Efficient Data and Energy Transfer in IoT with a Mobile Cognitive Base Station

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***Abstract*—In this paper, we consider a mobile cognitive base station (MB) to transfer data and energy to IoT devices. The MB receives requests for data and energy from the cluster heads of the IoT devices, then it adjusts its transmission power and location to transfer data and energy to the IoT devices. The goal is to support data and energy demands of IoT devices within a certain time to guarantee a certain quality of service while minimizing the total energy consumption. We consider the energy consumption due to the mobility of the MB in addition to the energy consumed for data and energy consumption. The MB operates underlaying a primary network, and hence, the MB adjusts its transmission power and location such that the primary users are protected from harmful interference. We developed a mathematical model to solve the problem and find the optimal locations and transmission powers that minimize the total energy consumption. Simulation results show how the IoT devices, the primary users, the number of the MB locations, service time and the mobility of the MB influence the total energy consumption. We show that increasing the number of the MB locations and the maximum tolerable time for delivering data and energy allow the MB to provision the service while reducing the total energy consumption.**

***Index Terms*—energy minimization, IoT, Mobile base station, moving base station, cognitive base station, energy transfer.**

I. INTRODUCTION

The Internet of Things (IoT) is an emerging technology that enables physical objects to be connected through the internet to collect and exchange data [1]. IoT facilitates the interconnection between devices and transforms them to smart objects. This transformation opens a new era of disruptive innovations that enhances the quality of life. Although the IoT is a promising technology, we need to overcome several challenges for a successful implementation of its applications.

Energy harvesting has emerged as an efficient method for achieving a sustainable energy source for IoT devices. The energy can be harvested from renewable sources like sunlight, heat, wind, and waves. However, these sources may not be effective for some IoT applications due to the limitations on their availability on certain locations and during certain times and the size of the energy harvesters. Therefore, Radio Frequency (RF) energy transfer is considered as an alternative method for charging wireless networks devices [2]. It is shown that RF energy harvesting is more suitable for IoT applications due to the fact that the energy can be transmitted wirelessly in the form of RF signal, low cost of implementation and small form factor implementation [3].

With the rapid increase in the IoT applications, more spectrum is needed to accommodate the users' demands. It is shown in [4] that some portions of the spectrum are crowded, whereas some portions are underutilized in some locations and during certain times. Cognitive radio is a promising technology that can be used to alleviate the problem of spectrum scarcity while utilizing the precious radio spectrum and supporting more demands [4]. In this paper, we propose the use of a mobile cognitive base stations (MB) to transfer data and energy to the IoT devices underlaying a primary network. The IoT devices send their requests for data and energy demands to cluster heads, then the cluster heads forward these requests to the MB. Once the MB receives the requests, the MB reacts accordingly to support the IoT devices with their data and energy demands.

The deployment of IoT devices outside urban area can be challenging if access to the internet and energy source are limited or not available. A typical application of the proposed MB is to charge batteries of IoT devices when replacing the batteries is hard or impossible. Another application of the proposed scheme is an MB transferring data updates to a group of isolated IoT devices where they are most likely to be isolated from the outside world due to the cost of using base stations or failure of the sink nodes [5]. Moreover, the MB can be utilized to transmit data that controls the operation of isolated actuators (which are IoT devices). For example, isolated actuators that control the operation of a remote farm can receive data from the MB to control the irrigation and other tasks according to most recent whether forecast information received from the MB.

Many works have been proposed to use mobile base stations in Wireless Sensor Networks (WSN) to collect data [6] and prolong the lifetime of network [7], [8]. Moreover, mobile base stations can be used to transfer energy to the sensors. In [7] and [9], mobile wireless chargers are designed to charge sensors node in WSN. In [10], the authors proposed the use of a mobile energy gateway which receives energy from a fixed charger before starting its charging tour. The authors in [11] jointly considered charging tour planning and depot positioning to charge the sensors in a large scale WSN using a mobile charger. In [12], the authors proposed a framework of energy replenishment to the sensors and anchor-based mobile data gathering in WSN.

The main contributions of this paper are as follows. We developed a mathematical model for data and energy transfer to the IoT devices using a mobile and cognitive base station. The MB operates underlaying a primary network; hence, the MB keeps its interference to the primary users below a certain threshold. Therefore, the MB optimizes its locations and transmission powers such that the primary users are protected and do not incur harmful interference. Moreover, the locations and the transmission powers of the MB are adjusted to minimize the total energy consumed for the mobility of the MB and transferring data and energy to the IoT devices. To guarantee a cretin quality of service for the IoT devices, the MB serves the IoT devices within a certain period. Hence, the MB adjusts its movement speed such that the demands are satisfied within a tolerable time and the energy consumed by the movement is reduced.

The rest of the paper is organized as follows. We describe the system model in Section II, then we formulate the mathematical model to optimize energy consumption used to transfer data and charge the IoT devices in Section III. In Section IV, we present the simulation results, and we conclude our paper in Section V.

II. SYSTEM MODEL

We consider in this paper a mobile base stations (MB), which supports energy and data demands for a set of fixed IoT devices, U. We assume that each IoT device is equipped with a single radio, and it uses time switched energy harvesting and data reception, i.e., the received signal from the MB can either be used to receive data or harvest energy. Moreover, we assume that the PUs and the IoT devices use omnidirectional antennas, and the MB utilizes directional antennas for data and energy transmission. The MB transfers data and energy underlaying a primary network. Hence, the MB keeps its interference to the primary users below a certain threshold to protect them from harmful interference. To guarantee a ceratin quality of service requirement, the MB transfers the required energy and data to all users within a duration T. The duration of each time slot is τ, and the total number of slots to support the required demands is $\lceil T/\tau \rceil$.

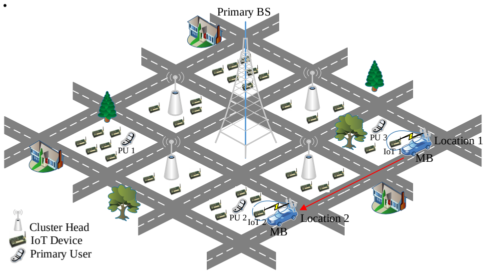


Fig. 1: A mobile cognitive base station (MB) transfers data and energy to IoT devices.

Fig. 1 shows the proposed MB transferring data and energy to a set of IoT devices. The IoT devices request their data and energy demands through cluster heads, then the cluster heads transfer the requests to the MB. Once the MB receives the demand requests, it moves to certain locations to transfer data and energy such that the demands are satisfied within a certain period of time. Since the MB operates underlaying a primary network, the MB adjusts its location and transmission power such that the primary users (PUs) within the signal range are protected.

Fig. 2 shows a scenario of the MB when its transmission from location 1 causes interference to PU 3. To avoid causing this interference, the MB adjusts it location by moving to location 3 and transmits to IoT 1 as shown in Fig. 3. Adjusting the location of the MB, the direction of the beam and the transmission power give the MB more flexibility in transferring data and energy while protecting the PUs.

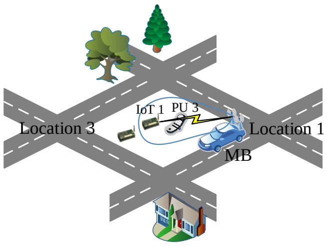


Fig. 2: The MB causes interference to PU 3.

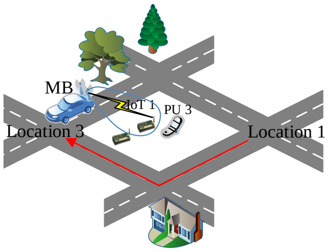


Fig. 3: The MB adjusts its location to avoid interfering with PU 3.

Let z be the index of the z^{th} location that the MB can move to, and Z be the set of all these indices. The Euclidean distance between the j^{th} IoT device, U_j, and the MB when it is located at location z is given by

$$d_{zL_j} = \left| z - L_j \right| \tag{1}$$

where L_j is the location of U_j. The gain of the channel between the MB when it is located at location z and U_j, G_{zL_j}, is given by

$$G_{zL_j} = \delta \; \alpha \; \beta A_t \; A_r \; D_{zL_j}^{-\zeta} \tag{2}$$

where α is the coefficient of fast fading due to multi-path propagation and β is the coefficient of slow fading due to shadowing, δ is the path loss constant and ζ is the path loss exponent, A_t and A_r are transmitting and receiving antenna gains, respectively, and D_{zL_j} is the distance between location z and location L_j. Similarly, the channel gain between primary user k and U_j is given by

$$g_{kj} = \delta \; \alpha \; \beta \; A_t \; A_r \; d_{kj}^{-\zeta} \tag{3}$$

where d_{kj} is the distance between primary user k and U_j. The gain of many practical directional antennas is approximated by [13]

$$A_t \approx \frac{30,000}{\theta \; \phi}. \tag{4}$$

where θ and ϕ are azimuth and elevation angles in degree, respectively.

The harvested energy $E_j^H(t)$ by U_j from the MB during slot t is defined as follows:

$$E_j^H(t) = \sum_{z \in Z} \eta^h \; \tau \; P_j(t) \; G_{zL_j} \; w_{zj}^h(t) \; \gamma_z(t). \tag{5}$$

where η^h is the energy harvesting efficiency factor, $w_{zj}^h(t)$ is a binary variable representing the beamforms of energy transmission from the MB to U_j, when the MB is located at location z during slot t, and $P_j(t)$ is the transmission power of the transmitted signal from the MB to U_j during slot t and the maximum transmission power is P^{max}. $\gamma_z(t)$ is a binary variable defined as follows:

$$\gamma_z(t) = \begin{cases} 1 & \text{If the MB is located at the } z^{th} \text{ location} \\ & \text{during slot } t. \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

The date rate of the down link between the MB and U_j during slot t is given by

$$R_j(t) = W \log_2 \left(1 + SINR_j(t)\right). \tag{7}$$

where W is the channel bandwidth and $SINR_j(t)$ is the signal to noise plus interference ratio for the signal transmitted by the MB to U_j during slot t $SINR_j(t)$ is given by

$$SINR_j(t) = \frac{\sum_{z\in Z} P_j(t)\; G_{zL_j}\; w^d_{zj}(t)\; \gamma_z(t)}{N_0 W + \sum\limits_{k\in PU^{tx}} P^k\, g_{kj}} \tag{8}$$

where P^k is the transmission power of primary user k, N_0 is the noise spectral density and $w^d_{zj}(t)$ is a binary variable representing the beamforms of data transmission from the MB to U_j, when the MB is located at location z during slot t.

Each IoT device U_j requests a Data Demand (DD_i) and/ or Energy Demand (ED_i), and the MB should support the demands of all IoT devices within a certain time, T. Let $UDD_j(t)$ and $UED_j(t)$ be the unsatisfied data and energy demands for U_j until slot t, respectively. $UDD_j(t)$ and $UED_j(t)$ are given, respectively, by

$$UDD_j(t) = \; UDD_j(t-1) - R_j(t)\; \tau \tag{9}$$

and

$$UED_j(t) = \; UED_j(t) - E^H_j(t) \tag{10}$$

where $UDD_j(1) = DD_j$ and $UED_j(1) = ED_j$.

The waiting time of U_j for data and energy transfer services, T^w_j is given by

$$T^w_j = \sum_{t=1}^{\lceil T/\tau \rceil} \tau\; V_j(t), \tag{11}$$

where $V_j(t)$ is a binary variable defined as follows:

$$V_j(t) = \begin{cases} 0 & \text{If } UDD_j(t) \le 0 \text{ and } UED_j(t) \le 0. \\ 1, & \text{otherwise.} \end{cases} \tag{12}$$

We assume in this paper that the MB is a base station attached to an electric vehicle. There are several factors affecting the total energy consumed by the electric vehicle including the movement speed and the travelled distance. The total power at the wheel of the electric vehicle during slot t is given by [16]

$$\begin{aligned} P_{Wheels}(t) = \big[& m\; a(t) + m\; v\; \cos(\Theta)\; \frac{C_r}{1000}\big(c_1\; S(t) + c_2\big) \\ &+ \frac{1}{2}\; \rho_{Air}\; f_A\; C_D\; S(t)^2 + m\; v\; \sin(\Theta)\big]\; S(t) \end{aligned} \tag{13}$$

where m is the vehicle mass, $a(t)$ is the acceleration of the vehicle during slot t, v is the gravitational acceleration, Θ is road grade, C_r, c_1 and c_2 are the rolling resistance parameters which depend on the road type and condition and the vehicle type, $S(t)$ is the MB speed during slot t, which is upper bounded by S^{max}, ρ_{Air} is the air mass density, f_A is the area of the vehicle front, C_D is the aerodynamic drag coefficient. After calculating the power at the wheels, we can find the power at the electric motor as follows:

$$P_{ElectricMotor}(t) = \frac{P_{Wheels}(t)}{\eta_{\text{Driveline}}\; \eta_{\text{Electric Motor}}} \tag{14}$$

where $\eta_{\text{Driveline}}$ and $\eta_{\text{Electric Motor}}$ are the efficiency of the driveline and the electric motor, respectively. Hence, the cost of the MB movement during slot t is given by

$$Q(t) = P_{ElectricMotor}(t)\; \tau. \tag{15}$$

III. PROBLEM FORMULATION

Let $\gamma_z(t)$ be a binary variable that equals to one only if the MB is located at z^{th} location during slot t. Since the MB can be located only at one location at a certain time, we have

$$\sum_{z\in Z} \gamma_z(t) = 1, \quad 1 \le \; t \le \lceil T/\tau \rceil. \tag{16}$$

We assume that the IoT devices use time switching energy harvesting and data reception. Hence, the IoT device cannot both receive data and harvest energy during one time slot. Therefore,

$$w^d_{zj}(t) + w^h_{zj}(t) \le 1, \quad \forall j \in U, 1\; t \le z \le |Z|, 1\; t \le \lceil T/\tau \rceil. \tag{17}$$

To receive data from an MB, the received signal is lower bounded by a threshold, μ^d, as follows:

$$\begin{gathered} \mu^d\; P_j(t) \le \frac{P_j(t)^2\; \sum_{z\in Z} G_{zL_j}\; w^d_{zj}(t)\; \gamma_z(t)}{N_0 W + \sum\limits_{k\in PU^{tx}} P^k\, g_{kj}}, \\ \forall j \in U, 1 \le z \le |Z|, 1 \le t \le \lceil T/\tau \rceil. \end{gathered} \tag{18}$$

In the above constraint, both sides are multiplied by $P_j(t)$ to enforce the constraint only if $0 < P_j(t)$. Similarly, the received signal used for harvesting energy is lower bounded by a threshold, μ^h, as follows:

$$\begin{gathered} \mu^h\; P_j(t) \le P_j(t)^2 \sum_{z\in Z} G_{zL_j}\; w^h_{zj}(t)\; \gamma_z(t), \\ \forall j \in U, 1 \le z \le |Z|, 1 \le t \le \lceil T/\tau \rceil. \end{gathered} \tag{19}$$

To satisfy the data demand for U_j, we have the following constraint:

$$DD_j \le \tau \sum_{t=1}^{\lceil T/\tau \rceil} R_j(t), \; \forall j \in U. \tag{20}$$

Moreover, the total energy demand is upper bounded by the total energy that can be harvested, i.e.,

$$ED_j \le \sum_{t=1}^{\lceil T/\tau \rceil} E^H_j(t), \quad \forall j \in U. \tag{21}$$

The total energy transferred by the MB cannot exceed its initial battery level, BL^{init}. Hence,

$$\begin{aligned} &\sum_{t=2}^{\lceil T/\tau \rceil} \sum_{q\in Z} \sum_{r\in Z} \gamma_q(t)\; \gamma_r(t-1)\; D_{qr}\; Q(t-1) + \\ &\sum_{t=1}^{\lceil T/\tau \rceil} \sum_{j\in U} \tau\; P_j(t) \le BL^{init}. \end{aligned} \tag{22}$$

Since the traveled distance by the MB cannot go beyond its speed, we have

$$\sum_{q\in Z} \sum_{r\in Z} \gamma_q(t)\; \gamma_r(t-1)\; D_{qr} \le S(t-1)\; \tau, \quad 1 < t \le \lceil T/\tau \rceil. \tag{23}$$

For two IoT devices located within one direction to the MB, we have the following constraint to ensure a successful data reception using directional antennas:

$$w_{zq}^d(t) + w_{zr}^d(t) \leq 1 + \Gamma_{z,q,r}, \quad \forall q,r \in U, 1\ t \leq \lceil T/\tau \rceil, 1 \leq z \leq |Z|. \tag{24}$$

where $\Gamma_{z,q,r}$ is a binary variable given by

$$\Gamma_{z,q,r} = \begin{cases} 0 & \text{If the MB is located at the } z^{th} \text{ location and node } r \text{ is located within the direction of the beam of the transmission from the MB to node } q. \\ 1, & \text{otherwise.} \end{cases} \tag{25}$$

To protect the date reception of the primary users, the total interference caused by the MB must remain under a certain threshold, i.e.,

$$\sum_{z \in Z} \sum_{j \in U} P_j(t) G_{zL_k} (w_{zj}^d(t) + w_{zj}^h(t)) \gamma_z(t)(1 - \Gamma_{z,j,k}) < \lambda^k, \quad \forall k \in PU^r, 1 \leq t \leq \lceil T/\tau \rceil. \tag{26}$$

where λ^k is a threshold for the interference to the primary user k. To satisfy a certain quality of service, the waiting time for each U_j must be less than or equals to T, i.e.

$$0 \leq T_j^w \leq T, \quad \forall j \in U. \tag{27}$$

The total energy consumed by the MB for transmitting data and energy to all IoT devices is given by

$$E^{Tx} = \tau \sum_{j \in U} \sum_{t=1}^{\lceil T/\tau \rceil} P_j(t). \tag{28}$$

We consider the total energy consumed by the MB due to its mobility, which is given by

$$E^{Mo} = \sum_{t=2}^{\lceil T/\tau \rceil} \sum_{q \in Z} \sum_{r \in Z} \gamma_q(t)\ \gamma_r(t-1)\ D_{qr}\ Q(t-1). \tag{29}$$

Our main objective is to minimize the total energy consumed for data and energy transfer (E^{Tx}) and mobility (E^{Mo}). Therefore, we formulate our optimization problem as follows:

$$\textbf{Minimize} : E^{Tx} + E^{Mo} \tag{30}$$

Subject to: Constraints (17-27)

$$0 \leq P_j(t) \leq P^{max}, \quad \forall j \in U, 1 \leq t \leq \lceil T/\tau \rceil. \tag{31}$$

$$0 \leq S(t) \leq S^{max}, 1 \leq t \leq \lceil T/\tau \rceil. \tag{32}$$

$$\gamma_{zj}(t) \in \{0,1\}, \quad \forall j \in U, 1 \leq z \leq |Z|, 1 < t \leq \lceil T/\tau \rceil. \tag{33}$$

$$w_{zj}^d(t), w_{zj}^h(t) \in \{0,1\}, \forall j \in U, 1 \leq z \leq |Z|, 1 \leq z \leq |Z|. \tag{34}$$

$$V_j(t) \in \{0,1\}, \quad \forall j \in U, 1 \leq t \leq \lceil T/\tau \rceil. \tag{35}$$

IV. Simulation Results

We consider in the simulation a moving base station 13 IoT devices and 10 PUs pairs distributed over a 500 m by 500 m area. The energy and data demands for each IoT device are 10 Joule and 10 Mbits, respectively. The MB moves close to the IoT devices, then it transfers data and energy to support the requested demands. The selected locations are determined by the above optimization problem to minimize total energy consumption. We used General Algebraic Modeling System (GAMS) [14] with Couenne solver [15] to calculate the optimal solution of the optimization problem. The multipath fading is exponentially distributed with unit mean and the shadowing is log-normal distributed with standard deviation of 8 dB.

The MB is a base station attached to a moving vehicle, and can move to certain locations to transfer data and energy to the IoT devices. The moving vehicle is an electric vehicle, and we used in our simulation the parameters associated with Nissan Leaf electric vehicle [16]. Table I shows the rest of the parameters used in the simulation.

TABLE I: Simulation Parameters

Parameter	Value	Parameter	Value
δ	10^{-2}	μ^d	-60 dBm
ζ	2	μ^h	-10 dBm
A_r	1	m	1521 kg
θ	15°	v	9.8066 m/s^2
ϕ	20°	Θ	0
η^h	0.6	C_r	1.75
τ	60 seconds	c_1	0.0328
W	6 MHz	c_2	4.575
N_0	-174 dbm/Hz	C_D	0.28
P^k	0.1 W.	ρ_{Air}	1.2256 kg/m^3
P^{max}	1 W.	f_A	2.3316 m^2
S^{max}	30 m/s.	η^h	0.6
T	5, 8 and 10 slots.	η Driveline	0.92
BL^{init}	30 kWh.	η Electric Motor	0.91

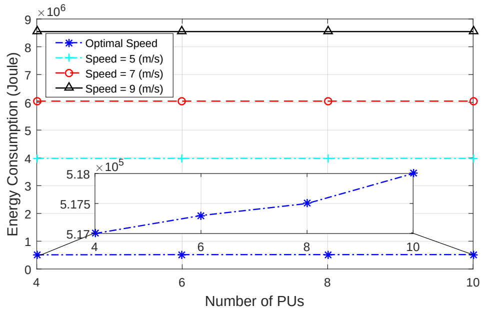
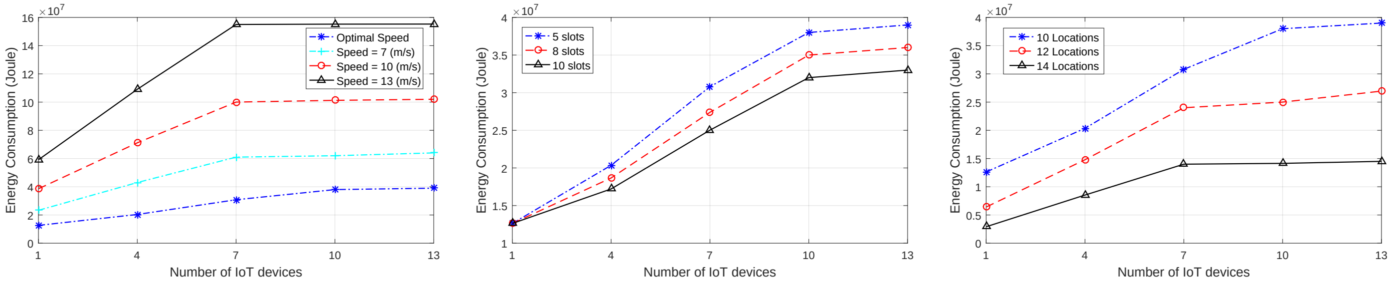


Fig. 4. The effect of PUs on the total energy consumption.

Figure 4 shows the total energy consumption when the number of PUs increases. The energy consumption is calculated for the MB when it can move to 16 locations in 100 m × 100 m area to serve 5 IoT devices. Increasing the number of PUs increases the chance of the MB movement since the MB may adjust its location to avoid causing harmful interference to the PU while transmitting to the IoT devices. Therefore, it is shown in Figure 4 that increasing the number of PUs increases the total energy consumption for the optimal solution. On the other hand, moving with non-optimal speeds increases the total energy consumption significantly. It is also shown that the effect



(a) (b) (c)

Fig. 5: The effect of (a) PUs, (b) the required time slots and (c) the number of locations on the total energy consumption.

of moving with non-optimal speeds on energy consumption dominate the effect of increasing the number of PUs.

Figure 5 (a) shows the total energy consumption when the number of IoT devices increases. Since supporting more IoT devices increases the possibility of the MB movement, the MB consumes more energy when it serves more IoT devices. Increasing the number of IoT devices increases energy consumption rapidly when the number of served IoT devices is small, and it increases slightly when the number of served IoT devices is large. The reason behind this behavior is that the MB has more chance to adjust its locations to serve more neighboring users with less mobility when the number of served IoT devices is larger. It is shown in Figure 5 (a) that the MB consumes more energy when it moves with a higher and constant speed. Since the demands for data and energy needed to be satisfied within a certain time, the MB adjusts its movement speed and transmission power accordingly. Therefore, the MB optimizes its movement speed dynamically to transfer data and energy within the tolerable time while minimizing energy consumption.

Figure 5 (b) shows the total energy consumption when the numbers of IoT devices and time slots increase. It is shown that the MB consumes more energy when the maximum time for delivering data and energy (T) is shorter. The IoT devices that tolerate more delay gives the MB more freedom to deliver data and energy over more time slots. The energy consumed for the MB movement dominates the total energy consumption. Hence, the MB may choose to transmit data and energy with lower transmission powers and over a longer period of time instead of moving closer to the destination and finishing the data and energy transfer faster. Therefore, allowing the MB to deliver data and energy over larger period of time may lead to more energy saving.

The effect of the number of locations on the total energy consumption is shown in Figure 5 (c). Increasing the number of locations that the MB can move to in order to transfer data and energy may lead to a reduction in energy consumption. The reason is that having more locations allows the MB to move closer to the destinations and transmits with a lower power and optimize its location to serve more IoT devices while reducing its movement.

V. CONCLUSION

In this paper, we consider a mobile base station that supports a group of fixed users with data and energy demands. The MB is required to transfer data and energy demands to all users within a cretin time. The objective is to minimize the energy consumed by MB in mobility and data and energy transfer. To improve the quality of the service for the users, the data and energy service waiting time needs to be minimized. Therefore, we formulated an optimization problem which optimizes the MB locations and transmission powers to achieve the desired goal. The simulation results showed that the number of IoT devices, PUs and locations of the MB, the tolerable time for delivering the data and energy to the IoT devices and the movement speed of the MB can impact the total energy consumption. Therefore, the location, speed and transmission power of the MB are adjusted to optimize the total energy consumption. We showed that more time slots and locations for the MB leads to more reduction in total energy consumption.

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