SURE: A Novel Approach for Self Healing Battery Starved Users using Energy Harvesting

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***Abstract*—Radio Frequency (RF) Energy Harvesting (EH) holds a promising future for energizing low power mobile devices in next generation wireless networks. Harvesting from a dedicated RF energy source acquires much more energy than simply harvesting from ambient RF sources. In this article, a novel Self-healing of Users equipment by Rf Energy transfer (SURE) scheme is introduced between the network operator and battery starved users to heal and extend their battery life time by sending dedicated energy from different sources in order to be aggregated and harvested by starved users. This approach depends on the concept of Energy as a Service (EaaS) where the network operator delivers energy to battery starved users in the next generation networks. A mixed integer non-linear optimization problem is formulated and solved efficiently using three heuristic algorithms. Simulation results prove that sufficient amounts of energy can be delivered to starved users while minimizing their uplink power requirements and guaranteeing a minimum uplink data rate.**

***Index Terms*—Energy Harvesting (EH), Self-Healing (SH).**

I. INTRODUCTION

There is significant on going research investigating a number of alternative ways to extract energy from the environment and convert it into electrical energy for energizing low power mobile devices directly, or store it for later use. One such energy source is Radio Frequency (RF) signals.

Radio Frequency (RF) energy is transmitted from billions of radio transmitters around the world, including mobile telephones, different Base Stations (BSs), and television/ radio broadcast stations. The ability to harvest energy from RF signals, enables wireless charging of low-power devices and has positive impact on product design, usability, and reliability. These RF radiations represent a widely available source of energy if it can be effectively and efficiently harvested.

RF energy harvesting techniques have recently been considered as alternative methods to power the next generation wireless networks, especially those using low-power such as Internet of Things (IoT) objects. RF energy harvesting has been used to power remote devices. For example, RF energy has been used to power individual nodes in a wireless sensor networks [1].

RF energy sources can be categorized into two categories [2]:

• Ambient RF: This RF energy is freely available. The frequency range of ambient RF transmission is 0.2-2.4 GHz, and this includes most of the radiations from domestic appliances, e.g., Television, Bluetooth, WiFi, mobile devices, in addition to different transmitting BSs.

• Dedicated RF: This on-demand supply generally has a relatively higher power density due to directional transmission, and it is used to recharge the nodes or mobile devices that require predictable and high amount of energy. As RF Energy Harvesting (EH) from dedicated RF sources is fully controllable, it is better suited for supporting applications with Quality-of-Service (QoS) constraints. Also, the harvester of this dedicated RF energy must pay for this dedicated service.

Delivering on-demand RF energy to the mobile devices is the same as giving Energy as a Service (EaaS) to them. In the next generation networks, the operator will be able to deliver energy via RF signals to the network users or even objects (i.e., Internet of Things (IoT) objects). EaaS is a promising service that will have high demand in 5G networks due to the large number of connected devices and at anytime there will be a number of devices that their battery is starved and they need a supplementary amount of energy to survive.

Two Energy Harvesting (EH) protocols are used: time switching and power splitting. In time switching, the time slot is partitioned into an EH period and a communication period. In power splitting, however, a portion of the received signal is used for EH and the remaining signal will be used to extract the information from the received signal.

There are three EH and transmission schemes defined in the literature: 1) harvest-use-store, 2) harvest-store-use and 3) harvest-use. In the latter, the node uses the harvested energy without storing it for future use. In the harvest-use-store, the harvested energy is immediately used, then the remaining energy, if any, is stored. Finally, in harvest-store-use, the harvested energy is partially/fully stored before it is used. These three different schemes are used depending on the nature of the mobile device and the transmission requirements.

Mobile devices are now part of everyone daily life. These devices are not used only in calls or even daily communications, they are now used in sensitive applications/purposes such as wireless transactions (Samsung pay or Apple pay), home security, remotely controlling other devices and emergency calls. In certain critical situations, the mobile user cannot use his mobile device or particulary cannot initiate an emergency call due to a depleted battery, especially if the mobile user cannot charge his device using the regular wired/wireless charger. In this article, we consider the scenario of high density UEs in a small area where the users have no access to any power outlets. This scenario appears in games such as football, soccer or Olympic games where fans enter the stadium 2 or 3 hours before the game and stay there for another 2 or 3 hours.

Our proposed solution is to introduce a win-win situation where the user will be able to use his mobile device for an extended period of time and the operator will charge the mobile user for extending his battery life. The operator will offer this emergency service using a cooperative Self-healing of Users equipment by Rf Energy transfer (SURE) scheme. This scheme will depend mainly on the nearby Base Stations (BSs) and Users Equipment (UEs) where all of them will dedicate RF energy to the battery starved user in order to be able to deliver enough energy for extending the battery life.

The procedures to implement the SURE scheme is that when a certain user has a very low battery level and needg to urgently use his UE for extended time, he will send a request to the network to extend the life time of his battery. The operator will start gathering the needed information from this target UE and the surrounding UEs (the cooperative UEs only) using Minimization of Drive Test (MDT) reports [4], these reports contain number of measurements measured by the UE itself. Then, the operator will decide which BSs and which cooperative UEs will be involved in the SURE scheme.

The MDT reporting schemes have been dened in LTE Release 10 specification [5]. The release proposes to construct a data base of MDT reports from the network using Immediate or Logged MDT reporting conguration. The release proposes to construct a data base of MDT reports from the network using Immediate and/or Logged MDT reports from UEs. Following are the key features of MDT: a) The ability of the UE to include location information as part of UE radio measurement reporting b) The ability of the UE to log radio measurements during the UEs idle state. The measurements including Reference Signal Received Power (RSRP) and quality of serving BS as well as of the three strongest neighboring BSs and the Channel Quality Indicator (CQI). These information are sent by the UE in a single vector $\mathcal{V}$ as follows:

$$\mathcal{V} = [RSRP_s, RSRP_{n1}, RSRP_{n2}, RSRP_{n3}, RSRQ_s, \\ RSRQ_{n1}, RSRQ_{n2}, RSRQ_{n3}, CQI, XYZ] \quad (1)$$

where the subscripts s and n denote the serving and neighboring cells, respectively. RSRQ is the reference signal received quality and XYZ refers to the location of the UE.

The MDT report of the target UE will help the network to detect which BSs can be involved in the SURE scheme. However, the MDT reports received from the cooperative users in the area will be used to determine which UEs will heal the target UE. The target UE will also relay his UL data to one of the healing UEs in order to minimize transmission power. This relay UE is chosen such that the transmission power of the target UE is minimized compared to sending his data directly to the serving BS given that the relay UE is much closer than the serving BS.

Many existing studies focused on EH [6]–[8], while a few of them have investigated battery starved users. In [9], the authors developed a comprehensive modeling framework for a K-tier uplink cellular networks with RF energy harvesting from the concurrent cellular transmissions. They used markov chain to model the level of stored energy in each user's battery. They showed that the gain of using RF energy harvesting can be highly improved by a proper choice of the network design parameters such as receiver sensitivity at the BSs and spatial densities of the BSs.

Self-Healing (SH) is part of self organizing networks (Reader is referred to [10] for self organizing networks detailed survey). Many existing studies in self healing focus on the BSs themselves either in homogeneous or heterogeneous networks [11]–[13]. In our scheme, we focus on users that are going to detach from the network because of their depleted battery. To the best of our knowledge, this article is the first to integrate SH and EH in the same scheme (i.e., SURE scheme).

II. System Model

The key mathematical notations used for the system model and optimization problem formulation are summarized in Table I.

TABLE I: Mathematical Notations

Notation	Definition
E_h^t	harvested energy by the target UE at time slot t
E_D	target UE's DL energy at time slot t
E_U	target UE's UL energy at time slot t
E_X	target UE's circuit consumed energy
E^{target}	maximum harvested energy by the target UE
P_o^t	target UE's UL transmission power at time slot t
P_m^t	UE's UL transmission power at time slot t
P_u	cooperative UE's transmission power during the EH process
P_{max}^{SH}	upper limit for target UE's transmit power during SH process
P_{min}	minimum allowed power for the target UE
γ_m^t	SINR of UE m at time slot t
B^t	target UE's maximum battery level at time slot t
B^{max}	target UE's maximum battery level
T^{UL}	the UL duration in each time slot
T^H	the harvesting duration in each time slot
T	total number of time slots considered in the SH process
R_{min}	target UE's minimum UL data rate
ϵ_m^t	decision variable determines which UE is selected for relaying
u^t	decision variable used to terminate the EH process
ξ	EH efficiency factor of UEs
V_th	EH threshold to activate the EH circuit
ν	path loss exponent in EH transmission
r_{h_u}	radius of the EH region
K	Very large positive number
α	scaling factor

We are considering a heterogeneous network with different BSs tiers (macrocells and small cells) in addition to two UE categories which are cooperative (agreed to cooperate in the healing process) and non cooperative UEs (regular UEs without any cooperation) in which macrocells are overlaid with uniformly distributed small cells and randomly located UEs. As we can see in Fig. 1, the battery starved UE (in the center) has initiated a healing request to the network after sending his latest MDT report. The serving BS will communicate with the neighboring BSs to inform them to start the healing

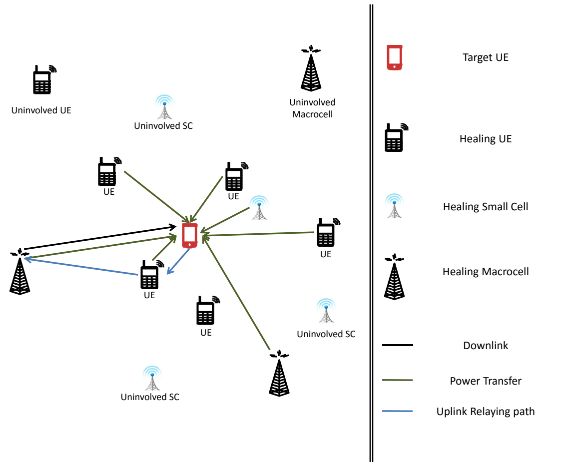

Fig. 1: Network Architecture

process. Also, the serving BS requests the MDT reports from the cooperative UEs located in the target UE's vicinity and depending on the position, compared to the target UE, and mobility, the serving BS will determine which UEs can heal the target UE. Finally, the target UE will harvest and aggregate the energy coming from all sources (different BS tiers and UEs tier). The healing process will continue until a certain metric is achieved such as threshold battery level or after the delivery of a predetermined amount of energy.

Fig. 2 shows one time slot of the target UE where the time switching technique is used so that the time slot is partitioned into tree portions to accommodate the EH period. The harvesting process is done in the first portion where the target UE first harvests from neighboring BSs and from a subset of the cooperative UEs. Then the target user begins its regular transmission with its serving BS (downlink and uplink). The downlink, as usual, is received from the serving BS. However, the uplink phase is done using relaying so that the target UE will relay its data to the nearest cooperative UE which will forward this data to the serving BS. This UL relying is implemented to minimize the uplink power consumption of the target UE.

A. *Selection Criteria*

The UEs involved in this cooperation approach must pre-register in the SURE scheme. Also, during the healing process, they must have sufficient energy in their batteries (if a cooperative UE does not have sufficient energy, it will be removed from the cooperative UE's list). Upon their cooperation and as an incentive, they are compensated by the network operator for their role in the healing process. In [3], the authors proved that cooperation schemes bring significant gains for both the operator and the cooperative users compared to a non cooperative scenario.

In SURE scheme, we introduce two selection decisions: 1) Selecting the BSs and UEs that will help the target UE to recharge its depleted battery. 2) Selecting the relay UE that will relay the target UE's UL data to minimize its battery consumption.

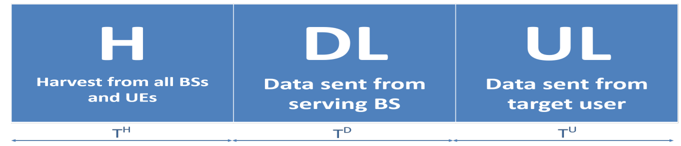

Fig. 2: Time slot partitioning

1) Selecting Cooperative UEs: The selection process can be done within the target UE's serving BS or a central control BS (i.e., macrocell). This selection process will return the BSs and UEs that are capable of transferring energy to the target UE. The cooperative BSs are chosen based on the target UE's MDT report where the three strongest neighboring BSs are chosen in addition to the serving BS (a total of four BSs).

On the other hand, the selection criteria for the cooperative UEs is totally different than that of the BSs. This is because the MDT report does not include any mutual information between the target UE and the helping UEs. However, the location of each UE is known from its MDT reports.

In order for the target UE to harvest RF energy from cooperative UEs, the input power to the target UE must exceed a predesigned threshold to activate the EH electronic circuit [14]. Thus, to harvest RF energy, the target UE received power from its nearby UEs cannot be small, which means that these UEs must be within a certain region around the target UE. This region is called the EH Region (EHR). The EHR consists of circles with radii r_{h_u} centered at each cooperative UE, where r_{h_u} is given by [15]:

$$r_{h_u} = (\xi \frac{P_u}{V_{th}})^{1/\nu} \tag{2}$$

where $\xi \in$ (0,1] is the EH efficiency factor of UE, V_{th} is the EH threshold to activate the EH circuit, and ν is the path loss exponent in EH transmission. It should be noted that the transfer distance in EHRs is generally short, which results in line-of-sight power transfer. As such, ν is not necessarily the same as the path loss exponent in data link transmission [15]. Then if the target UE falls in the EHR of any nearby UE, then this UE is chosen as a helping UE in the healing process.

This selection process is done offline because all the needed information (locations and transmission power of UEs) are known. In a real implementation of the SURE scheme scenario, the location of each UE is known from the MDT report sent to the serving BS from each UE including the target UE. Then the central BS will calculate the distances between the target UE and all UEs that are willing to cooperate.

Eq. (2) is used to check if the target UE lies within the EHR of each UE. When this condition is satisfied, this UE is added to the cooperative UE's set. This set of cooperative UEs is supposed to heal the target UE through the EH process.

2) Selecting UL Relay UE: Harvesting energy from surrounding BSs and UEs is sufficient but will not guarantee continue service and extended life time for the target UE battery. This is why we are trying here to minimize the UL transmission power of the target UE by relaying its UL data to one of the cooperative UEs. These cooperative UEs are already in the target UE vicinity. Assuming that all helping UE has enough battery level, then the selected UE relay must provide the best data rate to the target UE. Also, it will minimize the target UE's UL transmit power because the target UE will send its UL data to the best relay UE instead of sending its UL data directly to the serving BS. This selection criterion is done online and it will be discussed in detail in Section III.

B. Target UE Channel Model

The target UE has a starved battery, and for this reason the target UE relays its data in the UL via one of the cooperative UEs to communicate with the serving BS. This will minimize the target UE's energy consumption which will help extend the battery life and will effectively help in the healing process. The relay UE is chosen online to maximize the transmission rate and minimize the UL power of the target UE.

There are two types of relays; Amplify-and-forward (AF) relays which retransmit the signal without decoding while decode-and-forward (DF) relays decode the received signal, encode the signal again, and transmit. Each of these two types has its advantages and disadvantages (for more details reader is referred to [16]).

Our system model and formulation is based on the DF protocol. However, AF protocol is also applicable to our system model and formulation.

The maximum rate of the DF protocol $R_o^t(DF)$ can be expressed as:

$$R_o^t(DF) = \min(R_{m,o}^t, R_{m,d}^t) \tag{3}$$

where $R_{m,o}^t$ is the data rate of the wireless link between the target UE and the relay UE, $R_{m,d}$ is the data rate of the wireless link between the relay UE and the serving BS. The equations for these rates are given by Eqs. (4) and (5), respectively:

$$R_{m,o}^t = \frac{1}{2}\log_2(1 + \frac{P_o^t|h_{m,o}^t|^2}{N_o}) \tag{4}$$

$$R_{m,d}^t = \frac{1}{2}\log_2(1 + \frac{P_m^t|h_{m,d}^t|^2}{N_o}) \tag{5}$$

where P_o^t is the UL power of the target UE in time slot t, P_m^t is the UL power of the relay UE in time slot t, $h_{m,o}^t$ is the channel gain between the target UE and the relay UE and $h_{m,d}^t$ is the channel gain between the relay UE and the serving BS and N_o is the noise power.

Also, AF protocol can be used instead of DF protocol in this case the target UE data rate $R_o^t(AF)$ will be given as follows [17]:

$$R_o^t(AF) = \frac{1}{2}\log_2(1 + \frac{P_o^t P_m |h_{m,o}^t|^2 |h_{m,d}^t|^2}{N_o(P_o^t|h_{m,o}^t|^2 + P_m^t|h_{m,d}^t|^2 + N_o)}) \tag{6}$$

C. Energy Harvesting Model

Most of prior work assumed that the UEs can harvest the ambient energy received from all BSs. However, since wireless energy decays rapidly, as such, the received power from BSs located far away from the UE may be too low to be harvested by the UE. This can be overcome by using MDT reports to pre-determine the BSs and UEs that can effectively heal the target user.

The stored energy in the target UE's battery at the end of time slot t, denoted by B^t, is given as follows:

$$B^t = \max(0, B^{t-1} + E_h^t - E_c^t) \tag{7}$$

where B^{t-1} is the battery charge in the previous time slot, E_h^t is the harvested energy in time slot t, E_c^t is the consumed energy in the UL stage and is equal to $p_o^t T^{UL}$. The max operator used to make sure that the battery level at time t will never go to zero.

The target UE's total harvested energy during a certain time slot t E_h^t is defined as the total harvested energy from the BSs tier and from the UE tier. The E_h^t is given as follows:

$$E_h^t = T_H(\xi_1 \sum_{m=1}^{M} P_m^t |h_{m,o}|^2 + \xi_2 \sum_{k=1}^{K} P_{b_k}^t |h_{b_k,o}|^2) \tag{8}$$

where ξ_1 *and* ξ_2 are the the EH efficiency factors of UEs and BSs, respectively. P_m^t is the transmit power of the m^{th} cooperative UE. $P_{b_k}^t$ is the transmit power of the k^{th} BS depending on the type of the BS (macrocell or SC).

III. Formulating The Optimization Problem

The objective of this section is to formulate an optimization problem that will maximize the target UE's UL rate while minimizing the UL power and satisfying the energy constraints, power constraints and decision variables constraints.

A. The Objective Function

The objective function as it appears in Eq. (9) has two main terms; the fractional term which, in its numerator, maximizes the overall data rate of the target UE and, in its denominator, minimizes the total UL energy of the same UE. The second term is introduced to minimize the harvested energy. However, this minimization is constrained by achieving the target amount of energy (E^{target}) which the network operator is guaranteeing to the target UE. The objective function is given in Eq. (9).

$$\max_{\epsilon_m^t, P_o^t, u^t} \frac{\sum_{t=1}^{T}\sum_{m=1}^{M} \epsilon_m^t T^{UL} \min(R_{m,o}^t, R_{m,d}^t)}{\sum_{t=1}^{T} P_o^t \; T^{UL}} - \alpha \sum_{t=1}^{T} E_h^t u^t$$

(9)

where ϵ_i^t is a decision binary variable that is used to determine the relay UE that the target UE will depend on to relay his data to the serving BS in order to minimize his UL transmission power in each time slot t, T^{UL} is the uplink duration in each time slot, α is a scaling factor used to control the contribution of the second term to the objective function, given that $0 \leq \alpha \leq 1$, T is the total number of time slots and this number is constant within each SURE scheme, E_h^t is the harvested energy in time slot t, u_t is a decision binary variable used to terminate the EH process when the target UE harvests a certain amount of energy E^{target}.

B. Rate Constraint

A minimum rate must be guaranteed to the target UE. This rate is guaranteed because the objective function implicitly minimizes the target UE UL power. The rate constraint is given by Eq. (10)

$$\sum_{m=1}^{M} \epsilon_m^t \min(R_{m,o}^t, R_{m,d}^t) \geq R_{min} \tag{10}$$

where ϵ_m^t will equal to 0 for all m except for the relay UE where it will be equal to 1 (given that we have only one relay UE). Then, the rate between either the target UE and the relay UE or the relay UE and the serving BS must be greater than or equal to R_{min}.

C. Energy Constraints

In our optimization problem, we added two energy constraints; battery capacity constraint and energy causality constraint, as shown in the following subsections.

1) Battery Capacity Constraint: Although the target UE has a starved battery and this battery level is less than 10% of the maximum, we must guarantee that the harvested energy at each time slot plus the battery level at the previous time slot does not exceed the maximum. Referring to the time slot partitioning in Fig. 2, this constraint is considered to be evaluated after the harvesting duration and before any energy consumption either in the uplink or the downlink (considered at the boundary between T^H and T^D). This constraint is formulated as shown in Eq. (11).

$$B^{t-1} + E_h^t \leq B^{max}, \quad \forall\, t = 1, ..., T \tag{11}$$

where B^{t-1} is the target UE's battery level at the previous time slot and B^{max} is the maximum capacity of the target UE's battery.

2) Energy Causality Constraint: It is required that energy can not be consumed before it is harvested in each time slot which means that the consumed energy in uplink or downlink transmission or even consumed energy by the electronic devices must be less than or equal to the harvested energy in this time slot plus the battery charge at the previous time slot. Since the capacity of the battery is assumed to be finite,the harvested energy that can not be consumed in each slot will be stored in the battery for further use is constrained by Eq. (11). From the long term operation perspective, we obtain the energy causality constraint as shown in Eq. (12).

$$E_U^t + E_D^t + E_X \leq E_h^t + B^{t-1}, \quad \forall\, t = 1, ..., T \tag{12}$$

where E_U^t is the target UE's UL energy at time slot t, E_D^t is the target UE's DL energy at time slot t, E_X is the target UE's circuit consumed energy including energy dissipated in the electronic circuits and leakage energy.

D. Power Constraints

The power constraints in our formulation is simply an upper and lower limits on the target UE's UL power P_o^t in each time slot t. During the healing process, the upper limit of the target UE's UL power is set to P_{max}^{SH} where this limit is less than the upper limit in normal operation. This is because we are trying to minimize the power consumption of the target UE during the EH stage. Also, during the healing process the target UE relays its UL transmission to a relay UE, hence resulting in the target UE consuming much less power than sending the UL transmission directly to the serving BS, given that the relay UE is in the target UE's vicinity.

The upper and lower limits of the target UE's UL power are given in Eq. (13) and (14), respectively.

$$P_o^t \leq P_{max}^{SH}, \quad \forall\, t = 1, ..., T \tag{13}$$

$$P_o^t \geq P_{min}, \quad \forall\, t = 1, ..., T \tag{14}$$

where P_{min} is the lower limit of the target UE's UL power and this is the same during the SURE scheme or during the normal operation.

E. Decision Variables Constraints

In this formulation, we have two binary decision variables (ϵ and u^t). The former is used to choose the relay UE among the cooperative UEs. The latter is used to control the EH process. Following is a detailed explanation of the role of each decision variable.

1) Relay UE Decision Constraint: The relay UE selection is done online at each time slot t depending on which relay maximizes the target UE's rate. In each time slot, one UE is selected among the cooperative UE's to relay the target UE's data to the serving BS. This selection is done by limiting the selected UEs to only one at each time slot t using Eq. (15).

$$\sum_{m=1}^{M} \epsilon_m^t \leq 1 \tag{15}$$

Then from the objective function (Eq. (9)), it is obvious that ϵ_m^t is used to select UE m which maximizes the target UE's UL rate.

2) Energy Harvesting Decision Constraint: The target UE's battery is starved and the network operator main task is to extend the life time of this UE's battery by supplying a certain amount of energy E^{target}. The EH process is done during T time slots. There are two possibilities during these T time slots. The first possibility is that the energy supplied to the target UE is less than E^{target}. This can be due to the shortage in cooperative UEs or BSs. In this case, the operator will re-initiate the healing process for another T time slots until providing the target energy to the starved UE. The second possibility is that the operator supplied the target UE with E^{target} within T time slots. In this case and from the operator point of view, any additional supplied energy more than E^{target} is considered a waste of resources because the operator has to compensate the cooperative UEs for their exerted efforts in the healing process, in addition to the resources and energy consumed from the operator's network side. This is the motivation behind terminating the EH process after reaching a certain threshold (E^{target}).

This termination process is done with the aid of the binary decision variable u^t. This decision variable equals 1 as long as the harvested energy E_h^t did not exceed E^{target}. When it exceeds E^{target}, u^t is set to 0 and the harvesting process will terminate. Observe that when u^t goes to 0 it never goes to 1 again. This can be represented mathematically by Eqs. (16) and (17).

$$u^{t+1} \leq u^t, \quad \forall\, t = 1, ..., T \tag{16}$$

Eq. (16) is used to guarantee the following; if u^{t+1} goes to 0 it will never return back to 1 given that u^t has an initial value equals to 1. For example, if u^t equals to 1 then from Eq. (16), u^t in the following time slot ($u^t + 1$) can take the values 0 or 1. However, if u^t equals to 0 then u^{t+1} cannot take any value except 0.

Eq. (17) is used to set u^{t+1} to 0 or 1 depending on the value of accumulated harvested energy $\sum_{i=1}^{J} E_h^i u^i$ and target threshold E^{target} at each time slot. If the accumulated harvested energy is less than E^{target} then the numerator of the left hand side will be positive and given that K is a very large positive number, then this value will be between 0 and 1. Because the right hand side u^t must be greater than or equal to the right hand side, then u^{t+1} is forced to be set to 1. On the other hand, if the accumulated harvested energy is greater than E^{target} then the numerator of the right hand side will be negative and given that K is a very large number, then this value will be between -1 and 0. Because the left hand side u^t must be greater or equal the right hand side, then u^{t+1} can be set to either 0 or 1. Recalling the last term in Eq. (9), this is equivalent to minimizing u^t. Then in this case u^{t+1} will be forced by the minimization pressure to be 0 and not 1, although both of them are valid according to Eq. (17). At this point, u^{t+1} goes to 0 and it will never go back to 1 again during the remaining time slot before the whole process is terminated by the aid of Eq. (16).

$$u^{t+1} \geq \frac{E^{target} - \sum_{i=1}^{J} E_h^i u^i}{K}, \quad \forall\, t = 1, ..., T \quad \forall J = 1, ..., t \tag{17}$$

$\sum_{i=1}^{J} E_h^i u^i$ is the accumulated harvested energy at each time slot and K is a very large positive number used to limit the right hand side of Eq. (17) to be between -1 and 1.

Although u^t is a decision variable, it has limited combinations due to its special nature. Given $T = 10$ and u^t as a binary variable, then normally u^t will have 2^{10} different combinations. However, in our unique formulation (if it goes to 0 it will never go to 1 again), u^t has only 9 different combinations given that initially u^t equals to 1. For example, if E^{target} was reached in the 5^{th} time slot, then the final vector of u^t will be [1 1 1 1 1 0 0 0 0 0].

After elaborating the objective function and different categorized constraints in details, the optimization problem for SURE scheme is given by:

$$\max_{\epsilon_m^t, P_o^t, u^t} \frac{\sum_{t=1}^{T} \sum_{m=1}^{M} \epsilon_m^t T^{UL} \min(R_{m,o}^t, R_{m,d}^t)}{\sum_{t=1}^{T} P_o^t \; T^{UL}} - \alpha \sum_{t=1}^{T} E_h^t u^t$$

subject to

$$\sum_{m=1}^{M} \epsilon_m^t \min(R_{m,o}^t, R_{m,d}^t) \geq R_{min}, \quad \forall\, t = 1, ..., T,$$
$$B^{t-1} + E_h^t \leq B^{max}, \quad \forall\, t = 1, ..., T,$$
$$E_U^t + E_D^t + E_X \leq E_h^t + B^{t-1}, \quad \forall\, t = 1, ..., T,$$
$$P_o^t \leq P_{max}^{SH}, \quad \forall\, t = 1, ..., T$$
$$P_o^t \geq P_{min}, \quad \forall\, t = 1, ..., T$$
$$\sum_{m=1}^{M} \epsilon_m^t \leq 1, \quad \forall\, t = 1, ..., T$$
$$u^t \geq u^{t+1}, \quad \forall\, t = 1, ..., T$$
$$u^t \geq \frac{E^{target} - \sum_{i=1}^{J} E_h^i u^i}{K}, \quad \forall\, t = 1, ..., T, \quad \forall J = 1, ..., t$$
$$u^t \;\; \epsilon \;\; \{0, 1\}, \quad \forall\, t = 1, ..., T$$
$$\epsilon_m^t \;\; \epsilon \;\; \{0, 1\}, \quad \forall\, t = 1, ..., T, \quad \forall m = 1, ..., M$$

The formulated optimization problem is Mixed-Integer Nonlinear Programming (MINLP), non-convex and NP-hard due to the binary decision variables (ϵ_m^t and u^t) and the continues variable P_o^t in addition to the nonlinearity in the objective function and constraints.

IV. The Proposed Solutions

Nonconvex nonlinear functions as imposed by discrete variables easily lead to problems that are NP-hard in theory and computationally demanding in practice. Solving the aforementioned optimization problem is hard and this is why we will try to solve the problem heuristically. Three approaches (solvers) are used to solve this problem: 1) Basic Open-source Nonlinear Mixed Integer Programming (BONMIN) 2) Solving Constraint Integer Programs (SCIP) 3) Interior

Point OPTimizer (IPOPT). All these solvers are integrated in General Algebraic Modeling System (GAMS).

GAMS is a high-level modeling system for mathematical programming and optimization. It is designed for modeling and solving linear, nonlinear, and mixed-integer optimization problems. It consists of a language compiler and integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows to build large maintainable models that can be adapted quickly to new situations.

Both BONMIN and SCIP linearize the MINLP before solving which results in Mixed Integer Linear Problem (MILP). However, to solve the problem with IPOPT, we relax the decision variables of the MINLP resulting in Non Linear Problem (NLP).

A. Linearization of The Problem

The non-linearity of the original optimization problem appears in the objective function Eq. (9) and the rate constraint Eq. (10). Linearizing the objective function requires first eliminating the ”min” operator. To do that we will introduce a new variable R_x to the objective function and add two more constraints as shown in Eq. (18) , Eq. (19) and Eq. (20) , respectively.

$$\max_{\epsilon_m^t, P_o^t, u^t} \frac{\sum_{t=1}^{T}\sum_{m=1}^{M}\epsilon_m^t T^{UL} R_x^t}{\sum_{t=1}^{T} P_o^t\; T^{UL}} - \alpha \sum_{t=1}^{T} E_h^t u^t \tag{18}$$

$$R_x^t \leq R_{m,o}^t \tag{19}$$

$$R_x^t \leq R_{m,d}^t \tag{20}$$

The same approach will be used with the rate constraint Eq. (10) to eliminate the ”min” operator which will result in 2 new constraints. Then the linearization step is done within each solver where the logarithmic function is linearized using piecewise approximation. Following is the explanation for each linearization solver.

1) BONMIN Solver: BONMIN is an open-source solver for MINLPs [19]. BONMIN can handle MINLP models and it implements 3 different algorithms for solving MINLPs: a) B-BB (default): a simple branch-and-bound algorithm based on solving a continuous linear program at each node of the search tree and branching on integer variables which is based on spatial branch and bound sBB b) B-OA: an outer-approximation based decomposition algorithm based on iterating solving and improving of a MIP relaxation c) B-QG: an outer-approximation based branch-and-cut algorithm based on solving a continuous linear program at each node of the search tree. In our simulation, we used the first algorithm.

As BONMIN is an exact solver only for convex problems, but taking into consideration that the values of the heuristic solutions obtained using this approach are usually very close to the optimal ones.

A linearization step allows obtaining a linear programming relaxation of the main problem, which can be easily embedded in the sBB Algorithm. It is worth to mention that if the branching can be done over a binary variable or a continuous variable, the algorithm chooses the binary variable. The main difference between sBB with a usual BB algorithm for solving MILPs is that branching might occur on a continuous variable. It also uses a linear outer-approximation of the nonlinear problem for bounding purposes. The detailed description of the sBB algorithm can be found in [20].

2) SCIP Solver: SCIP includes capabilities to handle nonlinear functions that are specified via algebraic expressions. Similar to BONMIN, MINLPs are solved via an sBB algorithm using linear relaxations. The tightness of this relaxation depends heavily on the variable bounds, thus tight bounds for the nonlinear variables are crucial for SCIP. However, SCIP uses sBB based on a linear outer-approximation, which is computed by a reformulation of the MINLP [21].

B. Relaxation of The Problem

Although the linearization is done automatically inside the solver (BONMIN or SCIP), the decision variables relaxation must be done manually before solving the problem using any NLP solver. Relaxation arises by replacing the binary constraints by weaker constraints, that each variable belongs to the interval [0,1]. This relaxation will be applied to the two binary variables in our problem (ϵ_m^t and u^t) where after relaxation they will be bounded as follows:

$$0 \leq \epsilon_m^t \leq 1$$

$$0 \leq u^t \leq 1$$

After solving the relaxed NLP version of the original MINLP, the relaxed variables are rounded up to 1 or down to 0 depending on a certain threshold (0.5 in most cases) to return back to its binary nature, taking into consideration the constraints satisfaction, and then the objective function is evaluated.

1) IPOPT Solver: IPOPT is a software library for large scale nonlinear optimization of continuous systems. IPOPT implements a primal-dual interior point method, and uses line searches based on Filter methods. It tries to minimize the gap between the primal and dual solution of the NLP problem (reader is referred to [22] for more details regarding the IPOPT solver). Since IPOPT is not a MINLP solver, the relaxation and rounding are done manually before and after running IPOPT where the maual relaxation converts our original MINLP into NLP and then the rounding step is done after IPOPT returned the solution and before doing the evaluation of the objective function

V. SIMULATION RESULTS

In this section, numerical results are presented to prove the validity of the proposed SURE model to heal the energy starved users. The formulated optimization problem was

TABLE II: Simulation Parameters

Parameter	Value
Macrocell maximum power	43 dBm
SCs maximum power	30 dBm
UE max power	23 dBm
P^{SH}_{max}	20 dBm
R_{min}	20 b/s/Hz
B^{max}	40 KJ
$B^{initial}$	2 KJ
Target UE's battery charge	2.915 Ah
Target UE's battery voltage	3.82
E^{target}	8.5 KJ
E_X	50 J
Total number of macrocells	1
Total number of SCs	3
Total number of UEs	12
T	10
T^{UL}	$\frac{1}{3}$ time slot
T^{H}	$\frac{1}{3}$ time slot
N_o	-174 dBm/Hz
ξ	0.5
K	100000
α	0.01

solved using GAMS. GAMS is connected to a group of third-party optimization solvers. Among these solvers, three are used to solve our optimization problem which are: BONMIN, SCIP and IPOPT. The simulation parameters are shown in Table II.

A. Offline Cooperative UEs Selection

In our simulation model, the UEs and different types of BSs are distributed using PPP. Then the distance between the target UE and all other UEs is calculated via the central BS. Using Eq. (2), a UE is selected as a cooperative UE if the target UE lies in its EHR.

According to the locations of the UEs distributed randomly except the target UE which is located at the orgin, an average of 8 cooperative UEs are selected from a set of 12 UE. This average number of cooperative UEs is considered high due to the high density distribution of the UEs in limited space according to the proposed scenario. However, this scenario is realistic in the anticipated high dense 5G networks or in 4G networks in special high dense events such as Olympic games or football matches.

B. Online Relay UE Selection

Table III shows an example for ϵ^t_m, where m=8 and T=10, from our simulation to show that relay UE is changing from one time slot to the other. Also, a relay can be chosen in two different or successive time slots such as relay UE 1 and UE 3. A relay UE may not be chosen at anytime slot such as relay UE 4 and UE 7.

C. Harvested Energy

1) Target UE's Harvested Energy: The harvested energy during the SURE scheme depends mainly on the number of cooperative UEs and BSs. Fig. 3 shows the target UE's harvested energy versus time for different numbers of cooperative UEs and BSs. It is assumed that the target UE's battery initially holds only $5\%(2\ KJ)$ of its full battery level B^{max}. This explains why the starting point of the vertical axis is above $2\ KJ$. Also, all cooperative UEs and BSs are set to transmit using their maximum power. This configuration is used here to show the maximum energy that can be delivered to the target UE.

TABLE III: Relay UE online assignment for m=8 and T=10

ϵ^t_m	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
ϵ^t_1	0	1	0	0	0	0	0	1	0	0
ϵ^t_2	1	0	1	0	0	0	0	0	0	0
ϵ^t_3	0	0	0	0	1	1	0	0	0	0
ϵ^t_4	0	0	0	0	0	0	0	0	0	0
ϵ^t_5	0	0	0	0	0	0	1	0	1	0
ϵ^t_6	0	0	0	0	0	0	0	0	0	1
ϵ^t_7	0	0	0	0	0	0	0	0	0	0
ϵ^t_8	0	0	0	1	0	0	0	0	0	0

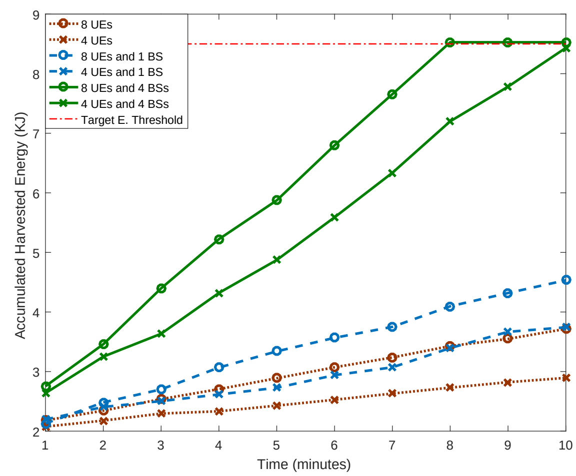

Fig. 3: Harvested Energy Versus Time

It is clear from the figure that as the number of cooperative UEs and/or BSs increases, the harvested energy increases. Because the BSs' (macrocells or small cells) transmission power is much greater than the UEs' transmission power, increasing the number of cooperative BSs (maximum k=4), the harvested energy, at the target UE, increases with higher rate than increasing the number of cooperative UEs. This appears clearly by comparing the set of green curves (k=4) with the other two sets (beside the cooperative UEs, one set has 1 BS and the other has no BSs). Moreover, For m=8 UEs and k=4 BSs, the green curve achieve the target energy threshold (E^{target}) at t=8 mins, then it remains constant because in this case the harvested energy will be greater than E^{target} and u^t will go to 0 and the harvesting process will be forced to terminate.

For (m=4 UEs and k=1 BS) and (m=8 UEs and k=0 BSs), these two curves (the intersecting blue and brown curves) give an indication that harvesting from 1 BS is equivalent to harvesting from 4 UEs, taking into consideration that the

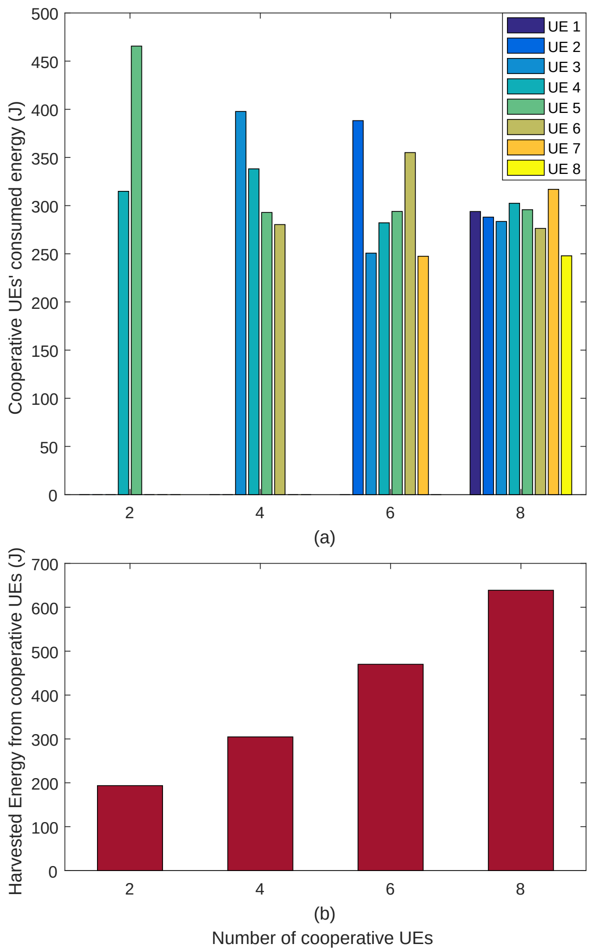

Fig. 4: (a) Cooperative UEs' consumed energy versus number of cooperative UEs (b) Target UE's harvested energy versus number of cooperative UEs

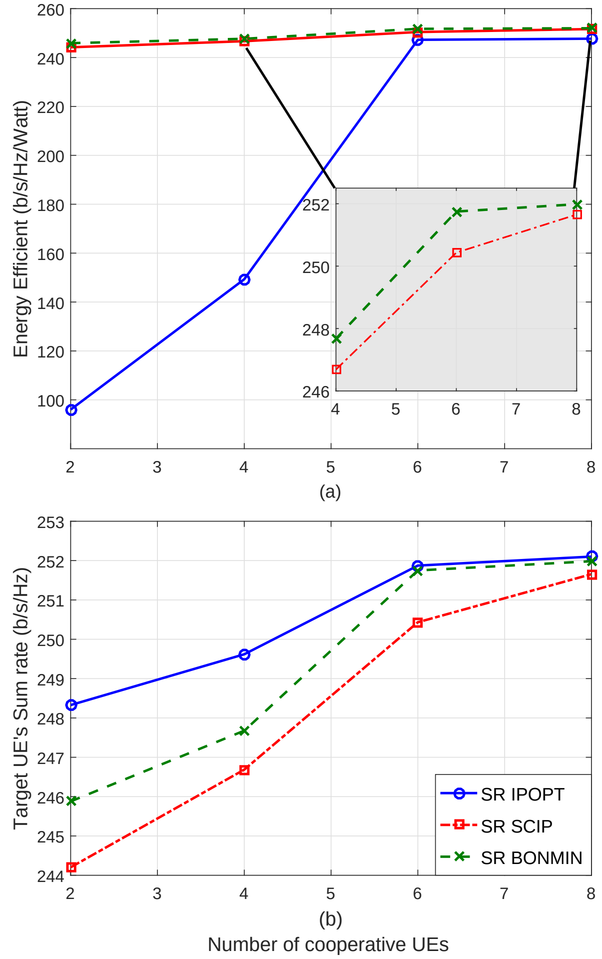

Fig. 5: (a) Target UE's energy efficient versus number of cooperative UEs (b) Target UE's sum rate versus number of cooperative UEs

cooperative UEs are much closer to the target UE than any BS. For m=8 UEs and k=0 BSs, the cooperative UEs can supply the target UE with almost double its initial battery level without the help of any BS.

2) Cooperative UEs Energy Consumption: Cooperative UEs are giving away a portion of their battery energy for being involved in the SURE scheme and in return they are rewarded/compensated from the network operator which results in a win-win situation. The operator must decide how many cooperative UEs are required to start any SURE scheme and how much energy they will give away. Fig. 4. (a) shows the consumed energy from each cooperative UE's battery when the number of cooperative UEs range from 2 to 8. As it is shown in the figure, as the number of UEs increases the consumed energy from each cooperative UE decreases. For m=8 UEs, almost all UEs have the same energy consumption. The differences in energy consumption appears from the feature that each time slot a cooperative UE is chosen to relay the target UE's UL data.

Fig. 4. (b) shows the amount of harvested energy at the target UE from the cooperative UEs only. It is obvious that as the number of cooperative UEs increases the amount of harvested energy at the target UE increases. By looking at Fig. 4. (a) and (b), we can see that having only 2 cooperative UEs is not a good choice to start the SURE scheme. At least 4 cooperative UEs are required (beside the cooperative BSs) to start the SURE scheme.

D. Energy Efficient and Sum Rate

After solving the optimization problem, the energy efficiency and sum rate equations are defined as in Eq. (21) and Eq. (22), respectively.

$$\sum_{t=1}^{T}\sum_{m=1}^{M} \epsilon_m^t \min(R_{m,o}^t, R_{m,d}^t) \tag{21}$$

$$\frac{\sum_{t=1}^{T}\sum_{m=1}^{M} \epsilon_m^t T^{UL} \min(R_{m,o}^t, R_{m,d}^t)}{\sum_{t=1}^{T} P_o^t \; T^{UL}} \tag{22}$$

where $R_{m,o}^t$ and $R_{m,d}^t$ are defined in Eq. (4) and Eq. (5), respectively, and the energy efficient equation is simply the sum rate over the total target UE's UL energy.

In Fig. 5, the sum rate and energy efficiency are presented using three different solvers; IPOPT (solving relaxed NLP), SCIP and BONMIN (both solving linearized MIP). Fig. 5. (a) shows the energy efficient versus the number of cooperative UEs. BONMIN solver has the highest values among the other two solvers (the zoomed sub figure shows that BONMIN is higher than SCIP). However, comparing BONMIN and SCIP with IPOPT shows that IPOPT has very poor energy efficiency values. This gives an indication that solving the MINLP using linearization (MIP) is much better than solving it using relaxation of the decision variables (NLP).

Fig. 5. (b) shows the target UE's UL sum rate when changing the number of cooperative UEs from 2 to 8. By increasing the number of cooperative UEs, the sum rate increases because the target UE will have more UE choices from which the target UE can choose the best UE's channel conditions to relay his UL data. Although the sum rate of IPOPT is the best among the other two solver, it has the poorest energy efficient values which indicates that the target UE's UL power is very high in this case. From Fig 5. (a) and (b) it can be inferred that BONMIN is the best solver for this problem where it has the best energy efficient values and its sum rate is higher than that of the SCIP solver.

VI. Conclusion

The growing number of wireless transmitters naturally results in increased RF power density and availability. On demand energy transfer will be universally present over an ever-increasing range of frequencies and power levels, especially in highly populated urban areas. In this article, a novel scheme named SURE proposed to heal battery starved users using on demand RF energy transfer. We formulated a MINLP optimization problem for the SURE scheme to maximize the sum rate and meanwhile minimize the UL power of the target UE. The formulated problem belongs to MINLP that is hard to solve directly. To achieve better scalability, we used three different heuristic algorithms to solve the problem named IPOPT, SCIP and BONMIN. The simulation results show that BONMIN is the best solver for this problem. Also, it is recommended that the SURE scheme starts with at least four cooperative UEs beside the cooperative BSs in order to at least charge the target UE's battery with 5% of its full capacity.

References

[1] Steven Percy, Chris Knight, Francis Cooray, Ken Smart, "Supplying the Power Requirements to a Sensor Network Using Radio Frequency Power Transfer", Sensor Network Journal, Vol. 12, no. 7, pp. 8571-8585, June 2012.

[2] D. Mishra, S. De, S. Jana, S. Basagni, K. Chowdhury and W. Heinzelman, "Smart RF energy harvesting communications: challenges and opportunities," IEEE Communications Magazine, vol. 53, no. 4, pp. 70-78, Apr. 2015.

[3] M. Tehrani, M. Uysal, H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: Challenges, solutions, and future directions", IEEE Communications Magazine, vol. 52, no. 5, pp. 86-92, May 2014.

[4] Baumann, Daniel. "Minimization of drive tests (MDT) in mobile communication networks." Proceeding zum Seminar Future Internet (FI) und Innovative Internet Technologien und Mobilkommunikation (IITM). Vol. 9, Mar. 2014.

[5] 3GPP TS 37.320, Universal Mobile Telecommunications System (UMTS); LTE; Universal Terrestrial Radio Access (UTRA) and Evolved Universal Terrestrial Radio Access (E-UTRA); Radio measurement collection for Minimization of Drive Tests (MDT); Overall description; Stage 2, 2011-04, v10.1.0 Release 10.

[6] H. Li, J. Xu, R. Zhang, and S. Cui, A general utility optimization framework for energy-harvesting-based wireless communications, IEEE Communications Magazine, vol. 53, no. 4, pp. 7985, Apr. 2015.

[7] V. Marian, B. Allard, C. Vollaire, and J. Verdier, Strategy for microwave energy harvesting from ambient field or a feeding source,IEEE Transaction on Power Electron., vol. 27, no. 11, pp. 44814491, Nov. 2012.

[8] H. Nishimoto, Y. Kawahara, and T. Asami, Prototype implementation of ambient RF energy harvesting wireless sensor networks, IEEE Sensors, pp. 12821287, Nov. 2010.

[9] A. H. Sakr and E. Hossain, "Analysis of K -Tier Uplink Cellular Networks With Ambient RF Energy Harvesting," IEEE Journal on Selected Areas in Communications, vol. 33, no. 10, pp. 2226-2238, Oct. 2015.

[10] O. G. Aliu, A. Imran, M. A. Imran and B. Evans, "A Survey of Self Organisation in Future Cellular Networks," IEEE Communications Surveys and Tutorials, vol. 15, no. 1, pp. 336-361, First Quarter 2013.

[11] O. Onireti, A. Zoha, J. Moysen, A. Imran, L. Giupponi, M. Imran, A. Abu Dayya, "A Cell Outage Management Framework for Dense Heterogeneous Networks," IEEE Transactions on Vehicular Technology, vol. 65, no. 4, pp. 2097-2113, May 2015.

[12] M. Selim, A. E. Kamal, K. Elsayed, H. M. Abdel-Atty and M. Alnuem, "Fronthaul cell outage compensation for 5G networks," IEEE Communications Magazine, vol. 54, no. 8, pp. 169-175, Aug. 2016.

[13] W. Wang, Q. Zhang, "Local cooperation architecture for self-healing femtocell networks," IEEE Wireless Communications Magazine, vol. 21, no. 2, pp. 42-49, Apr. 2014.

[14] T. Le, K. Mayaram and T. Fiez, "Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks," IEEE Journal of Solid-State Circuits, vol. 43, no. 5, pp. 1287-1302, May 2008.

[15] H. H. Yang, J. Lee and T. Q. S. Quek, "Heterogeneous Cellular Network With Energy Harvesting-Based D2D Communication," IEEE Transactions on Wireless Communications, vol. 15, no. 2, pp. 1406-1419, Feb. 2016.

[16] A. Bou Saleh, S. Redana, B. Raaf, T. Riihonen, J. Hamalainen and R. Wichman, "Performance of Amplify-and-Forward and Decode-and-Forward Relays in LTE-Advanced," in Proc. of the 70th IEEE Vehicular Technology Conference (VTC Fall), Anchorage, Alaska, USA Sept. 2009, pp. 1-5.

[17] X. Ji, W. P. Zhu and D. Massicotte, "Transmit Power Minimization for Two-Way Amplify-and-Forward Relaying With Asymmetric Traffic Requirements," IEEE Transactions on Vehicular Technology, vol. 65, no. 12, pp. 9687-9702, Dec. 2016.

[18] S.Hmlnen, H.Sanneck, andC.Sartori, LTESelf-Organising Networks (SON): Network Management Automation for Operational Efciency. Hoboken, NJ, USA: Wiley, 2012.

[19] https://projects.coin-or.org/Bonmin "last access 01.06.2017"

[20] P. Belotti, J. Lee, L. Liberti, F. Margot and A. Wchter, "Branching and bound tightening techniques for nonconvex MINLPs", Optimization Methods and Software vol. 24, pp. 597-634, 2009.

[21] Stefan Vigerske, Ambros Gleixner, "SCIP: Global Optimization of Mixed-Integer Nonlinear Programs in a Branch-and-Cut Framework", ZIB-Report, Takustr.7, 14195 Berlin, Aug. 2016.

[22] http://web.mit.edu/ipopt_v3.11.6/doc/documentation.pdf "last access 01.06.2017".