=1}^{K-1}, \{E_{i}^{EH}\}_{i=1}^{K-1} \)
2. Let \( L_{1}^{s} = \phi \) and \( L_{1}^{t} = \phi \) (empty sets).
3. utilize (12) to compute \( \{p_{i}^{EH}\}_{i=1}^{K-1} \).
4. utilize (20) to compute \( \{\gamma_{i}^{s}\}_{i=1}^{K-1} \).
5. utilize (23) to obtain \( \theta_{e} \).
6. \( L_{1}^{s} \leftarrow \tau_{1} \quad L_{1}^{t} \leftarrow \tau_{K} \)
7. for \( i = 2 \) to \( K-1 \) do
   8. if \( \gamma_{i}^{s} > \theta_{e} \) then
      9. \( L_{i}^{s} \leftarrow \tau_{i} \)
   else
      \( L_{i}^{s} \leftarrow \tau_{i} \)
   end if
8. end for
9. Input: \( \{\tau_{i}^{s}\}_{i=1}^{L_{1}^{s}}, \{h_{i}^{s}\}_{i=1}^{L_{1}^{s}}, \{E_{i}^{EH}\}_{i=1}^{L_{1}^{s}} \), \( K-1 \)
10. Utilize (12) again to compute new \( \{p_{i}^{EH}\}_{i=1}^{K-1} \).
11. Initialize relay buffer, \( B_{0} = 0 \):
12. for \( i = 1 \) to \( K \) do
13. if \( \tau_{s} \in L_{1}^{s} \) then
14. \( B_{i} = B_{i-1} + \tau_{s} \cdot \log(1 + h_{s}^{s}p_{i}^{t}) \)
15. else
16. if \( \log(1 + h_{s}^{s}p_{i}^{t}) > B_{i} \) then
17. \( p_{i}^{t} = \frac{B_{i-1}}{h_{s}^{s}} \)
18. \( B_{i} = B_{i-1} - \tau_{s} \cdot \log(1 + h_{s}^{s}p_{i}^{t}) \)
19. end if
20. end if
21. end for
22. Output: \( \{B_{max(i,n)}\}_{i=1}^{K} \)

node. However, since the only CSI is available, the epoch allocation is determined based on the channel fading gain \( (h_{s}^{s}) \) only as a threshold. Specifically, the epoch is allocated to source or relay for the \( i \)th interval \( (i = 1, 2, ..., K) \) as
\[
\left\{ \begin{array}{ll}
L_{i}^{s} \leftarrow \tau_{i} & \text{if} \ i = 1, \ or \ \frac{1}{h_{s}^{s}} \leq \theta_{a} \\
L_{i}^{t} \leftarrow \tau_{i} & \text{if} \ i = K, \ or \ \frac{1}{h_{s}^{s}} > \theta_{a}
\end{array} \right.
\]
where the threshold based on the average fading \( \theta_{a} = \frac{\sum_{i=1}^{K} \tau_{i}}{K} \), and \( (\kappa) \) is a scalar factor. We consider that the epoch \( (\tau_{i}) \) is dedicated to the source in two cases: first at the beginning of transmission, second when the channel fading gain is higher than the threshold. In the second case, the \( i \)th epoch is dedicated to the relay transmission. Although the proposed solution is heuristic, it has been shown in the numerical results that the proposed algorithms in a delay-tolerant network are achieved higher throughput compared to the proposed algorithms in a delay-limited network as well as Algorithm 2 in [15] with the price of no-bounded delay. The proposed algorithm is referred to Relay In Demand using Average Fading (RID-AF). The following flow chart demonstrates the RID-AF algorithm, as it is illustrated in Fig.3.

7. Simulation Results

In this section, we provide simulation results to evaluate the performance of the proposed offline and online resource allocation algorithms for both delay-tolerant and delay-limited networks. We set our parameter values as the same as [13]. We consider a band-limited fading channel in the source-relay link and additive white Gaussian noise channel in the relay-destination link, with bandwidth \( (BW) = 1 \text{MHz} \) and noise power spectral density \( N_{0} = 10^{-10} \text{W/Hz} \). The path loss and the transmission block length are assumed to be 100dB and 100ms, respectively. Consequently, the rate power function is determined as \( r = \log(1 + h_{s}p_{i}^{t}) \). We assume i.i.d. Rayleigh fading channels, where the gain \( h \) follows Rayleigh distribution with mean \( (\bar{m} = 5) \) whereas \( h = 1 \) for AWGN channels. Energy Harvesting rate \( D_{i}^{EH} \), on the other hand, follows Poisson distribution with arrival rate \( (\lambda = 1) \), which is multiplied in the unit of the average EH rate on the source \( (E_{s}^{EH} = [1, 2, ..., 10]) \). The simulation was done using Matlab and it was run for 10000 random EH realizations.

7.1. Performance of RGWF algorithm for a point-to-point communication

Fig.4 shows the average throughput versus the source average EH rate with infinite energy capacity over Rayleigh fading channel. We compare the RGWF scheme performance with a conventional non-EH source, where the same total amount of energy is available to allocate at the start of the process; and the baseline performance, where the source node starts its transmission as soon as the harvested energy arrives over Rayleigh fading channel. It is shown that with the increasing rate of the harvested energy, the throughput loss of the RGWF over the non-EH network is more significant due to the fact that higher amount of harvested energy has to follow causality constraint, and therefore, loss flexibility of allocation. On the other hand, the proposed RGWF outperforms baseline scheme in the entire range of energy arrival rate.

7.2. Resource Allocation Schemes for Delay Limited Two-hop Communication

In this subsection, we show the performance of the proposed resource allocation schemes for a delay limited relaying in a two-hop wireless network with EH source
over Rayleigh fading channel whereas the non-EH relay link experiences AWGN environment. We compare the throughput performance of the proposed algorithms to the baseline algorithms where fixed power allocation and time scheduling are applied to both nodes. For example, each epoch is divided into two-equal time slots and they are assigned to the source and the relay respectively. All proposed algorithms are also compared with the upper bound of the short-term throughput for a conventional non-EH nodes.

Fig. 5 shows the impact of high channel SNR and low channel SNR versus the throughput when the channel link faces Rayleigh fading. The figure shows the average throughput for the resource allocation schemes that proposed for a delay-limited network versus \( E_{o}^{EH} \) for \( (K \to \infty) \) and with a constant relay peak transmit power \( P_{RM} = 10mW \). It is noticeable that the average throughput increases as \( E_{o}^{EH} \) increases for all considered schemes. As expected, we can also observe that the performance of the offline proposed resource allocation scheme is superior to the online schemes for all \( (E_{o}^{EH}) \). The reason behind is because of the fact that the non-causal information of CSI and harvested energy is available before starting the transmission in offline scheme whereas only causal information of CSI and harvested energy is available for online case.

On the other hand, Fig. 5 can be analyzed from two perspectives. The first perspective shows the large throughput gap between our proposed RGWF based algorithm; RIPE, and the baseline policy from one hand and it reaches to its upper bound from another hand. In addition, when the network is delay limited, it is clear that the proposed RIPE algorithms with data rates based are alternated exactly between the upper bound and baseline performance, which indicates that the throughput performance is degraded in price of less complexity and less feedback overhead. In addition, the proposed online RIPE scheme with 10-rates performs better than the proposed online RIPE scheme with 5-rates when source link faces Rayleigh channel due to the fact that more data rates are available as options especially when the SNRs are varying among the epochs. Moreover, we observe that the difference between the performances of RIPE-10 and RIPE-5 rates increases with increasing \( E_{o}^{EH} \).

### 7.3. Resource Allocation Schemes for Delay Tolerant Two-hop Communication

In this subsection, we show the performance of proposed resource allocation schemes for a delay tolerant relaying in a two-hop wireless network with EH source over Rayleigh fading channel whereas the non-EH relay link has AWGN channel. We compare the throughput performance of the proposed offline and online algorithms to the baseline scheme where fixed power allocation and slot allocation are applied to both nodes. For example, assuming the total number of epochs are even, the odd epochs are assigned to the source and even epochs are assigned to the relay. All the proposed algorithms are also compared with the upper bound of the short-term throughput for a conventional non-EH two-hop network over Rayleigh fading channel.

Fig. 6 shows the average throughput for the resource allocation schemes proposed for a delay tolerant network versus average EH rate on the source \( E_{o}^{EH} \) for \( (K \to \infty) \) and with a constant relay peak transmit power \( P_{RM} = 10mW \) over Rayleigh fading channel. It is quite clear that the throughput performance of the RID-AC algorithm has surpassed the performance of the RID-AF algorithm with average fading. Moreover, we can notice that the average throughput of the offline proposed RID-AC scheme increases sharply as \( E_{o}^{EH} \) increases, whereas the average throughput of the online proposed RID-AF scheme increases exponentially as \( E_{o}^{EH} \) increases. Fig. 7, on the other hands, shows the average throughput versus \( \kappa \) with different source average EH rate. It can be observed that the average throughput has direct relationship with the scale factor, and the network gains the maximum throughput when \( \kappa = 2 \).

## 8. Conclusion

This paper considers a single-hop and a two-hop communication systems with energy harvesting constraints on the source in a fading channel environment and we
extended the simple and the elegant RGWF approach that solves the power allocation problem numerically into a simulation representation. The importance of this representation is that providing more insights to the problems and the solutions in such that various wireless systems can be analysed. We show the advantage of adapting the RGWF algorithm for the throughput maximization problem under Rayleigh fading channel. For a two-hop communication system, we proposed two schemes that maximize the network performance from throughput perspective for both delay tolerant and non-delay tolerant networks. Transmission scheduling time has been derived for the source and the relay based on RGWF-EH profile to obtain an efficient transmission policy. Numerical results illustrated that optimizing both transmission scheduling and power allocation result in gaining higher throughput. Moreover, simulations show that the proposed approach is simple, efficient and provide significant guidelines on network deployment and resource management in a green radio network with EH sources.

Acknowledgement

The authors sincerely acknowledge the support from Natural Sciences and Engineering Research Council (NSERC) of Canada under Grant numbers RGPIN-2014-03777, and the support from Al-Majmaah University in Saudi Arabia to this research.

References

Mohammed Baljon received the B.Eng. degree in Electrical and Computer Engineering from King Abdulaziz University, Jeddah, Saudi Arabia, in 2007. He also obtained the M.Eng. degree in Internetworking Engineering from Dalhousie University, Halifax, NS, Canada, in 2012. He is currently working toward the Ph.D. degree at the Department of Electrical and Computer Engineering, Ryerson University, Toronto, Canada. Currently, his research interests include energy harvesting networks, relay systems, wireless communications and green communications.

Lian Zhao (S’99-M’03-SM’06) received her PhD degree from the Department of Electrical and Computer Engineering (ELCE) from University of Waterloo, Canada, in 2002. She joined the Electrical and Computer Engineering Department, Ryerson University, Toronto, Canada, as an Assistant Professor in 2003 and a Professor in 2014. Her research interests are in the areas of wireless communications, radio resource management, power control, cognitive radio and cooperative communications, and smart grid. She has been an Editor for IEEE Transaction on Vehicular Technology since 2013 and awarded TOP 15 Editor in 2015. She has served as the symposium co-chair for IEEE Global Communications Conference (GLOBECOM) 2013 Communication Theory Symposium; Web-conference co-chair for IEEE Toronto International Conference Science and Technology for Humanity (TIC-STH) 2009; She has been a member of NSERC (Natural Sciences and Engineering Research Council) Evaluation Group for Electrical and Computer Engineering since 2015. Associate Chair for Graduate Studies at ELCE department from 2013 to 2015. She received Canada Foundation for Innovation (CFI) New Opportunity Research Award in 2005; Ryerson Faculty Merit Award in 2005 and 2007; Faculty Research Excellence Award from ELCE Department of Ryerson University in 2010, 2012, and 2014; and the Best Student Paper Award (with her student) from Chinacom in 2011, the Best Paper Award (with her student) from 2013 International Conference on Wireless Communications and Signal Processing (WCSP), and 2016 Best Land Transportation paper award from IEEE Vehicular Technology Society. She is a licensed Professional Engineer in Ontario, a senior IEEE member and a member of the IEEE Communication/Vehicular Society.