Efficient Energy Transport in 60 Ghz for Wireless Industrial Sensor Networks

Efficient Energy Transport with 60 GHz for Wireless Industrial Sensor Networks

He Li, *Member, IEEE*, Kaoru Ota, *Member, IEEE*, Mianxiong Dong, *Member, IEEE*

***Abstract*—Radio-frequency (RF) energy transport is a viable technology to power small-sized sensors in Wireless Industrial Sensor Networks (WISN). 60 GHz wireless communication is the leading technology for next generation wireless networks and a potential technology to build WISNs. In this article, we focus on the efficiency of RF energy transport in WISNs with 60 GHz communications. We also present an antenna sphere with the supported analytics of the directional antenna in 60 GHz wireless communication. We describe and solve the spherical distribution problem of the directional antenna to maximize the efficiency of energy transport in the WISNs. Based on our extensive simulations, the antenna distribution performs better than other solutions in given WISN environment.**

***Index Terms*—Industrial Sensor Networks, Energy Harvesting, 60 GHz**

I. Introduction

Wireless RF energy transport is a feasible method to provide energy for the small-sized devices. Generally, RF energy transmission includes far-field RF transmission, inductive RF energy transmission [1] and non-radiative RF energy transmission [2]. In wireless sensor networks (WSN), people use far-field RF energy transmission to power sensors. Thus, in this energy transmission, there are two methods to get energy: the first, referred to RF energy harvesting, uses ambient RF energy as a source while the second, RF energy transport, uses a dedicated RF source [3]. Since WISN are usually isolated through external radio waves, RF energy transport is a possible way for energy transmission in this environment [4].

In WISNs, researchers and companies have proposed solutions for wireless RF energy transport to power industrial sensors [5][6][7]. A simple method is adding an RF energy receiving module in each sensor for harvesting energy from wireless signals [8]. The drawback challenge here is that energy efficiency is not sufficient when using the same frequency for both energy transport and signal transmission. The popular frequency for energy transport is 915 MHz while WIFI frequency is 2.4 GHz. Since a single wireless module cannot support a broad range of operating frequencies, different antennas and modules are needed to support these two wireless frequencies.

A possible solution is dividing the energy transport and signal transmission. In some commercial systems, with the general WIFI access point, a specific device for wireless RF energy transport is deployed for sending energy to sensors. For example, in a typical battery-free sensor system, except the general wireless access points with omnidirectional antennas, a specifically designed energy transport device is deployed with one or more wide beam directional panel antenna working at the frequency of 915 MHz [9]. Although it is convenient to separate frequency bands for energy transport and communication, the additional energy transport devices adds more cost to this solution. Another problem is that an access point cannot be determine when energy transport phase for scheduling the energy assignment.

A potential way is to use the same frequency with a single device for both network communications and energy transport. From some previous work, the energy transport efficiency can be improved by optimizing the design of the antenna for focusing energy in wireless waves. Generally, multiple directional antennas perform better than omnidirectional antennas in RF directional energy transport. However, directional antennas need higher frequency band for improved directivity. However, with general antennas and devices, the wireless Ethernet uses the 2.4 GHz or 5 GHz band which is not enough for focusing wireless waves in RF energy transport.

Extremely high frequency communications, especially 60 GHz communications, will play very important roles in future industrial sensor networks [10]. Since the frequency band becomes extremely high, the size of antenna for 60 GHz communications becomes much smaller than general wireless communication with better directivity. Furthermore, since it is difficult to work in non-line-of-sight (NLOS) environment with extremely high frequency communications, existing 60 GHz networks usually use directional communication with some reflection optimization. In this environment, narrow beam directional energy transport can perform better than omnidirectional or wide beam directional ways. As a result, we focus on the narrow beam RF directional energy transport with 60 GHz in WISN environment.

In this article, we first discuss the antennas design and energy transport efficiency with the 60 GHz communication technology. We calculate the received energy with the horn antenna which is a popular type of antennas working at 60 GHz. With the discussion, we find it is possible to deploy horn antennas for both network communication and energy transport. Thus, for covering all sensors in the WISN, we present an antenna sphere model to use multiple antennas distributed on a sphere. With this model, we state the problem which attempts to minimize the transmitted energy for power all sensors in a given WISN. To solve this problem, we design an equivalence transformation that simply the antenna distribution as an ellipse covering problem. After that, we compare the energy transport efficiency of the directional 60 GHz RF energy transport to the omnidirectional and general

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915 MHz solutions.

The remainder of this paper is organized as follows. Section II introduces the WISN environment and the 60 GHz communication technology. Section III analyzes the efficiency of RF energy transport with a single antenna. Section IV try to optimal an antenna distribution to maximize energy transport efficiency. Section V evaluate the RF energy transport performance through extensive simulations. Finally, this paper is concluded Section VI.

II. WISNs and 60 GHz Communications

In this section, we first brief the environment of WISNs. Then, we discuss the 60 GHz communication technologies.

A. WISN

WISNs are useful for factory automation involving a variety of applications (e.g., industrial process control and machine maintenance) [11]. For example, machine vision is an application of computer vision for industrial process control and WISNs can replace I/O devices and control networks of machine vision. Through WISN, machine vision can detect product defects then improve the quality of manufacturing [12].

For better understanding of a typical WISN, we introduce an example shown in Fig. 1. Similar to general sensor networks, industrial sensor networks also include three types of devices, namely, sink, aggregators and sensors. Sensors collect information data from machines and environment then send it to the aggregators. Usually, for a single machine, there are several sensors with one aggregator. To connect sensors and aggregators together, some popular wireless protocols (e.g., Zigbee, ISA-100.11a, WiFi, and Bluetooth) are deployed in the devices. For the energy supplement, except using battery or the power grid, some researchers and companies provide energy harvesting and transport solutions.

Aggregators are usually used for collecting and buffering data from sensors and transferring data to the sink node. In selected systems, these devices equip larger storage space and more powerful processors than general sensors while in other systems, aggregators and sensors have the same hardware settings. In the former type, aggregators usually use higher performance network for the communications with the sink nodes while in the latter, all devices use the same network protocol. As a result, with higher power supplement, the aggregators in the former environment cost more energy. Another important function of aggregators is the sensor management that sensing applications and modules are deployed through aggregators.

The sink node plays a bridge between the control node and WISN. Usually, the sink node has stable energy supplement from the power grid and has wired or stable wireless network connection with the terminal in the control room.

B. 60 GHz Communication

60 GHz communications will be an important wireless technology in the future. It uses 60 GHz band as the carrier frequency to accommodate high-throughput wireless communications. 60 GHz band has many benefits such as free, availability,

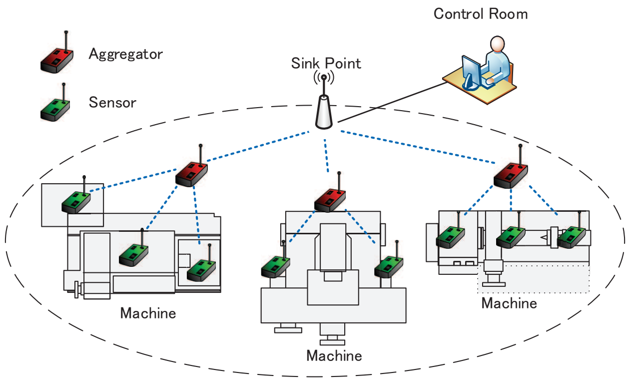


Fig. 1. Typical industrial sensor network

and large channel capacity. In Japan, the Multimedia Mobile Access Communication (MMAC) committee is looking at using 60 GHz to support ultra-high-speed wireless indoor LANs with a bandwidth of 150 Mb/s. Additionally, there is about 8 GHz band for all kinds of wireless communications [13].

However, there are many challenges in 60 GHz implementations. One difficulty is that it is very hard to use 60 GHz for NLOS communications. Previous research shows that 60 GHz wireless channel causes 20 to 40 dB increased free space path loss and suffers from 15 to 30 dB/km atmospheric absorption depending on the atmospheric conditions.

Another difficulty is to design the millimeter-wave transceivers. There are many challenges in the design of 60 GHz transceivers, which include increased phase noise, limited amplifier gain, and the need for transmission line modeling of circuit components.

When WISNs are deployed in a single building, it is not difficult to resolve the above challenges. Here, the communication distance is limited to tens of meters in WISNs. For small distances to be bridged in WISN environment, the 10-15 dB/km attenuation has no significant impact. This means that 60 GHz communications can efficiently be used for short-range communications such as datacenter networks. Researchers use 60 GHz communications to replace wired links on top-of-rack (ToR) switches [14]. Here 60 GHz communications can greatly improve network performance and provide much finer monitoring and controlling machines than general wireless protocols.

III. RF Energy Transport with 60 GHz

In this section, we discuss the energy efficiency of RF energy transport with 60 GHz communications. As shown in Fig. 2 and to simplify the discussion, we consider a single sink node with 60 GHz directional antenna and a single wireless sensor with RF energy receiving (harvesting) antenna.

We choose the standard 60 GHz WR-15 waveguide horn antenna which is a popular antenna model for extremely high frequency communications. We use G_h to denote the antenna gain in dB and ϕ_v and ϕ_h to denote the degrees of the vertical

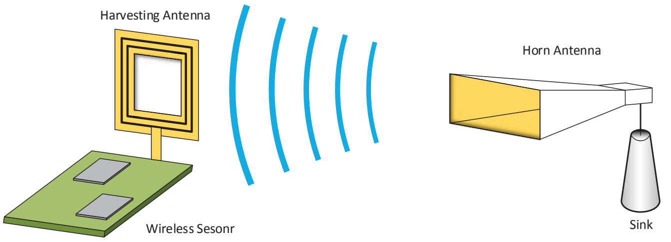


Fig. 2. Wireless sensor receives energy from the sink equipped a horn antenna

TABLE I
COMMERCIAL WR-15 ANTENNA MODELS WORKING AT 60 GHZ

Model	Gain	Beam (H)	Beam (V)	P_r
PE-W15A001	3 dBi	360°	35	-36 dBm
PE9881-20	20 dBi	20°	20°	-19 dBm
PE9881-24	24 dBi	7.5°	10°	-15 dBm
PE9881-34	34 dBi	3°	3°	-5 dBm
PE9881-42	42 dBi	1.9°	1.9°	3 dBm

and horizontal beamwidth. Then, we calculate the G_h, ϕ_v and ϕ_h with the given antenna. Since the size of the antenna used in WISN is very small, within the distances of factory buildings, the calculation of beamwidth and gain can be approximated to be relevant to the flared flange dimension and wavelength. We use a to denote the size of the flared flange dimension (narrow), b to denote the size of the flared flange dimension (wide), and λ to denote the wavelength.

Thus, the gain can be calculated approximately as

$$G_h = \frac{10 \cdot (a \cdot b)}{\lambda^2}. \quad (1)$$

Then, we analyze the energy propagation. We use G_r to denote the receiving antenna gain, r to denote the distance between the sink node and the sensor, P_h to denoted the transmitted power, and P_r to denote the received power. For an energy transport pair in free space, the propagation is described by the Friis transmission equation. To simply the calculation, we assume the energy is transported in free space. With Friis equation, we calculate the energy received by the sensor with units of dBW can be calculated as

$$P_r = P_h + \frac{10 \cdot (a \cdot b)}{\lambda^2} + G_r - 20 \cdot log_{10}(\frac{4 \cdot \pi \cdot r}{\lambda}). \quad (2)$$

Considering the directivity of the horn antenna, we also assume each sensor equips similar horn antennas with smaller size. Thus, we list some commercial models and calculate the energy transport performance with $G_r = 20$ dBi, $P_h = 15$ dBm, and $r = 20$ meters as follows.

From Table I, we can find the received energy is related to the antenna design. In a previous RF energy transport system, the battery can be charged if the received power is more than 18 μW [3]. Therefore, in our RF energy transport method, we choose the third model as the antenna of the sink node and the second model for each sensor.

IV. ANTENNA DISTRIBUTION OPTIMIZATION

In this section, we try to distribute antennas in a sphere to cover all sensors in the factory building. We first introduce the model of the distribution scenario then present the reflection with the building ceiling. Finally, we state the distribution problem and describe the solution.

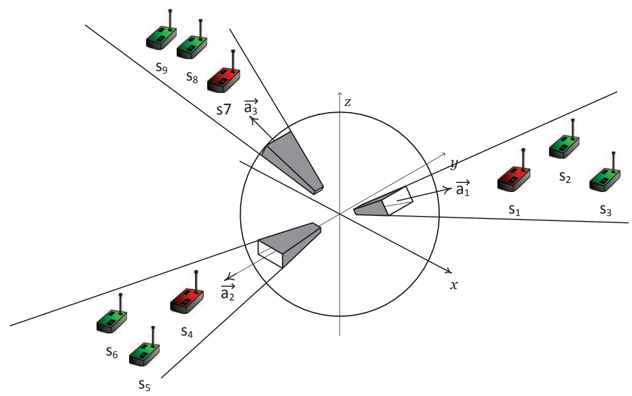


Fig. 3. Antenna distribution in 60 GHz energy harvesting

A. Antenna Spherical Distribution

Since the single directional antenna cannot cover all sensors in WISN, we use antennas on the sink node. As shown in Fig. 3, with horn antennas, we design an antenna sphere and the flared flange of each antenna is distributed on this sphere. Thus, to connect these antennas, it is convenient to put the sink node in the center of the sphere.

We use R_h to denote the radius of the sphere and put the center of the sphere in the ordinate origin. We use a set S to denote all sensors in the space and s_i to denote one sensor in S. For each sensor $s_i \in S$, we use a triple (x_i, y_i, z_i) to denote the three-dimensional coordinate. We use a set A to denote all antennas and a_j to denote the one antenna in A. For each antenna $a_j \in A$, we use a vector $\overrightarrow{a_j}$ to denote the beam direction. For each two antenna a_j and a_k, we use θ_{vjk} and θ_{hjk} to denote the vertical and horizontal components of the angle between these two vectors.

For each sensor s_i, we use P_{ri} to denote the received power and P_i to denote the rated power. Thus, for basically working, the received power should no less than the rated power. For each antenna a_j, we use $\overrightarrow{a_{vj}}$ and $\overrightarrow{a_{hj}}$ to denote the vertical and horizontal beam direction. With $\overrightarrow{a_{vj}}$ and $\overrightarrow{a_{hj}}$, we define θ_{hj} to denote the angle between $\overrightarrow{a_{hj}}$ and X-axis and θ_{vj} to denote the angle between $\overrightarrow{a_{hj}}$ and Y-axis. To denote the degrees of the vertical and horizontal beamwidth, we define ϕ_{hj} and ϕ_{vj}. Thus, since we assume $R << \sqrt{x_i^2 + y_i^2 + z_2^2}$, we use a 0-1 value X_{ij} to describe the relationship between the antennas and sensors, given by

$$X_{ij} = \begin{cases} 1, & s_i \text{ is in the beam area of } a_j \\ 0, & s_i \text{ is not in the beam area of } a_j \end{cases} \quad (3)$$

where $i \in [1, |S|]$ and $j \in [1, |A|]$.

With value X_{ij}, for sensor s_i, we use a value P_{rij} to denote the energy received from antenna a_j. Therefore, the received

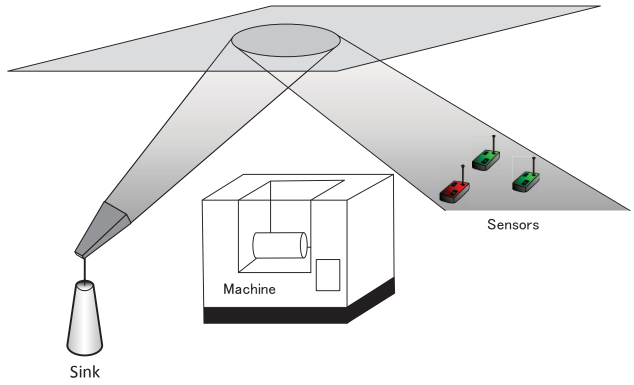


Fig. 4. Ceiling reflects the wave from the sink to sensors

energy is more than the rated energy P_i as follows.

$$P_i \leq \sum_{j=1}^{|A|} X_{ij} P_{rij} \tag{4}$$

B. Reflection

Since it is difficult to use 60 GHz for NLOS communications, we should consider how to transport energy to those sensors behind obstacles. From some existing work, a feasible method is using refection beamforming [15]. An example is shown in Fig. 4, where a sink node bounces its signal off of the ceiling to the sensors. This creates an indirect line-of-sight (LOS) path between the sink node and sensors, bypassing obstacles such as machines, etc.

Using ceiling reflection, beamforming will bypass obstacles in the horizontal plane, eliminating the problem for using 60 GHz for NLOS communications. Since ceiling reflectors should produce no loss, it should produce an indirect LOS path following the free-space energy propagation, which means the received energy can be calculated by (2). We use r_{ij} to denote the distance between sensor s_i and antenna a_j. The problem is how to calculate the distance r_{ij} with ceiling reflection.

For finding the distance between the sink node ans sensors, we use some similar processing with the light reflection. We assume the ceiling reflectors as mirrors and use light simulate wireless beam. Thus, we can use mirror images of the sensor and for each sensor s_i, the distance between the image and the sink node is the same with the distance r_{ij}. We use h to denote the ceiling height. Therefore, by assuming that $R << r_{ij}$, we can get the distance $r_{ij} = \sqrt{x_i^2 + y_i^2 + (z_i + h)^2}$.

Another problem is how to determine whether the sensor $s_i \in S$ in the beam from the antenna a_i. It is easily to calculate X_{ij} by using the mirror images.

C. Problem Statement and Solution

With the formulation of the antenna distribution, we can now define the distribution problem. We assume each antenna transports the same energy and same size with the objective of minimizing the number of antennas to cover all sensors. Thus, the problem can be stated as follows.

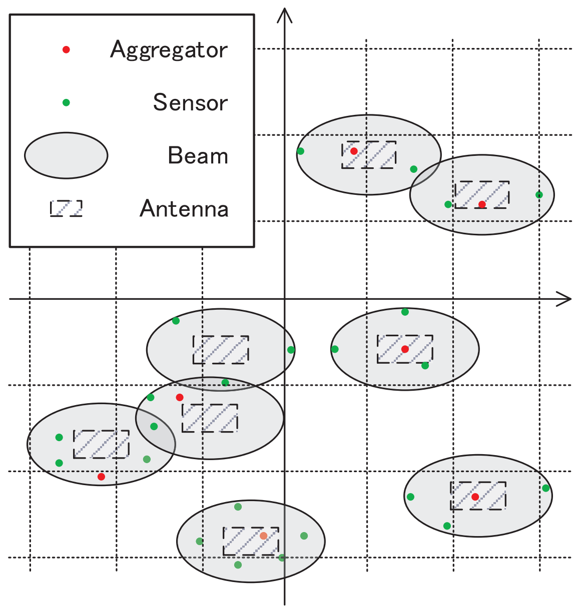


Fig. 5. Example of ellipse covering problem in solving antenna distribution

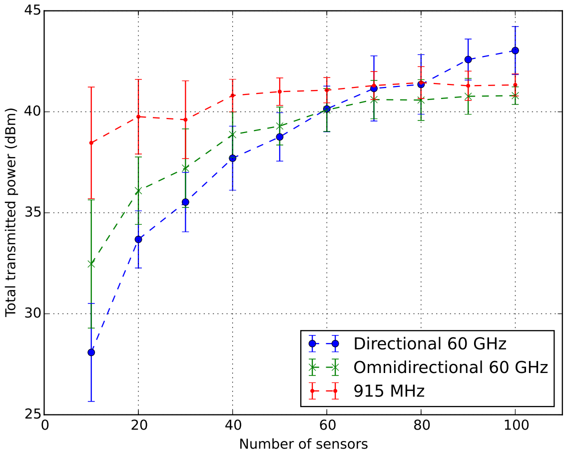
Antenna Spherical Distribution Problem: Given a set of sensors and a sphere, the distribution problem attempts to distribute minimal horn antennas on this sphere to transport energy such that all sensors can be supplied with enough energy.

For solving this, we find an equivalent problem with simple model. For each sensor s_i, since $R << r_i$, the problem can be equivalent to an ellipses covering points problem.

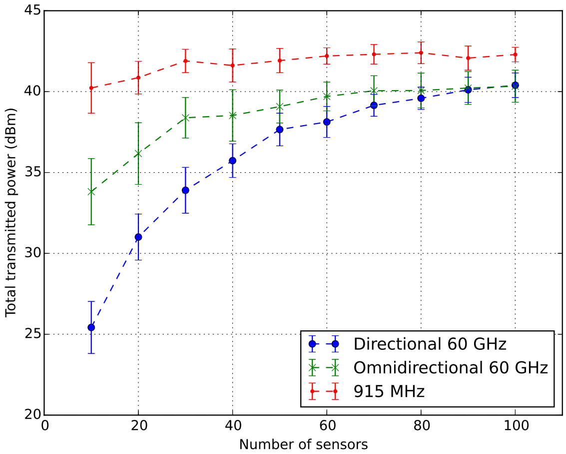
As shown in Fig. 5, the ellipse covering problem attempts to put ellipses to cover the points on the sphere. The points are the projections of sensors on the antenna sphere. The ellipses are the projections of wireless beams on the antenna sphere. If a point is covered by an ellipse, the projected sensor can receive energy from the projected antenna. The rectangles mean the size of antennas. When putting ellipses on the sphere, it is not allowed to generate overlap area of the antennas. For those sensors need more energy from multiple antennas, we can put overlap beam area to cover it, which means those sensors can receive energy from multiple antennas.

With this problem transforming, it becomes simpler than the original one and we design a strategy to solve this problem. Thus, we describe the main procedures for transforming and problem solution. First, we find out those sensors need ceiling reflection in the building and calculate the positions of their images. Then, we project all sensors to the sphere. The projection position of each sensor s_i is the intersection of the line from s_i to the center of the sphere and the sphere. Meanwhile, we calculate the needed transport energy for each sensor.

After transforming to the ellipse covering problem and since there are several methods to solving circular covering problem, it is not hard to find one method to solve this covering problem.



(a) Low antenna position



(b) High antenna postion

Fig. 6. Total transmitted energy for covering different number of sensors with low and high antenna positions

Considering that the size of the beam area is not so large and sensor distribution is not very dense, we design a quick covering strategy. We try to cover the entire area with beam areas and with minimal overlap. Then, we remove those areas without covering any sensor. Finally, we add some antennas for covering those sensors which need more energy.

V. Performance Evaluation

In this section, we use simulations to evaluate the efficiency of energy transport with 60 GHz for WISNs. First, we introduce the simulation settings then we analyze the results from simulations-based experiments.

Considering the industrial sensor network environment, we try to simulate a single factory with machines. We use a rectangle area as the workshop floor with the size of 100×50 meters and we set the height of the workshop area is 30 meters. For the machines, we also use some cuboids of different sizes. The length, width and height of these cuboids are uniformly distributed from 1 meters to 4 meters. In simulations, we generate from 2 to 20 machines with different sizes to the factory area. We put 1 aggregator and 5 sensors on each machine. For each sensor or aggregator, the position on the machine is randomly selected.

For the sink node, we use two positions for deploying the antenna sphere. In the first type, we put the sink node on the floor with a height of 7 meters while the second type, we put the sink node on the ceiling with the height of 27 meters. The radius of the antenna sphere is 0.35 meters. Thus, we choose the WR-15 waveguide horn antenna with the flared flange dimension sizes of $30, 15$ millimeters. The gain of this antenna is 24 dBi, vertical beamwidth is 10 degrees, and horizontal beamwidth is 7.5 degrees. We set the output power P_h per each antenna is 15 dBm and the limited

For comparison, we also defined two settings with different antennas as follows.

(1) 60 GHz omnidirectional antenna: We put a WR-15 omnidirectional antenna in the factory to transport energy for all sensors. The gain of this antenna is set to 3 dBi shown in Table I. Since it is very hard to use this antenna for energy transport, we assume this antenna can cover all sensors in free space.

(2) 915 MHz directional panel antenna: We put 9 high gain directional panel antennas in the factory area to transport energy for all sensor. The gain of this antenna is set to 15 dBi. The horizontal and vertical beamwidth of each panel antenna is 40 and 40 degrees. Considering the better performance of NLOS communications than 60 GHz, we also assume the energy is transport in free space. With the same size of the 60 GHz antenna, the gain of the 915 MHz receiving antenna is set to 2 dBi.

Then, we test the total energy transmitted by all antennas with different sensor density. We set the number of machines from 2 to 20 and test the total energy transmitted by the sink node. We run each simulation 20 times and get the average values and standard deviation. The lowest required power per each sensor is set to 18 μW or -17.4473 dBm.

As shown in Fig. 6(a), for covering all sensor in WISN, when the number of sensors is no more than 60, we find the total transmitted power with 60 GHz directional antennas performs similar with the traditional 915 MHz energy transport solution. The omnidirectional 60 GHz energy transport solution performs worse with low sensor density. When the number of sensors increases beyond 80, the directional antennas solution performs worse than the other two solutions. Since we use dBm as the unit of the result, the difference of the energy cost between the three solutions is more than several times especially when the number of sensors is less than 40.

As shown in Fig. 6(b), when we choose the position that placing antennas on the ceiling, the energy efficiency with directional antennas solution performs much better than the low antenna position. When the number of sensors less than 30, the transmitted power with directional antennas is near 30 dBm, which means the total power is near 1 watt. Since the average distance is farther than the low antenna position settings, the other two solutions perform much worse than the directional antennas solution when the number of sensors is less than 60. When the sensor density becomes higher, the difference of the total transmitted power between three solutions becomes smaller.

From the simulation results, with directional antenna distribution optimization, the energy efficiency in 60 GHz energy transport is much better than the transitional way with low sensor density. When the sensor distribution becomes dense, for covering this WISN, it needs more antennas for energy transport. Since the number of sensors in a typical WISN is limited by the factory room space, we consider the 60 GHz energy transport technology is a feasible solution for energy supplement with our spherical antenna distribution.

VI. Conclusion

With its high performance and large capacity, 60 GHz communications will be an important technology for future WISN generations. Meanwhile, with its good directivity, RF energy transport with 60 GHz becomes a feasible solution for powering sensors in WISNs. After analyzing the efficiency of the RF energy transport with 60 GHz with different antenna, we chose the directional horn antenna and proposed a spherical antenna distribution that uses multiple directional antennas to cover more sensors. We formulate the distribution problem and then designed an equivalent problem transforming to solve it. Finally, in the performance evaluation, we compared the energy efficiency of our RF energy transport to the general 60 GHz solution and a commercial 915 MHz solution. From the result, with general density of sensors in WISNs, our energy transport solution performs much better than other two approaches. In the future, we will plan to acquire few antennas for 60 GHz communications and implement our design in the real-world environment. Meanwhile, we will try to find a better antenna distribution strategy to archive the optimal solution.

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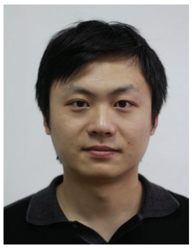

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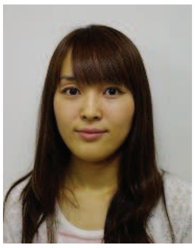

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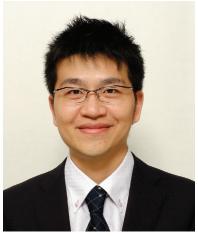

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