Proactive Content Push in Heterogeneous Networks with Multiple Energy Harvesting Small Cells

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***Abstract*—Energy harvesting is an emerging technology providing clean energy for wireless communication systems. Due to the randomness in energy arrivals, wireless service process needs to be matched with energy provision to avoid energy waste or shortage. Other than passively adjusting energy usage according to traffic and energy profiles, a framework, namely, GreenDelivery has been proposed to proactively push popular contents to users in advance, such that harvested energy can be utilized more efficiently. In this paper, a heterogeneous network with multiple GreenDelivery small cells is considered. Due to spatial proximity, adjacent small cells might conflict with each other due to simultaneous transmissions or repeated pushes of identical contents to the same user, which calls for a more sophisticated design of push scheme in a multi-cell scenario. To tackle the interference, small base station (SBS) scheduling is proposed, exploiting the intermittent nature of renewable energy, to temporally separate the transmission of adjacent small cells. Heuristic push schemes are then proposed to further reduce the user requests handled by macro base stations (MBS) with centralized and distributed realizations. Simulations show that the proposed push schemes outperform the baseline scheme in which contents are pushed in the descending order of their popularities, especially when content popularity is more uniformly distributed.**

I. Introduction

As the need for wireless communications increases rapidly with the growth of the number of terminals and the demands for higher transmission rate, energy consumption in cellular networks requires urgent attention. One promising methods for reducing carbon emission in wireless networks while improving network capacity is to utilize renewable energy from ambient environment to power base stations. Apart from power consumption reduction, energy harvesting module is also valued for its convenient and flexible deployment in hard-to-reach areas, such as in-body implant [1] [2], to prolong system lifespan. Due to the randomness of renewable energy availability, an energy-harvesting device may suffer from energy shortage, which is caused by excessive service, or battery overflow, owing to redundant energy arrivals and insufficient energy buffer. Both cases are resulted from the spatial-temporal mismatch of energy arrival and traffic demands. To deal with this issue, several recent works have investigated optimized energy usage under the mismatch of energy and traffic profiles [3].

Different from matching energy usage with arrived energy and data, ref. [4] proposes a novel architecture named GreenDelivery to combine passive adjustment of power with proactive caching and push based on predicted user behaviors. In the GreenDelivery framework, energy-harvesting SBSs are deployed in addition to MBSs. By caching popular contents in advance, small cells can push contents to users, and thus equivalently serve users before the needs actually occur. The benefits of this framework are straightforward. On the one hand, the requests handled by MBSs can be reduced, especially when users' demand for contents has a clear group pattern, and this in term reduces the grid power consumption from MBSs. On the other hand, by scheduling the push process to match with energy arrivals, energy shortage and overflow can be avoided, such that renewable energy can be more efficiently utilized.

There are several papers on how to schedule caching and push procedure in small cells. For a single-cell case, the optimal push policy for energy harvesting SBS is investigated in [5] and [6]. Ref. [7] emphasizes the impact of limited storage device on network performance. However, neither interference or redundant pushes in multi-cell scenarios is considered. In [8], network with multiple cache-enabled small cells are considered. SBSs in [8] multicast contents to users when requests are received, while renewable power source and proactive push are not included in the framework. In the GreenDelivery architecture [4], intuitively, SBSs should always push the most popular content that has not been pushed at each time interval. However, considering the coverage overlap between multiple SBSs, the possibility of repeated content push from different SBSs might leads to a distinct push scheme where the most popular content is not always the best choice. Along with the randomness of energy arrivals and the lack of information exchange between SBSs, the optimal policy can be much more difficult to obtain.

In this paper, we consider the mutual interference and coverage overlap between multiple SBSs, and design the order in which contents should be pushed to reduce the number of user requests handled by the MBS. Since both interference and coverage overlap are resulted from spatial proximity among SBSs, the two problems are usually coupled, which impedes the analysis. Utilizing the intermittency of renewable energy, SBSs are scheduled into disjoint subsets, by which interference and coverage overlap can be dealt with independently, such that the analysis can be simplified. Centralized and distributed push schemes are proposed based on the separated transmission between SBS subsets. It is observed in simulations that

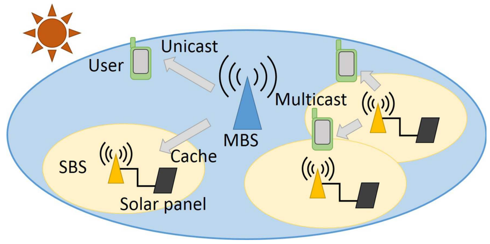


Fig. 1. Heterogeneous network with GreenDelivery SBSs.

the proposed schemes achieve a higher gain over the baseline scheme on the reduction of requests handled by the MBS when the content popularity distribution is more uniformly distributed.

This paper is organized as follows: In the next section, the system model is introduced. Section III proposes a SBS scheduling policy which temporally separates the transmission of adjacent SBSs. Section IV presents the proposed online centralized and distributed policy. Simulation results are give in Section V. Section VI concludes this paper.

II. System model

Consider a heterogeneous cellular system with one MBS and several SBSs, as depicted in Fig. 1. The MBS is grid-powered, while SBSs only have access to their own energy harvesting modules, which gather energy from the environment and store the harvested energy in a battery for later usage. The MBS serves the users in its coverage area with traditional functions such as unicast. Meanwhile, it can send popular contents to the SBSs under its coverage through a wired or wireless backhaul. After receiving those contents, SBSs cache them in the storage and proactively push the contents to their users by multicast, so that the request can be served before it arrives. If a request has not been handled by one of the SBSs, MBS will serve the request by unicast.

A. Network topology

Denote the set of SBSs as $\mathcal{S}$ with $|\mathcal{S}| = M$. Each user is associated with the SBS that offers the maximum downlink signal-to-interference-and-noise-ratio (SINR). Assuming that each SBS operates with an identical transmit power P_0, we have that

$$\frac{P_r}{P_0} = \beta D^{-\alpha}, \tag{1}$$

where P_r is the received power, β is the pathloss constant, α is the pathloss exponent, and D is the distance between the user and its corresponding SBS. Since SBSs are powered by renewable energy, which has an intermittent nature, SBSs are not always able to work due to energy shortage or scheduling issues. Let $\mathcal{S}_t$ denote the set of SBSs that are transmitting at time t. Denoting the distance between the i-the SBS and a user of interest as D_i, and the noise as N_0, the SINR at the user is therefore given by

$$\gamma_t = \frac{\beta D_{s_t}^{-\alpha}}{\sum_{i \in \mathcal{S}_t \setminus \{s_t\}} \beta D_i^{-\alpha} + \frac{N_0}{P_0}},$$

in which s_t is the SBS that the representative user is associated with at time t: $s_t = \arg\min_{i \in \mathcal{S}_t} D_i$. Furthermore, SINR γ_t needs to exceed threshold γ in order to guarantee reliable transmissions.

In an energy harvesting system, only the case with insufficient energy supply is considered, since if energy is available all the time, there is not much difference from grid-power scenarios. It is assumed that contents have an identical size so that it consumes the same amount of time T_s under constant transmit power P_0 to complete each push process. Thus, the energy consumption of each push process is $E = (1+\eta)P_0 T_{\mathrm{s}}$, where η is the ratio between the circuit power and transmit power P_0. When SBS remains silent, energy consumption is ignored. An energy arrival is defined as the instant when energy unit of size E Joules is harvested since the last arrival. Since each push process consumes one energy unit of E Joules, battery can be quantitized as multiples of E Joules. We will see that in the rest of the paper, the push schemes can be implemented at each arrival of energy, such that a battery of unit size is sufficient.

To focus on the analysis of push schemes in multi-cell scenario, user mobility is ignored. The distribution of users in the coverage of the MBS is assumed to be a homogeneous Poisson point process (PPP) with intensity r.

B. Content push in GreenDelivery

The cached contents are represented with a set $\mathcal{C}$ with $|\mathcal{C}| = L$. The j-th content has popularity c_j, which suggests the probability of the j-th content being requested by a user. Without loss of generality, assume that content popularities are sorted in an ascending order, *i.e.*, $c_j < c_{j+1}$. It is assumed that before the deadline, the popularity of contents do not update, and that the MBS only caches once to the SBSs at the beginning.

Time is slotted according to the content push duration T_{s} with index $\tau \in N_{>0}$, *i.e.*, the slot τ denotes the time interval $[(\tau-1)T_{\mathrm{s}}, \tau T_{\mathrm{s}})$, such that at each slot, SBSs can fulfill one content push process given sufficient energy. Due to the insufficiency of energy arrival, it is assumed that there is at most one energy arrival within several slots.

C. Objective

The purpose of designing a push policy is to reduce the requests handled by the MBS, while obeying the energy constraint of each SBS. Different from the single SBS case, when considering the push operation of neighboring SBSs, users located near multiple SBSs might receive a low SINR when nearby SBSs transmit together such that the signal can not be decoded correctly, and receive contents from distinct SBSs at different slots since SBSs can be silent sometimes. The *coverage* of an SBS at the i-th slot is defined as the area where users are associated with the SBS and can receive a signal with SINR higher than threshold γ. Based on this, *coverage overlap* among multiple SBSs is defined as the area where users are under the coverage of the SBSs at least once. To proactively serve as many potential requests as possible,

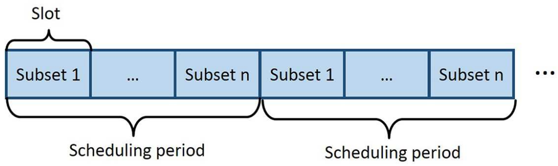


Fig. 2. SBSs transmitting in separated slots by SBS scheduling.

the coverage of SBSs need to be enlarged, such that contents can be pushed to more users. Besides, due to the overlap of SBSs, the pushed contents need to be carefully chosen, in order to avoid meaningless repeated pushes of the same content. Thus, the problem becomes that at each time slot, the SBSs decide on whether to push one content to the users and which content to push. Note that, since serving unicast request always reduces the number of requests handled by the MBS by one, while multicast push can serve multiple users, it is assumed that unicast is always dominated in the GreenDelivery framework, such that only multicast push function of the SBSs is considered.

III. SBS SCHEDULING

Due to severe interference between densely deployed small-cells, deploying more base stations can not significantly increase coverage [9]. Since energy shortage might occur in the system, SBSs are not always transmitting. Thus, in order to reduce the interference in the network, we make use of the silence of SBSs due to the intermittent nature of power supplement in energy harvesting systems, and schedule the transmission of adjacent SBSs in separated time slots, as shown in Fig. 2, such that interference can be reduced. Assuming that SBSs can harvest one energy unit every n slots on average, by separating SBS into $\lfloor n \rfloor$ disjoint subsets, where $\lfloor \cdot \rfloor$ is the floor function, energy can be utilized without waste while interference can be reduced at the same time. In this paper, a case of SBSs separated into two subsets is presented. Similar method can be applied to the case of $n > 2$.

Since users are always associated with the nearest SBS, interference comes from SBSs at a longer distance compared with the associated SBS. Therefore, the overall interference from the j-th SBS to the i-th SBS's associated users can be approximated by the power of the signal of the j-th SBS at the center of the i-th SBS. This is convenient to implement in real-world system by sequentially having the SBSs sending dummy signals and evaluating the signal power at other SBSs, which do not require an explicit pathloss model. Let $w_i = 1$ when the i-th SBS is assigned to the first subset $\mathcal{S}^{(1)}$ and $w_i = -1$ if it is assigned to the second subset $\mathcal{S}^{(2)}$. The goal is to minimize the average power of signals from other SBSs at the center of each SBS, which can be formulated as

$$\begin{aligned} \min_{\mathbf{w}} \quad & \frac{1}{M}\sum_{i\in\mathcal{S}}\sum_{j\in\mathcal{S}\backslash\{i\}}\frac{w_i w_j+1}{2}e_{ij} \\ \text{s.t.} \quad & w_i \in \{-1,1\}, \forall i \in \{1,2,\cdots,M\}, \end{aligned} \tag{2}$$

where e_{ij} is the pathloss at the distance between the i-th SBS and the j-th SBS. Subtracting (2) from $\frac{1}{M}\sum_{i\in\mathcal{S}}\sum_{j\in\mathcal{S}\backslash\{i\}}e_{ij}$, problem (2) is equivalent to the following one:

$$\begin{aligned} \max_{\mathbf{w}} \quad & \frac{1}{M}\sum_{i\in\mathcal{S}}\sum_{j\in\mathcal{S}\backslash\{i\}}\frac{1-w_i w_j}{2}e_{ij} \\ \text{s.t.} \quad & w_i \in \{-1,1\}, \forall i \in \{1,2,\cdots,M\}. \end{aligned} \tag{3}$$

Denoting the network by an undirected graph $\mathcal{G} = (\mathcal{S}, \mathcal{E})$, in which $\mathcal{S}$ is the set of all the SBSs, and $\mathcal{E}$ contains the edges between every two SBSs. The weight of an edge equals $e_{i_1 i_2}$. Problem (3) is equivalent to finding the weighted maximum cut of the undirected graph $\mathcal{G}$. However, weighted maximum cut has been proven to be NP-hard. The best approximation algorithm known so far is presented in [10], which achieves an approximation ratio of 0.878. In this paper, we adopt Goemans and Williamson's algorithm [10] to separate SBSs into two scheduling subsets.

Note that, by staggering the transmissions of SBSs, SBSs from $\mathcal{S}^{(1)}$ and $\mathcal{S}^{(2)}$ transmit in separated time intervals. Thus, there is no interference between SBSs from different subsets. By assuming that SBSs from the same subset transmit dummy information without energy consumption in their corresponding slots when battery or data buffer is empty, which is a typical method in the analysis of inter-cell interference, a conservative lower bound of SINR at each position can be calculated. Due to this technique, coverage overlap is only considered between the subsets. Therefore, the coverage of an SBS and the overlap between SBSs can be derived or obtained by Monte-Carlo simulations. While interference have been fully considered in a subset, overlap between the coverage of the two subsets can have a large impact on the push scheme, since repeated push of the same content can not reduce the requests handled by the MBS. In the rest of the paper, the coverage of the i-th SBS is denoted as S_i, and the overlap between SBS $i_1 \in \mathcal{S}^{(1)}$ and $i_2 \in \mathcal{S}^{(2)}$ as $S_{i_1 i_2}$. We will study push policy when repeated push of the same content does not bring extra gain.

In the rest of the paper, every two slots, in which each SBS has one chance to push, is regarded as a scheduling period. Thus, the t-th scheduling period represents the interval $[2(t-1)T_\text{s}, 2tT_\text{s})$. Further, it is assumed that there are T scheduling periods before the deadline.

IV. CONTENT PUSH SCHEMES

Denote the decision by the i-th SBS at the t-th scheduling period as follows:

$$u_{i,t} = \begin{cases} 0, & \text{stay silent;} \\ j, & \text{push content } j. \end{cases}$$

Since repeated transmission of the same content in a single cell does not bring extra reward, policies with $u_{i,t_1} = u_{i,t_2} > 0$ are strictly dominated. Thus, only the push schemes where all the contents can be pushed at most once need to be considered. We set $x_{i,j} = 1$ if the j-th content is pushed by the i-th SBS in

T scheduling periods, and $x_{i,j} = 0$ otherwise. Then, the push scheme can be represented by $X = (x_{i,j})_{M\times L}$. Therefore, the expected number of requests reduced by the i-th SBS regardless of the other subsets can be expressed as:

$$R_i = rS_i \sum_{j=1}^{L} x_{i,j} c_j. \tag{4}$$

When users in the overlap area of two SBSs receive the same pushed contents during the process, the total number of reduced requests does not equal the sum of (4) by all the SBSs. The expected number of reduced requests is given by

$$\begin{aligned} R(X) \quad = \quad & r\sum_{j=1}^{L} c_j \Bigg(\sum_{i_1\in\mathcal{S}^{(1)}} S_{i_1} x_{i_1,j} + \sum_{i_2\in\mathcal{S}^{(2)}} S_{i_2} x_{i_2,j} \\ & - \sum_{i_1\in\mathcal{S}^{(1)}} \sum_{i_2\in\mathcal{S}^{(2)}} S_{i_1 i_2} x_{i_1,j} x_{i_2,j} \Bigg). \end{aligned} \tag{5}$$

Regarding the constraints in energy availability, and assuming non-causal knowledge of the energy and request arrivals, the offline centralized problem can be formulated as follows:

$$\begin{aligned} \max_{X} \quad & R(X) && (6) \\ \text{s.t.} \quad & \sum_j x_{i,j} \le B_i, \forall i \in \{1, 2, \cdots, M\}, \\ & x_{i,j} \in \{0, 1\}, \\ & \forall i \in \{1, 2, \cdots, M\}, j \in \{1, 2, \cdots, L\}, \end{aligned}$$

where B_i is the total harvested energy during the T scheduling periods at the i-th SBS, and the objective function is given by (5). Despite the complexity in finding the solutions to (6), it is still worth looking into the offline problem since it gives the global upper bound on the performance of push scheme. In the simulation, a local search algorithm is applied to program (6) to approach a local optimum of the problem.

A. Centralized online push algorithm

For the online case, the central controller observes the energy arrivals at each SBS in a casual manner, such that it makes push decisions based on the previous arrivals and pushes. In order to schedule the push process of the SBSs in an online manner, an intuitive method is to acquire as much system utility as possible at each scheduling period. Thus, a heuristic greedy scheme is proposed. In this algorithm, the central controller observes the energy arrival of each SBS and allocates the push contents according to previous decisions. The problem is formulated as:

$$\begin{aligned} \max_{u_{i,t}} \quad & R_t = R(X_t) - R(X_{t-1}) && (7) \\ \text{s.t.} \quad & \mathbf{1}[u_{i,t} > 0] \le B_{i,t}, \forall i \in \{1, 2, \cdots, M\}, \end{aligned}$$

in which X_t is the decision matrix up to the t-th scheduling period, and $B_{i,t}$ is the battery state at the t-th scheduling period. Since each push does not reduce system utility, in the greedy policy, SBSs push a content whenever there is an energy arrival.

For the greedy scheme, we propose a heuristic algorithm which is polynomial-time. At each scheduling period, the SBSs with energy arrivals form a undirected graph $\mathcal{G}_t = (\mathcal{V}_t, \mathcal{E}_t)$, where $\mathcal{V}_t$ contains the nodes with value S_j that represent the j-th SBS who harvests energy in the current scheduling period, and $\mathcal{E}_t$ contains the edges between the node. An edge $(i, j) \in \mathcal{E}$ means that there is overlapping between the i-th SBS and the j-th SBS, and the value $e_{i,j}$ of edge (i, j) equals $S_{i,j}$. The algorithm works as following:

Algorithm 1 Algorithm for centralized push policy of grouped SBSs.

1. A Breadth First Search (BFS) [11] is perform in $\mathcal{G}_t$ to find all the connected components which are represented by the trees $T_i, i = 1, 2, \cdots, n$;
2. For each layer $L_{i,k}, k = 1, 2, \cdots$, update the marginal reward based on the decisions by the former layer, and each SBS choose the content with the highest reward;
3. Update the marginal reward based on the current decision by the SBSs for all the SBSs.

Since the number of edges in the graph is $O(M^2)$, the BFS is $O(M^2)$, while the second step is $O(ML)$, and the third and fourth steps both are $O(M^2)$. Thus, the complexity of this algorithm is $O(M^2L)$.

B. Distributed online push algorithm

In order to avoid the huge overhead on information exchange and computational burden, a distributed algorithm is more suitable for a large network. In a distributed architecture, computation is made locally in each SBS and real-time information about other SBSs is not available. For sure that system performance might degrade when a distributed architecture is applied, but it is more applicable in real systems. While real-time information exchange is not possible, prior knowledge, *e.g.*, the probability distribution of energy arrivals of other SBSs, can contribute to the design of push policies. In the distributed network, harvested energy in each scheduling period is assumed to be an independent and identically distributed (i.i.d) Bernoulli variable with size E and probability ρ.

An online distributed algorithm is defined as follows: At each scheduling period, the i-th SBS observes the energy arrival $B_{i,t}$ and former decisions $\mathbf{x}_{i,t-1}$, and decides on which content to push. In an online distributed algorithm, battery states and former decisions are unknown to each other. Each SBS needs to consider not only its own battery state, but also the potential behavior of other SBSs. Inspired by the baseline push scheme in which popular contents are given higher priority, we have one subset of SBSs push the contents in the descending order of their popularities, thus only look into the other subset of SBSs and find their optimal push policy.

Under the given push policy for subset 1, the probability that the j-th contents can be pushed equals the probability of there being at least $L-j+1$ energy arrivals, which is written as

$$\begin{aligned} & \mathbb{E}\left[x_{i_1,j}\right] \\ = \; & \text{Prob}\left[B_{i_1} \geq L-j+1\right] \\ = \; & \begin{cases} \displaystyle\sum_{k=L-j+1}^{T} \mathrm{C}_T^k \rho^k (1-\rho)^{T-k}, & \text{if } T \geq L-j+1; \\ 0, & \text{if } T < L-j+1. \end{cases} \end{aligned}$$

Applying this policy, the objective function becomes

$$\begin{aligned} \mathbb{E}\left[R(X)\right] = r \sum_{j=1}^{L} c_j \Bigg\{ \sum_{i_1 \in \mathcal{S}^{(1)}} S_{i_1} \mathbb{E}\left[x_{i_1,j}\right] \\ + \sum_{i_2 \in \mathcal{S}^{(2)}} \mathbb{E}\left[x_{i_2,j}\right] \left(S_{i_2} - \sum_{i_1 \in \mathcal{S}^{(1)}} S_{i_1 i_2} \mathbb{E}\left[x_{i_1,j}\right] \right) \Bigg\} \end{aligned} \tag{8}$$

In order to maximize the right-hand size of (8), we calculate the expected marginal number of reduced requests $c_j \left(S_{i_2} - S_{i_1 i_2} \mathbb{E}\left[x_{i_1,j}\right]\right)$ of pushing the j-th content, and schedule the push at its descending order. The detailed description of the algorithm is shown in Algorithm 2.

Algorithm 2 Algorithm for distributed push policy of grouped SBSs.

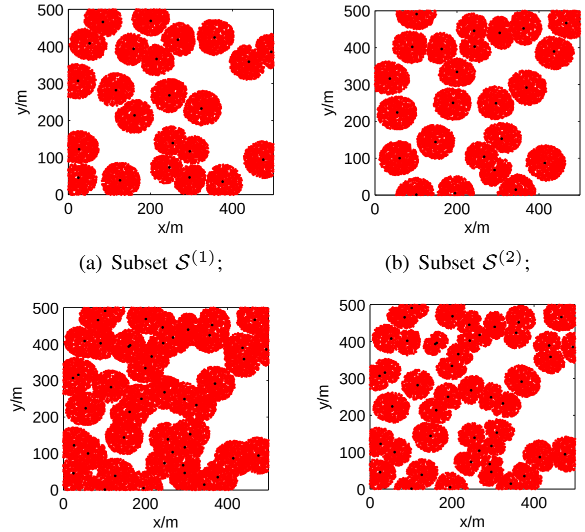
1: At each energy arrival of SBS $i_1 \in \mathcal{S}^{(1)}$, push the content with the highest reward and that has not been pushed yet;
2: Calculate the marginal reward

$$C_{i_2,j} = c_j \left(S_{i_2} - \sum_{i_1 \in \mathcal{S}^{(1)}} S_{i_1,i_2} \mathbb{E}\left[x_{i_1,j}\right] \right)$$

for SBS $i_2 \in \mathcal{S}^{(2)}$ push the j-th content;
3: At each energy arrival of SBS $i_2 \in \mathcal{S}^{(2)}$, push the content with the highest $C_{i_2,j}$ and that has not been pushed yet.

V. Numerical results

In this section, the numbers of reduced requests by different policies are compared to the ones by the *baseline* scheme in which content with higher popularity is always pushed first. Consider an area of 500m×500m, in which SBSs are deployed according to PPP with intensity $\lambda = 0.0002/\text{m}^2$, which results in 50 SBSs in the target area on average. Pathloss component α is chosen to be 4, while pathloss constant β, transmit power P_0, and noise N_0 are designed to satisfy that the SNR at the edge of each cell, which has a radius of $r_0 = 50$m, equals threshold γ. Energy arrivals follow Bernoulli process with probability $\rho = 0.8$. For the offline centralized problem, an local search algorithm, labeled `Offline`, is applied to approach a local optimum of the problem. `Greedy` represents the greedy algorithm for centralized online problems in Section IV-A. Algorithm 2, which is an online distributed scheme, is marked `Distributed`.



(a) Subset $\mathcal{S}^{(1)}$; (b) Subset $\mathcal{S}^{(2)}$;

(c) With SBS scheduling; (d) Without SBS scheduling;

Fig. 3. Coverage of different network topologies.

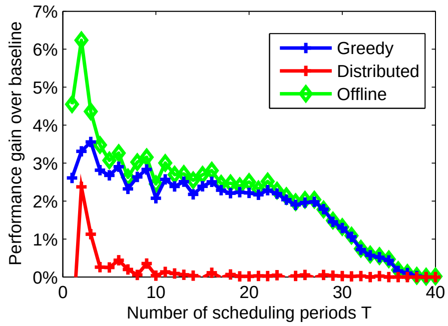
Fig. 3 shows a generated example of the network, in which Goemans and Williamson's algorithm is applied to separate SBSs into two subsets. By uniformly distribute sample nodes in the network and evaluate its received SINR, coverage of the network can be obtain through simulation. Fig. 3(a) and Fig. 3(b) show coverage of the SBSs in $\mathcal{S}^{(1)}$ and $\mathcal{S}^{(2)}$ when interference within the subsets is considered, respectively. Fig. 3(c) combines the coverage of Fig. 3(a) and Fig. 3(b), while Fig. 3(d) illustrates the coverage when SBSs are not scheduled and transmitting at the same time. Simulation shows that in the example network, SBS scheduling leads to a sum coverage of 73%, while the original network covers 58% of the area. Notice that users outside SBSs' coverage are solely handled by the MBS. Through simulations, the overlapping area between SBSs of the two subsets is also obtained.

By distribute users according to PPP with intensity $0.12/\text{m}^2$, the performance gain of SBSs under different policies with respect to the baseline scheme are compared. It is assumed that there are $L = 30$ contents identically cached in each SBS, and the popularities of contents follow Zipf distribution

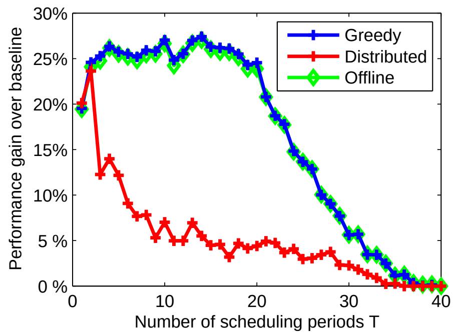
$$c_j = \frac{(L-j+1)^{-\xi}}{\sum_{k=1}^{L} (L-k+1)^{-\xi}},$$

in which ξ is the Zipf exponent. When ξ is small, content popularities tend to be more equal and vary less as j changes.

Fig. 4(a) and Fig. 4(b) illustrate the Performance gain under the three push schemes with respect to the number of scheduling periods. Content popularities follow Zipf distribution with exponent $\xi = 1$ and $\xi = 0.1$, respectively. Since there are $L = 30$ contents in the system, all the contents can be pushed to users by each SBS when the number of scheduling periods before deadline is large enough, which makes all the policies yielding the same reward, thus the gain goes to zero. In the figures, there is a significant gap between centralized policies and distributed policies when the number



(a) $\xi = 1$.



(b) $\xi = 0.1$.

Fig. 4. Performance gain over baseline *vs* the number of scheduling periods.

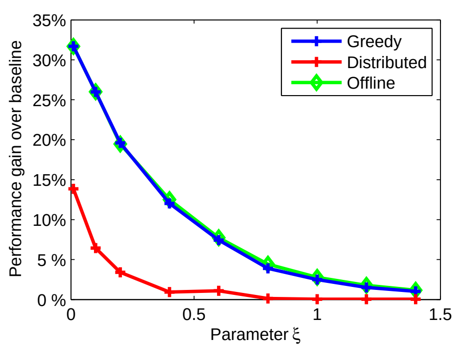


Fig. 5. Performance gain over baseline under different content popularity distribution.

of scheduling periods is smaller than the cache size, indicating that information exchange in the network is rather crucial to the multi-cell scenario. However, the difference within the two centralized policies is not as obvious. Although greedy algorithm is operated in an online fashion, it leads to a total reward close to the heuristic offline algorithm. In Fig. 5, the number of scheduling periods is set to 10, and the gain under different values of Zipf parameter ξ is compared. It can be seen that when ξ is small, *i.e.*, when the popularities among contents are more equal, the policies can achieve a larger gain. This result is intuitive. When content popularity distribution has a larger variance, the high marginal reward in successful push one of the content, rather than the overlap between SBSs, becomes the dominant factor.

VI. Conclusions

Proactive push by energy harvesting SBSs can efficiently utilize the harvested energy while reduce the traffic burden on the MBS. However, when SBSs are densely deployed, the interference among SBSs can notably aggravate network performance. Exploiting the insufficiency of energy supply by energy harvesting, transmissions of adjacent SBSs are separated in pre-allocated times. With this method, the coverage of SBSs can be improved by reducing the interference since the interference are limited within the SBSs that transmit simultaneously. Online centralized and distribute push policies are proposed to schedule the push sequence of each SBSs such that more requests can be served in advance. In the simulations, the performance of the proposed online centralized algorithm is shown to be close to the offline benchmark. Besides, an online distributed algorithm, which does not require information from other SBSs, is proposed. Simulation results shows that the algorithms markedly outperforms the baseline scheme when content popularity is more uniformly distributed.

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