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Exploiting Correlations of Energy and Information: A New Paradigm of Energy Harvesting Communications

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Abstract

For deployment flexibility and device lifetime prolonging, energy harvesting communications have drawn much attention recently, which however, encounter energy domain randomness in addition to the channel state randomness and traffic load randomness. The three-dimensional randomness makes the resource allocation problem extremely difficult. To resolve this, we exploit the inherent correlations of energy arrival and information. The correlations include self correlations of energy profiles and mutual correlations between energy and information in both time and spatial domains. The correlations are explicitly explained followed by a state-of-art survey. Candidate mechanisms exploiting the correlations for the ease of resource allocation are introduced along with some recent progress. Finally, a case study is presented to illustrate the performance of the proposed algorithm.

Keywords

energy harvesting; wireless communications; spatial and temporal correlations; resource allocation

1 Introduction

With the rapid growth of mobile multimedia traffic requirements, wireless networks tend to be deployed more and more densely, resulting in more and more energy consumption. At the same time, with the emergence of Internet of Things [1] and wearable devices [2], large quantities of wireless sensors are appearing, causing stringent requirement on flexibility of deployment and cruising ability. By gathering energy from ambient environment (solar, wind, radio waves and so on) to power wireless devices, energy harvesting communication system is one of the candidate technologies to reduce CO2 emission and support flexible and sustainable wireless communications. Nowadays, the energy harvesting technology is drawing much attention from industrial community. For instance, China Mobile has deployed 13,000 renewable energy powered base stations (BSs) by May 2017 [3], and Powercast is developing wireless power harvesters [4]. It is expected that energy harvesting technology will be widely used in the future wireless networks.

A key feature of the ambient energy is that the energy arrival is random, leading to unstable power supplies. Thus, in addition to channel fading and traffic load variation, another dimension of randomness, the unstable power input needs to be considered, which makes the design of energy harvesting communications extremely difficult. Conventionally, the problem is mainly studied by two ways of simplifications. The first is to assume that all the dynamics (energy arrival, data arrival and channel fading) are known in advance, and the resource allocation can be optimized with offline global information [5]–[10]. The advantage of offline analysis is that structural properties can be found. However, since the non-causal information cannot be accurately predicted in reality, the offline results can hardly be used in causal systems. The other way is to consider only one or two types of randomness. For instance, one can analyze the system capacity in non-fading AWGN channel [11], [12], or optimize the resource allocation with constant energy arrival rate [13]–[15]. Nevertheless, the design with three-dimensional randomness is still an open problem.

In the real environment, the three-dimensional randomness is neither independent nor purely random, but is closely correlated with one another. For instance, real data shows that the solar energy arrival is quite stable and changes slowly in sunny day [16], while the network traffic load varies drastically [17], and the peak energy arrival rate and the peak traffic load appear in different time periods. On one hand, the correlation property can be utilized to simplify the problem formulation; on the other hand, it may cause other problems. Specifically, the stable energy arrival can be viewed semi-static. Hence, the

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randomness in energy domain can be omitted, while the mismatch between energy arrival and traffic load may severely degrade the system performance.

In this paper, we investigate a new paradigm of studying the energy harvesting communications by exploiting the inherent correlations between energy and information. We mainly focus on two types of correlations: 1) Self correlation of energy arrival process; 2) mutual correlation between energy and information. A thorough description on these correlations and state-of-art survey are given, based on which potential mechanisms based on them are discussed. In addition, a case study is provided to illustrate the importance of correlation properties.

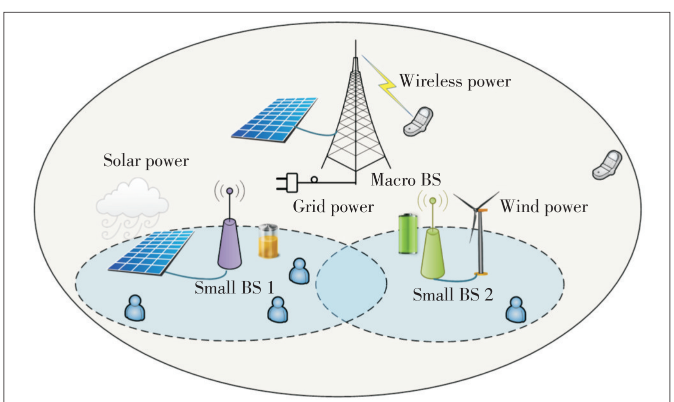
The rest of the paper is organized as follows. Section 2 describes the correlation properties. Section 3 proposes some correlation-aware mechanisms. A case study is given in Section 4. Finally, Section 5 concludes the paper.

2 Inherent Correlations of Energy and Information

A typical application scenario of energy harvesting technology in heterogeneous cellular networks is depicted in **Fig. 1**. It can be seen that the macro BS is plugged into power grid with stable power supply to provide a basic network coverage. A supplementary solar panel is connected to reduce the grid power consumption. The small BSs 1 and 2 are powered by solar power and wind power, respectively. Some low-power mobile devices that are located close to the BSs can harvest energy from the radio signal, i.e., wireless power transfer. In real systems, the energy arrival process should be characterized by temporal and spatial correlations with itself as well as with network traffic. In this paper, the correlations are mainly discussed based on the cellular scenario as in Fig. 1. Nevertheless, the properties and algorithms are not limited to this case. They can also be extended to any other energy harvesting communication scenarios.

2.1 Self Correlations of Energy Arrival

The energy arrival process in real systems can be viewed as



▲Figure 1. Cellular networks with energy harvesting.

a “semi-static” stochastic process due to the embedded self correlations. The term “semi-static” means that the energy arrival keeps constant to some extent or is known by some mechanisms. Such a property can be used to reduce the complexity of the resource allocation design. The self correlations are discussed in both time domain and spatial domain as detailed in the following.

2.1.1 Temporal Self Correlation

Based on the solar radiation data collected by the Measurement and Instrumentation Data Center (MIDC) [16], it is observed that the outdoor solar power in sunny days is quite stable, i.e., the energy arrival is strongly correlated in time domain (correlation coefficient ≈ 1). The energy arrival rate only changes at a long time scale following a predictable profile. When the energy harvester harvests energy from radio signals, the energy arrival process is predictable and even controllable by information exchange in the control plane. If the correlation properties are properly modeled, the complexity of resource allocation can be reduced.

The temporal self-correlation has been exploited in the literature. Define an energy harvesting frame as a set of consecutive slots during which the energy arrival rate keeps constant. In a single energy harvesting frame, power allocation and scheduling policies have been proposed for relay networks [13] and distributed networks [14]. For multiple energy harvesting frames, the outage minimization problem has been studied in [18]. However, there is a lack of a general framework to formulate the self correlations in energy harvesting communications. In fact, in wireless power transfer, the energy arrival may change in each slot, but it is self correlated from power transmitter side. It is also possible that the wireless channel is static such as line-of-sight (LOS) links, while the energy arrival rate varies rapidly. In this case, the channel state is strongly self correlated, which can also be taken advantage of.

2.1.2 Spatial Self Correlation

In the multi-node case, the self correlation exists not only in the time domain, but also in the spatial domain. The energy arrivals in different nodes may be different due to either diverse types of energy harvesters (e.g., solar v.s. wind) or various environments (e.g., solar power in cloudy day). The spatial energy distribution is modeled and analyzed in [19] which shows significant impact of spatial correlation on the network performance such as coverage. In this case, cooperation among nodes becomes quite important for coverage guarantee and energy-efficiency enhancement.

Some simple cases have been studied considering the spatial correlation of energy arrivals. For a two-node communication link with correlated energy harvesting transmitter and receiver, the optimal transmission policy is found in [20]. When two BSs cooperatively serve the cell-edge users, how they adapt the conventional network MIMO scheme to the spatial correlated case is considered in [15]. It can be seen that some nice results are obtained in these simple cases. However, the solutions cannot be applied to cases with multi-node directly, where a node's decision depends on its neighbors' states, while its neighbors also depend on their neighbors, and so on. Hence, the high complexity of solving such problems due to the coupling effect over the network is a major challenge.

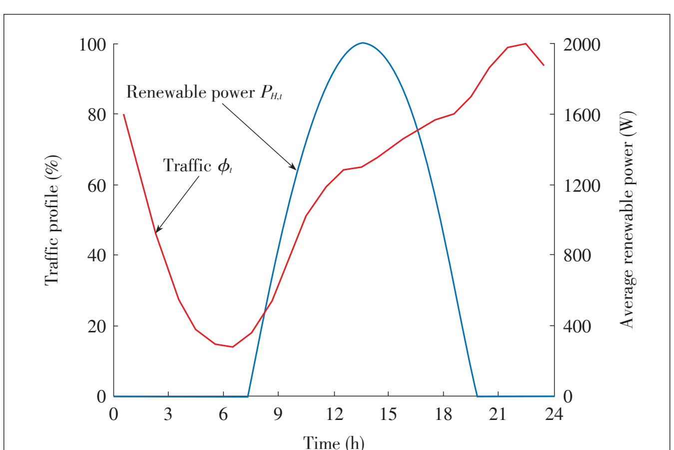
2.2 Mutual Correlations between Energy and Information

The classic Shannon's formula $R=\log_2(1+P/N)$ describes the basic relation between energy and information. However, it is only for a single link with additive white Gaussian noise (AWGN) channel, and considers greedy source and constant transmit power. In reality, burstiness exists in both the data traffic and the energy arrival. The amount of traffic that can be carried by a certain amount of energy depends on both temporal and spatial relations between energy arrival and traffic requirement.

2.2.1 Temporal Mutual Correlation

By drawing the 24 hour traffic profile based on [21] and the renewable power profile based on [22] together in **Fig. 2**, it can be seen that they do not match with each other in the time domain. The peak power meets a medium traffic load, while the peak traffic even meets zero power. Such a negative correlation between power and traffic may have severe impact on the wireless communication if the harvested energy is not smartly allocated to satisfy the traffic requirement.

Large battery is a promising solution. It has been proved that with ergodic energy arrival process, if the battery capacity is sufficiently large, the randomness in the energy domain is wiped out, and the system is equivalent to the one with the average power constraint [11], [23]. However, the battery capacity is limited in practice due to hardware constraints and expensive cost. Even if a large battery is equipped without financial limitation, the imperfections during charging and discharging as well as the limited lifetime will become an inevitable problem. With limited battery capacity, how to dynamically match harvested energy with traffic requirement needs some novel techniques.



▲**Figure 2. Traffic profile and renewable power profile over time.**

2.2.2 Spatial Mutual Correlation

The spatial mutual correlation can be illustrated by the example in Fig. 1. There are three users in small BS 1's coverage, but only one in small BS 2's. When the weather becomes cloudy and windy, BS 1 may be deficient in energy while BS 2 may be over charged. In this case, the traffic distribution mismatches the energy distribution in space. The users in BS 1's coverage may be out of service, while BS 2's battery may overflow. The negative correlation effect in spatial domain also degrades the service performance.

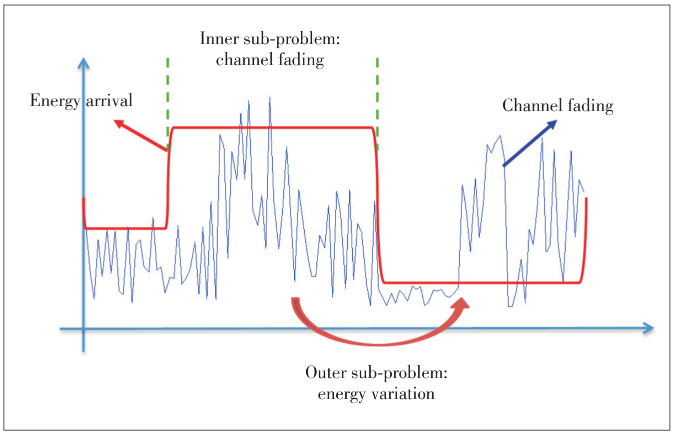
By jointly considering the traffic requirement and the energy profile, wireless resource allocation problem and dynamic BS sleeping problem are studied in [24] and [25], respectively. However, these works assume that the energy arrivals are identical in all the nodes, i.e., uniform energy distribution over space. For non-uniform distribution, the system needs to be redesigned from network planning to resource allocation, both of which should be traffic aware.

3 Exploiting Correlations for Energy Efficient Communications

As shown in the previous section, the correlations inside the energy arrival process and between energy and traffic profiles are of significant impact on energy harvesting communications. Some of them can be utilized to simplify the problem, while some others should be carefully handled to eliminate the passive impact, both requiring novel algorithm design. As a starting point, this section presents some potential mechanisms to exploit the correlation properties.

3.1 Low-Complexity Resource Management Based on Temporal Correlation

If the channel fading and the energy arrival are viewed as purely random process, a two-dimensional randomness results in high complexity for transmission policy optimization. Exploiting temporal correlation can potentially reduce the complexity. For instance, when the change of energy arrival rate is slower than the channel fading, a two-stage power allocation algorithm can be applied to decouple the two-dimensional randomness as shown in **Fig. 3**. In particular, when the energy arrival rate keeps constant, an inner sub-problem adjusts the power allocation according to the channel fading only. The period with constant energy arrival rate is called energy harvesting frame. Then an outer problem deals with energy management among frames considering the change of energy arrival rate. As a consequence, the energy arrival and the channel fading are decoupled. Hence, the complexity is greatly reduced. Similarly, the two-stage algorithm can also be applied to the



▲Figure 3. Two-stage power allocation algorithm for decoupling channel fading with energy variation.

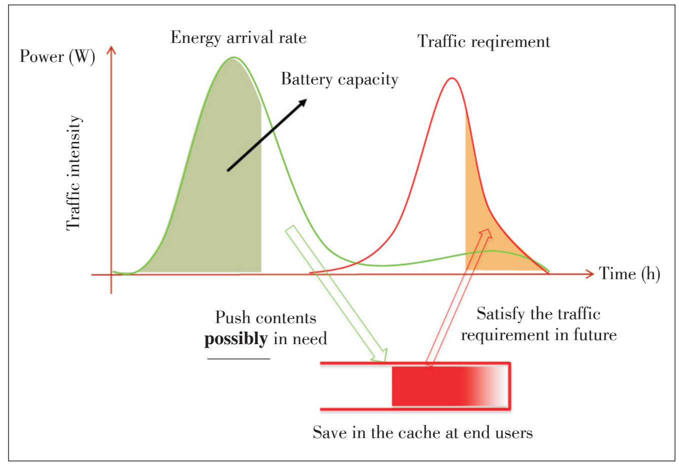
case in which the channel state varies slower than the energy arrival.

For the case in which energy arrival and channel fading changes in the same time scale, such as simultaneous wireless information and power transfer (SWIPT) [26], the two-stage algorithm is infeasible. Nevertheless, good news is that the transmit power is controllable. Thus, through information exchange between transmitter and receiver, the harvested energy well adapts to the wireless channel. Since the wireless power transfer is usually of low efficiency, it is mainly adopted with sufficiently strong channel gain. The information transmission is still possible in medium or even poor channel conditions. Taking the advantage of correlation between energy transfer and channel fading, the energy harvesting efficiency can be enhanced.

3.2 Energy-Aware Content Caching and Push

We now focus on how to deal with the negative temporal correlation between energy and information. The energy profile and the traffic profile usually mismatch, and the limited battery capacity is not sufficient to wipe out energy domain randomness. Thus, the storage ability in information domain should be taken into account, i.e., content caching. As shown in **Fig. 4**, the energy profile (green curve) and the traffic requirement (red curve) mismatch in the time domain, and the battery capacity is limited. When the battery is full, the continuously arrived energy can be used to push contents possibly needed in the future to the end users. Later, when the actual traffic demand is generated, part of it can be satisfied by the users' local cache. Thus, the barrier built up by the limited battery is broken, and the energy is "moved" from now to the future. Based on content caching and push mechanism, we have proposed a framework, namely GreenDelivery [27], to enable efficient content delivery with energy harvesting based small cells. In addition, content push policy for a single cell has been designed in [28].

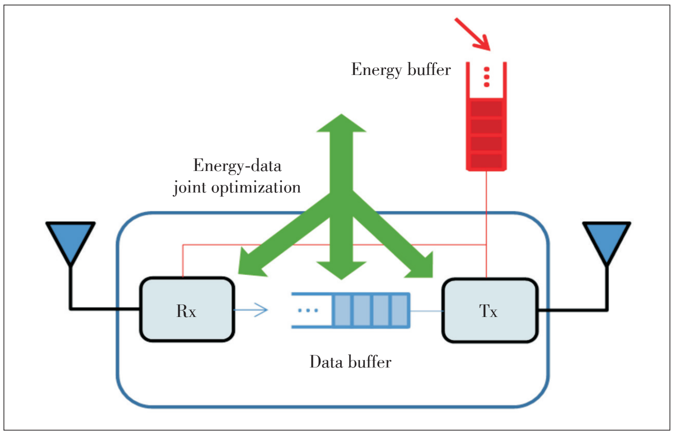
Although GreenDelivery well exploits the correlation between energy and information, the study on caching-aided energy harvesting communications is still in its infancy. Lots of problems need to be further examined. Firstly, the content caching schemes strongly depend on the statistic information of content popularity and long-term energy arrival process. Online algorithms are needed to accurately learn and predict the content popularity as well as energy statistics. Secondly, content caching consumes both energy and storage space of the devices. When the practical caching cost is accounted, the performance gain we can get may be reduced. The conditions on which an expected performance gain is achievable should be clarified. Finally, in a network with multiple cells, how BSs cooperate to reduce the content caching cost and improve file hitting probability over asymmetric energy and traffic distribution needs to be studied. This problem is actually related to how to exploit the spatial correlation between energy information, which will be further discussed later.



▲Figure 4. Solving energy-information mismatch problem via proactive caching and push.

3.3 Joint Transceiver Design with Energy Harvesting

In multi-hop relay networks, the relay nodes not only receive but also transmit data, and they may be powered wirelessly for deployment flexibility. As shown in **Fig. 5**, the relay node maintains two buffers: data buffer and energy buffer. Both data transmission and receiving consumes energy, while the spectral efficiency of data transmission is strongly related to channel state. Thus, the transceiver module should be jointly designed and optimized so that data buffer, energy buffer and channel state are well managed. Intuitively, data should be transmitted when the channel is good. If the data buffer is almost empty, the relay node needs to receive data from the source. Otherwise, the good channel state may not be fully utilized as there is no data to transmit. Either half-duplex (HD) or full-duplex (FD) mode is applicable in the relay nodes. The FD mode is expected to achieve a higher spectral efficiency compared with the HD mode, but consumes more energy due to the additional signal processing circuits for self-interference can-



▲Figure 5. Joint transceiver optimization for balancing the data queue and the energy queue.

cellation. In summary, the energy arrival process and the channel fading are correlated temporally via the controllable data buffers (by controlling the transceiver´s working mode). Similarly, different nodes are also correlated spatially.

Transmission policy optimization has been studied in [29] for a simple multi-hop topology, i.e., the system is composed of a source node, a relay node, and a destination node. A tradeoff between HD and FD is observed by exploiting the temporal correlation between energy buffer and channel states of the two hops. For a generalized multi-hop network, how to exploit the correlation between nodes spatially is a challenge issue.

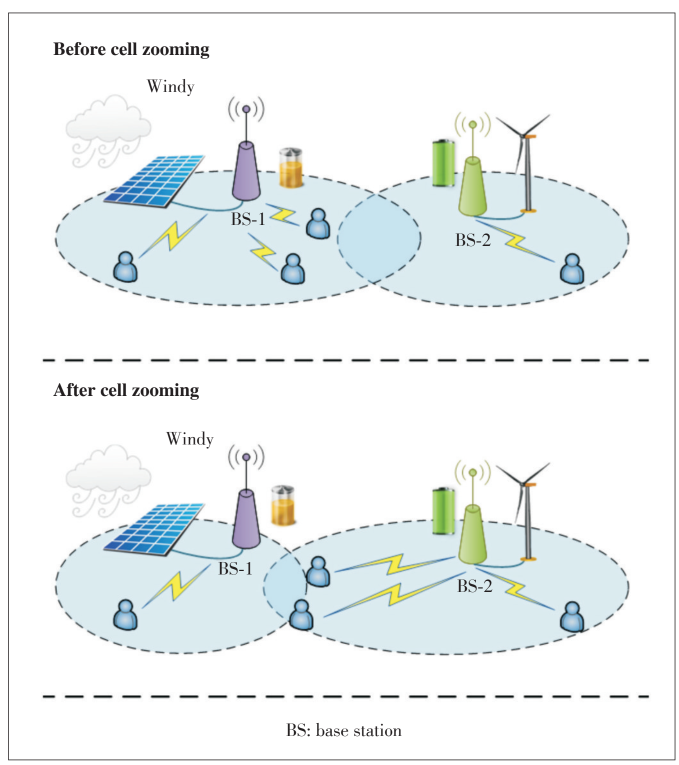
3.4 Dynamic Network Planning and Traffic Offloading

Conventional network planning determines the locations of BSs based on the expected average traffic load requirement as well as deployment and operation costs. For the energy harvesting communications, the deployment should be re-designed considering the energy distribution and the randomness of energy arrivals. First of all, a heterogeneous network topology where macro BSs are plugged into power grid to guarantee a stable network coverage, and small BSs can be powered by any energy source, is a necessity. Secondly, the planning of small BSs depends on the correlations between the energy and traffic. If the energy harvesting devices are deployed independent to the BSs and connect to the small BSs via power lines, the energy and traffic profiles are decoupled. Conventional network planning can be applied by additionally considering the deployment cost of power lines. If the energy harvesting devices are equipped on each BS, which can reduce the cost for deploying power lines, joint traffic-energy-aware network planning should be designed. For instance, the BSs should be density deployed when either the traffic load is high or the energy arrival rate is low so that the spectral resources and the available energy amount are sufficient.

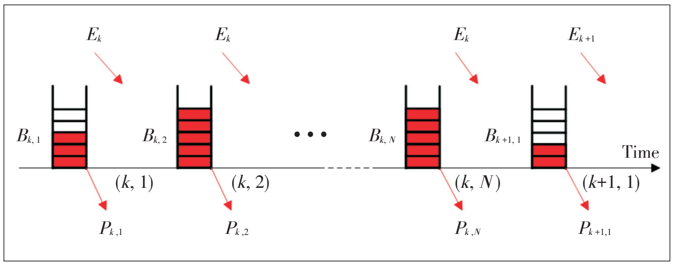
Due to the dynamics of energy arrival and traffic load, the nodes in the network may need the help of neighbor nodes when the energy is insufficient and the traffic load is high. Traffic offloading [30] is a candidate solution to realize the neighborhood cooperation. As shown in **Fig. 6**, the traffic offloading is based on energy-aware cell zooming [31]. When the energy profile and the traffic profile do not match for the two BSs, the BS with lower energy shrinks its coverage and the other with higher energy expands its coverage. As a result, the energy is "moved" from the cell on the right to the one on the left, and all the users can be served with sufficient energy. This is an efficient mechanism to transform the negative correlation between energy and traffic into a positive correlation over the space.

4 Case Study: Two-Stage Power Allocation with Semi-Static Energy Arrival

In this section, we present a case study to show how time correlations can be utilized to simplify the algorithm corresponding to Section 3.1. In particular, we consider a single link where the transmitter is powered by the energy harvested from ambient environment. It is assumed that the change of energy arrival rate is slower than the channel fading, i.e., the energy arrival rate changes every N ($N \geqslant 1$) fading blocks, i.e., an energy harvesting frame. The timeline of energy profile is shown in **Fig. 7**, where the time slot is denoted by (k, n) with k representing index of frames and n representing index of fading blocks in each frame, E_k is the energy arrival rate in frame k, $B_{k,n}$ is the battery energy state in slot (k, n), and $P_{k,n}$ is the transmit power. The channel gain in slot (k, n) is denoted as



▲Figure 6. Energy-aware cell zooming for realizing traffic offloading.



▲**Figure 7. Timeline of energy profile.**

$\gamma_{k,n}$. Thus, the battery energy state evolves as

$$B_{k,n+1}=\min\{B_{k,n}-P_{k,n}+E_k,B_{\max}\}, \tag{1}$$

where $B_{k,N+1}=B_{k+1,1}$, and $B_{\max}$ is the battery capacity. The data rate is related to the transmit power and the channel gain, denoted as $r(P_{k,n},\gamma_{k,n})$. We aim to maximize the average data rate by optimizing the power allocation, i.e.,

$$\max \lim_{K\to\infty}\frac{1}{KN}E\left[\sum_{k=1}^{K}\sum_{n=1}^{N}r(P_{k,n},\gamma_{k,n})\right]. \tag{2}$$

The problem can be formulated as a Markov decision process (MDP) and solved by dynamic programming (DP) approach [32]. The DP algorithm deals with a set of MDP problems which can be divided into stages. In each stage, the system state $x_k\in S$ dynamically changes under the influence of control action u_k and random parameter w_k embedded in the system, and the reward function $g_k(x_k,u_k,w_k)$ is additive over time. The objective is to maximizing the average reward function $\lim_{K\to\infty}(1/K)\sum_{k=1}^{K}g_k(x_k,u_k,w_k)$ by optimizing the state-dependent control policies $u_k=\mu_k(x_k),\ k=1,\ldots,K.$ Theoretical results show that a scalar λ and a vector $h=\{h(i)|i\in S\}$ satisfy Bellman's equation

$$\lambda+h(i)=\max_{u\in U(i)}\left[E_w(g(i,u,w)+\sum_{j\in S}p_{i,j}(u)h(j)\right], \tag{3}$$

where $p_{i,j}(u)$ is the transition probability from state i to state j under action u. Then λ is the optimal average reward and can be solved by value iteration based on the following equation

$$h^{(k+1)}(i)=\max_{u\in U(i)}\left[E_w(g(i,u,w)+\sum_{j\in S}p_{i,j}(u)h^{(k)}(j)\right]-\lambda^{(k)}, \tag{4}$$

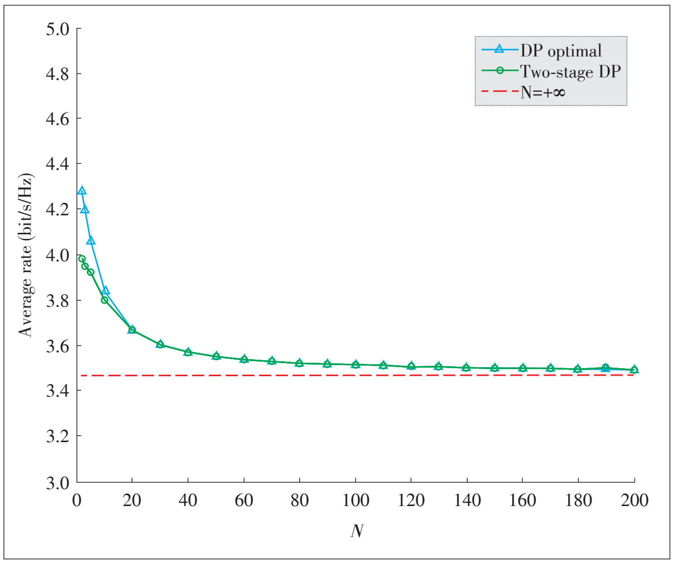
where $\lambda^{(k)}=\max_{u\in U(s)}\left[E_w(g(s,u,w)+\sum_{j\in S}p_{s,j}(u)h^{(k)}(j)\right]$ for a fixed state s. It converges to the optimal average reward λ.

In our problem, the system state includes the battery energy state $B_{k,n}$, channel state $\gamma_{k,n}$, energy arrival rate E_k, and the number of slots since the last change of energy arrival rate. The control action is the power allocation $P_{k,n}$, and the per-stage reward is the data rate $r(P_{k,n},\gamma_{k,n})$. By directly applying the above DP algorithm, the problem can be solved. However, it can be seen that the state space would be huge if the energy harvesting frame is long, which results in the curse of dimensionality problem. To resolve this, we exploit the correlation feature in time domain to reduce the computational complexity.

The original problem can be decoupled into two sub-problems, finite horizon power allocation in each energy harvesting frame, and infinite horizon energy management among frames. If the initial battery state and the terminal battery state are given, the optimal power allocation in a frame is irrelevant to the other frames since the energy arrival rate is known and fixed. In this sense, we can formulate an inner problem of finite horizon power allocation within a frame. On the other hand, given the expected per-frame reward obtained by solving the inner problem, the optimization among frames can be formulated as an outer problem that determines the initial/terminal battery energy of each frame, which is equivalent to determining the optimal amount of energy to be used in each frame. The inner and outer problems can be solved by finite horizon DP algorithm and infinite horizon DP algorithm, respectively. The system state of the inner problem includes battery state and channel state, and that of the outer problem includes battery state, channel state, and energy arrival rate. By comparison, the state space of the inner and outer problems are much smaller than the DP optimal one. The algorithm to solve the inner and outer problems sequentially is termed as two-stage DP algorithm.

We run some numerical simulations to evaluate the performance of the proposed two-stage DP algorithm. Consider a binary system settings, i.e., both the channel gain and the energy/power take only two values, $\gamma_{k,n}\in\{0,1\}$, $E_k\in\{0,1\}$, and $P_{k,n}\in\{0,1\}$. The channel fading is assumed independently and identically distributed (i.i.d.), and the channel state is good ($\gamma_{k,n}=1$) with probability p = 0.7, and is bad ($\gamma_{k,n}=0$) with probability $1-p$ = 0.3. In good channel state, the data rate with a unit of power is $r(1,1)=r_1$. In bad state, the data rate is $r(1,0)=r_0$. If the transmit power is zero, the data rate is zero. One unit of energy is harvested with probability q = 0.7, and there is no energy arrival with probability $1-q$ = 0.3.

The comparison of the two-stage DP algorithm and the DP optimal algorithm is shown in **Fig. 8**. It can be found that there is a performance gap between the two algorithms when N is small, which gradually vanishes as N becomes larger. Specifically, the gap is neglected when $N\geqslant 20$. As N increases, the average rate reduces for both of the algorithms, and converges to a fixed point as shown by the red dashed line. The result demonstrates that the proposed low-complex algorithm well approaches the DP optimal algorithm. In addition, it is interesting to note that the average rate with small value of N is larger than that with large value of N. As smaller value of N refers to more randomness in energy arrival process, it shows that the randomness actually helps to improve the overall performance



▲Figure 8. Performance comparison of the two-stage DP algorithm and the DP optimal algorithm.

by the concept of opportunistic scheduling. As both energy arrival and channel fading are random, there are more opportunities that good channel state meet sufficient energy arrival.

5 Conclusions

This paper discussed the inherent correlations of energy and information, which can be exploited to facilitate the resource allocation for energy harvesting communications. The temporal self correlation of energy arrival process results in a semi-static energy profile so that joint-energy-channel-aware power allocation can be decoupled. With the spatial correlation, neighboring nodes can help each other. The negative correlation due to the mismatch between energy and traffic in temporal domain can be effectively resolved via the content caching technique. In the spatial domain, the mismatch problem can be relieved by energy aware traffic offloading. In summary, the correlations between energy and information are key features for characterizing the three-dimensional randomness. Accurately modeling and properly using the correlations would be a feasible path to realize intelligent resource allocation in energy harvesting wireless communications.

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