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RF Energy Harvesting for Wireless Devices

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Abstract:- Radio Frequency (RF) energy transfer and harvesting techniques have recently become alternative methods to empower the next generation wireless networks. As this emerging technology enables proactive energy replenishment of wireless devices, it is advantageous in supporting applications with quality of service requirements. In this paper, some wireless power transfer methods, RF energy harvesting networks, various receiver architectures and existing applications are presented. Finally, some open research directions are envisioned.

Keywords:- RF Energy Harvesting, Simultaneous wireless information and power transfer (SWIPT), Receiver power, Wireless power transfer, Power management module.

I. INTRODUCTION

Energy harvesting is a process in which energy from external sources like solar power, thermal energy, wind energy etc., is captured and stored for small, wireless devices like those used in wearable electronics and wireless sensor networks[1]. It is also called power harvesting or energy scavenging. The ambient energy may come from stray electric or magnetic fields or radio waves from nearby electrical equipment, light, thermal energy or kinetic energy such as vibration or motion of the device. The efficiency of conversion is usually low and the power gathered is often in milli-watts or in microwatts but it is enough to recharge small micro-power devices such as remote sensors. This technology is being developed to eliminate the need for battery replacement or charging of such wireless devices.

Wireless power transmission is a collective term that refers to a number of different technologies for transmitting power by means of time-varying electro-magnetic fields [5]. The technologies, listed in the table, differ in a number of aspects like directivity, efficient power transmission, type of electromagnetic energy they use. The current focus is to develop wireless systems to charge mobile and handheld computing devices such as cell phones, digital music player and portable computers without being connected to a wall plug.

Wireless power uses much of the same fields and waves as wireless communication devices like radio, which involves power transmitted without wires by electromagnetic fields, used in cell phones, radio, television broadcasting, and Wi-Fi. In radio communication, the goal is to transmit information, so that the amount of power reaching the receiver is unimportant as long as it maintains the required signal to noise ratio. In wireless communication technologies, only tiny amounts of power reach the receiver. By contrast, in wireless power, the amount of power received is the important thing, so the efficiency i.e., fraction of transmitted power that is received, is a significant parameter [9]. For this reason wireless power technologies are more limited by distance than wireless communication technologies.

Types of Field Regions

Electric and magnetic fields are created by charged particles in matter such as electrons. A Stationary charge creates an electrostatic field in the space around it. A steady current of charges creates a static magnetic field around it. These fields contain energy but they cannot carry power because they are static, but time-varying fields can. Accelerating electric charges, such as are found in an alternating current of electrons in a wire, create time-varying electric and magnetic fields in the space around them. These fields can exert oscillating forces on the electrons in a receiving antenna, causing them to move back and forth which represents alternating current which can be used to power a load.

The oscillating electric and magnetic fields surrounding moving electric charges in an antenna device can be divided into two regions depending on distance from the antenna. The fields have different characteristics in these regions, and different technologies are used for transmitting power.

Table 1.1 Different wireless power technologies

Technology	Range	Directivity	Frequency	Devices	Applications
Inductive Coupling	Short	Low	Hz – MHz	Wire Coils	Induction Stove tops
Resonant Inductive Coupling	Mid	Low	MHz– GHz	Tuned Wire Coils, lumped elements resonators	RFID, Smart Cards
Capacitive Coupling	Short	Low	KHz –MHz	Electrodes	Power routing in large scale integrated circuits
Magneto dynamic	Short		Hz	Rotating Magnets	Charging electric vehicles
Microwaves	Long	High	GHz	Parabolic Dishes, Phased Arrays, Rectannas	Solar power satellite
Light Waves	Long	High	THz	Lasers, Photocells, lenses, Telescopes	Power drone aircraft, Powering space elevator climbers

Near-field or **non-radiative region** – The area within about 1 wavelength of the antenna is the near field region. In this region the oscillating electric and magnetic fields are separate and power can be transferred via electric fields by capacitive coupling between metal electrodes, or via magnetic fields by inductive coupling between coils of the wire. These fields are not radiative, that is the energy stays within a short distance of the transmitter. If there is no receiving device or absorbing material within their limited range, no power leaves the transmitter. The range of these fields is short, and depends on the size and shape of the antenna devices, which are usually coils of wire. The fields, and thus the power transmitted, decrease exponentially with distance, so if the distance between the two antennas is much larger than the diameter of the antennas, very little power will be received. Therefore, these techniques cannot be used for long distance power transmission.

Resonance, such as resonant inductive coupling, can increase the coupling between the antennas greatly, allowing efficient transmission at somewhat greater distances, although the fields still decrease exponentially. Therefore the range of near-field devices can be divided into two categories:

- **Short range** - up to about one antenna diameter. This is the range over which ordinary non-resonant capacitive or inductive coupling can transfer practical amounts of power.
- **Mid-range** - up to 10 times the antenna diameter. This is the range over which resonant capacitive or inductive coupling can transfer practical amounts of power.

Far-field or **radiative region** - Beyond about 1 wavelength of the antenna, the electric and magnetic fields are perpendicular to each other and propagate as an electromagnetic wave such as radio waves, microwaves or light waves. This part of the energy is radiative, that is it leaves the antenna whether or not there is a receiver to absorb it. The portion of energy which does not strike the receiving antenna is dissipated and lost to the system. The amount of power emitted as electromagnetic waves by an antenna depends on the ratio of the antenna's size to the wavelength of the waves. Antennas about the same size as the wavelength such as monopole or dipole antennas, radiate power efficiently, but the electromagnetic waves are radiated in all directions, so if the receiving antenna is far away, only a small amount of the radiation will hit it. Therefore these can be used for short range, inefficient power transmission but not for long range transmission.

II. NEAR-FIELD OR NON-RADIATIVE TECHNIQUES

The near-field components of electric and magnetic fields die out quickly beyond a distance of about one diameter of the antenna. Since power is proportional to the square of the field strength, the power transferred decreases with the sixth power of the distance or 60 dB per decade. In other words, doubling the distance between transmitter and receiver causes the power received to decrease by a factor of $2^6 = 64$.

Inductive coupling

The electrodynamic induction wireless transmission technique relies on the use of a magnetic field generated by an electric current to induce a current in a second conductor. This effect occurs in the electromagnetic near field, with the secondary in close proximity to the primary. As the distance from the primary is increased, more and more of the primary's magnetic field misses the secondary. Even over a relatively short range the inductive coupling is grossly inefficient, wasting much of the transmitted energy [3].

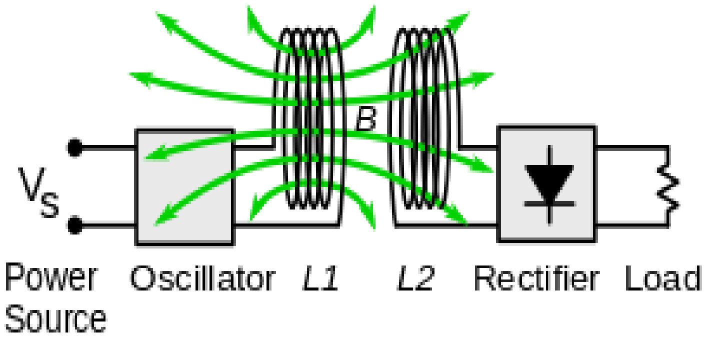

Fig 1.1: Inductive wireless power system

This action of an electrical transformer is the simplest form of wireless power transmission. The primary coil and secondary coil of a transformer are not directly connected; each coil is part of a separate circuit. Energy transfer takes place through mutual induction. Principal functions are stepping the primary voltage either up or down and electrical isolation. Mobile phone and electric toothbrush battery chargers, Induction cookers are examples of this principle. The main drawback to this basic form of wireless transmission is short range. The receiver must be directly adjacent to the transmitter or induction unit in order to efficiently couple with it.

Common uses of resonance-enhanced electrodynamic induction are charging the batteries of portable devices such as laptop computers and cell phones, medical implants and electric vehicles. A localized charging technique selects the appropriate transmitting coil in a multilayer winding array structure. Resonance is used in both the wireless charging pad and the receiver module to maximize energy transfer efficiency. Battery-powered devices fitted with a special receiver module can then be charged simply by placing them on a wireless charging pad.

This technology is also used for powering devices with very low energy requirements, such as RFID patches and contactless smartcards. Instead of relying on each of the many thousands or millions of RFID patches or smartcards to contain a working battery, electrodynamic induction can provide power only when the devices are needed.

CAPACITIVE COUPLING

In capacitive coupling, the dual of inductive coupling, power is transmitted by electric fields between electrodes such as metal plates. The transmitter and receiver electrodes form a capacitor, with the intervening space as the dielectric. An alternating voltage generated by the transmitter is applied to the transmitting plate, and the oscillating electric field induces an alternating potential on the receiver plate by electrostatic induction, which causes an alternating current to flow in the load circuit. The amount of power transferred increases with the frequency and the capacitance between the plates, which is proportional to the area of the smaller plate and (for short distances) inversely proportional to the separation.

Capacitive coupling has only been used practically in a few low power applications, because the very high voltages on the electrodes required to transmit significant power can be hazardous, and can cause unpleasant side effects such as noxious ozone production [5]. In addition, in contrast to magnetic fields, electric fields interact strongly with most materials, including the human body, due to dielectric polarization. Intervening materials between or near the electrodes can absorb the energy, in the case of humans possibly causing excessive electromagnetic field exposure. However capacitive coupling has a few advantages over inductive. The field is largely confined between the capacitor plates, reducing interference, which in inductive coupling requires heavy ferrite flux confinement cores. Also, alignment requirements between the transmitter and receiver are less critical. Capacitive coupling has recently been applied to charging battery powered portable devices and is being considered as a means of transferring power between substrate layers in integrated circuits.

MAGNETO-DYNAMIC COUPLING

In this method, power is transmitted between two rotating armatures, one in the transmitter and one in the receiver, which rotate synchronously, coupled together by a magnetic field generated by permanent magnets on the armatures. The transmitter armature is turned either by or as the rotor of an electric motor, and its magnetic field exerts torque on the receiver armature, turning it. The magnetic field acts like a mechanical coupling between the armatures. The receiver armature produces power to drive the load, either by turning an electric generator or by using the receiver armature as the rotor in an induction generator [3].

This device has been proposed as an alternative to inductive power transfer for noncontact charging of electric vehicles. A rotating armature embedded in a garage floor or curb would turn a receiver armature in the underside of the vehicle to charge its batteries. It is claimed that this technique can transfer power over distances of 10 to 15 cm with high efficiency, over 90%. Also, the low frequency stray magnetic fields produced by the rotating magnets produce less electromagnetic interference to nearby electronic devices than the high frequency magnetic fields produced by inductive coupling systems.

III. FAR-FIELD OR RADIATIVE TECHNIQUES

Far field methods achieve longer ranges, often multiple kilometer ranges, where the distance is much greater than the diameter of the device. The main reason for longer ranges with radio wave and optical devices is the fact that electromagnetic radiation in the far-field can be made to match the shape of the receiving area using high directivity antennas or well-collimated laser beams. The maximum directivity for antennas is physically limited by diffraction [12].

In general, visible light and microwaves are the forms of electromagnetic radiation best suited to energy transfer. The dimensions of the components may be dictated by the distance from transmitter to receiver, the wavelength and the Rayleigh criterion or diffraction limit, used in standard radio frequency antenna design, which also applies to lasers. Electromagnetic radiation experiences less diffraction at shorter wavelengths (higher frequencies).
Microwave power beaming can be more efficient than lasers, and is less prone toatmospheric attenuation caused by dust or water vapor.

Microwaves

Power transmission via radio waves can be made more directional, allowing longer distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectanna may be used to convert the microwave energy back into electricity. Rectenna conversion efficiencies exceeding 95% have been realized. Power beaming using microwaves can be used to transmit the energy from orbiting solar power satellites to Earth [5].

Power beaming by microwaves has the difficulty that for most space applications the required aperture sizes are very large due to diffraction limiting antenna directionality. These sizes can be somewhat decreased by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets [13].

Lasers

In the case of electromagnetic radiation closer to the visible region of the spectrum (tens of micrometers to tens of nanometers), power can be transmitted by converting electricity into a laser beam that is then pointed at a photovoltaic cell. This mechanism is generally known as "power beaming" because the power is beamed at a receiver that can convert it to electrical energy.

Compared to other wireless methods:

- Collimated monochromatic wavefront propagation allows narrow beam cross-section area for transmission over large distances.
- Compact size: solid state lasers fit into small products.
- No radio frequency interference to existing radio communication such as Wi-Fi and cell phones.
- Access control: only receivers hit by the laser receive power.

Drawbacks include:

- Laser radiation is hazardous. Low power levels can blind humans and other animals. High power levels can kill through localized spot heating.
- Conversion between electricity and light is inefficient. Photovoltaic cells achieve only 40%–50% efficiency.
- Atmospheric absorption, and absorption and scattering by clouds, fog, rain, etc., cause up to 100% losses.
- Requires a direct line of sight with the target.

Laser power beaming technology has been mostly explored in military weapons and aerospace applications and is now being developed for commercial and consumer electronics [5].

IV. RF ENERGY HARVESTING NETWORKS

2.1 Architecture:

A typical centralized architecture of an RF-EHN, as shown in Fig.2.1, has three major components, i.e., information gateways, the RF energy sources and the network nodes/devices. The information gateways are generally known as base stations, wireless routers and relays. The RF energy sources can be either dedicated RF energy transmitters or ambient RF sources (e.g., TV towers). The network nodes are the user equipment that communicates with the information gateways. Typically, the information gateways and RF energy sources have continuous and fixed electric supply, while the network nodes harvest energy from RF sources to support their operations. In some cases, the information gateway and RF energy source can be the same. As shown in Fig.2, the solid arrow lines represent information flows, while the dashed arrow lines mean energy flows [14].

The information gateway has an energy harvesting zone and an information transmission zone represented by the dashed circles in Fig. 2.1. The devices in the energy harvesting zone are able to harvest RF energy from the information gateway. The devices in the information transmission zone can successfully decode information transmitted from the gateway. Generally, the operating power of the energy harvesting component is much higher than that of the information decoding component. Therefore, the energy harvesting zone is smaller than the information transmission zone.

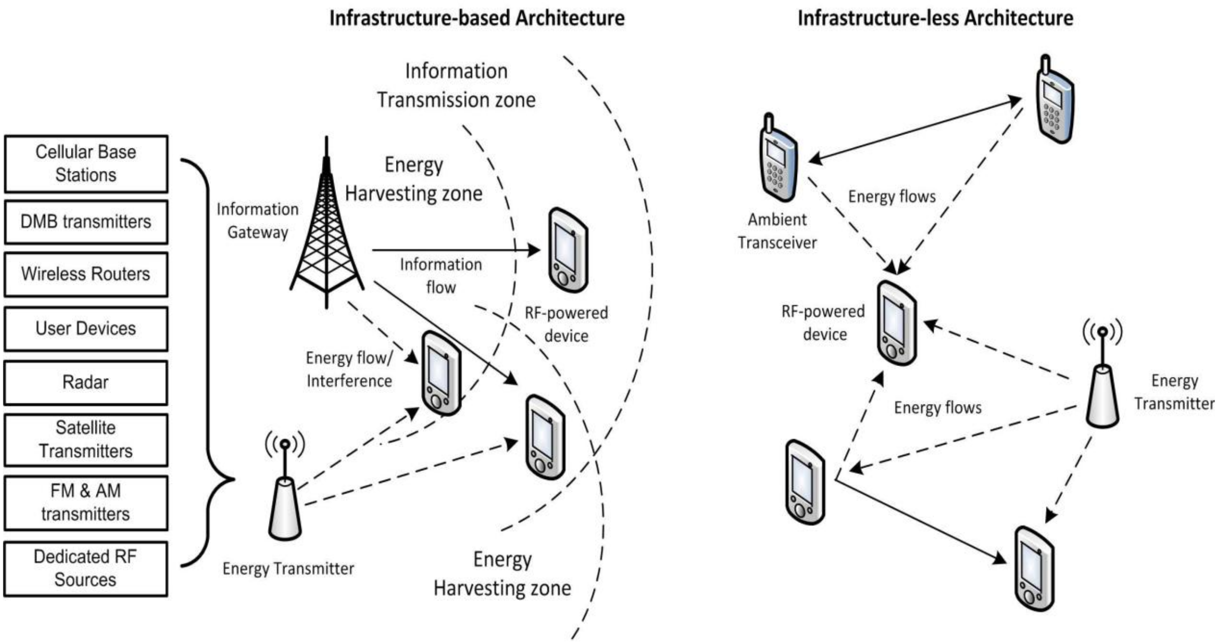

Fig. 2.1. A general architecture of an RF energy harvesting network.

Figure 2.2 also shows the block diagram of a network node with RF energy harvesting capability. An RF energy harvesting node consists of the following major components:
• The application,
• A low-power microcontroller, to process data from the application,
• A low-power RF transceiver, for information transmission or reception,
• An energy harvester, composed of an RF antenna, an impedance matching, a voltage multiplier and a capacitor, to collect RF signals and convert them into electricity,
• A power management module, which decides whether to store the electricity obtained from the RF energy harvester or to use it for information transmission immediately, and
• An energy storage or battery.

The power management module can adopt two methods to control the incoming energy flow, i.e., *harvest-use* and *harvest-store-use*. In the *harvest-use* method, the harvested energy is immediately used to power the network node. Therefore, for the network node to operate normally, the converted electricity has to constantly exceed the minimum energy demand of the network node. Otherwise, the node will be disabled. In the *harvest-store-use* method, the network node is equipped with energy storage or a rechargeable battery that stores the converted electricity. Whenever the harvested energy is more than that of the node's consumption, the excess energy will be stored in the battery for future use.
Figure 2.2 illustrates the block diagram of an RF energy harvester.

• The antenna can be designed to work on either single frequency or multiple frequency bands, in which the network node can harvest from a single or multiple sources simultaneously. Nevertheless, the RF energy harvester typically operates over a range of frequencies since energy density of RF signals is diverse in frequency.
• The impedance matching is a resonator circuit operating at the designed frequency to maximize the power transfer between the antenna and the multiplier. The efficiency of the impedance matching is high at the designed frequency.
• The main component of the voltage multiplier is diodes of the rectifying circuit which converts RF signals (AC signals in nature) into DC voltage. Generally, higher conversion efficiency can be achieved by diodes with lower built-in voltage. The capacitor ensures to deliver power smoothly to the load. Additionally, when RF energy is unavailable, the capacitor can also serve as a reserve for a short duration.

The efficiency of the RF energy harvester depends on the efficiency of the antenna, the accuracy of the impedance matching between the antenna and the voltage multiplier, and the power efficiency of the voltage multiplier that converts the received RF signals to DC voltage.

For the general node architecture introduced above, the network node has the separate RF energy harvester and RF transceiver. Therefore, the node can perform energy harvesting and data communication simultaneously. In other words, this architecture supports both *in-band* and *out-of-band* RF energy harvesting. In the in-band RF energy harvesting, the network node can harvest RF energy from the same frequency band as that of data communication. By contrast, in the out-of-band RF energy harvesting, the network node harvests RF energy from the different frequency band from that used for data communication. Since RF signals can carry energy as well as information, theoretically RF energy harvesting and information reception can be performed from the same RF signal input. This is referred to as the simultaneous wireless information and power transfer (SWIPT) concept. This concept allows the information receiver and RF energy harvester to share the same antenna or antenna array [16].

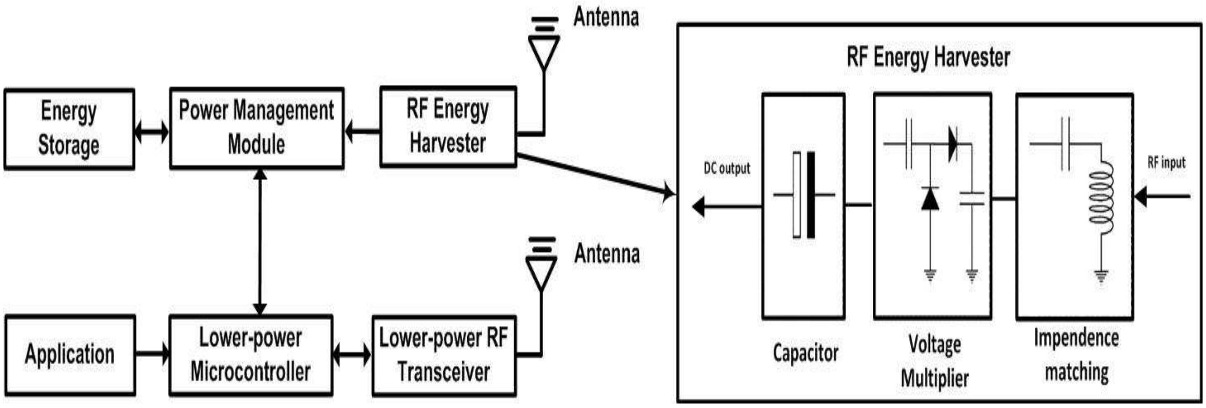

Fig. 2.2. A general architecture of an RF energy harvesting device

2.2 RF Energy Propagation Models:

In RF energy harvesting, the amount of energy that can be harvested depends on the transmit power, wavelength of the RF signals and the distance between an RF energy source and the harvesting node. The harvested RF power from a transmitter in free space can be calculated based on the Friis equation as follows:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi d)^2 L} \qquad (2.1)$$

Where P_R is the received power, P_T is the transmitted power, L is the path loss factor, G_T is the transmit antenna gain, G_R is the receive antenna gain, λ is the wavelength emitted, and d is the distance between the transmit antenna and the receiver antenna.

The free-space model has the assumption that there is only one single path between a transmitter and a receiver. However, due to RF scattering and reflection, a receiver may collect RF signals from a transmitter from multiple paths. The two ray ground model captures this phenomenon by considering the received RF signals pass through a line-of-sight path and a reflected path separately. The harvested RF power from a transmitter according to the two ray ground model is given by

$$P_R = \frac{P_T G_T G_R {h_t}^2 r^2}{d^4 L} \qquad (2.2)$$

Where h_t and h_r are the heights of the transmit and receive antennas, respectively.

The above two deterministic models characterize RF propagation based on determinate parameters. By contrast, probabilistic models draw parameters from a distribution, while allows a more realistic modeling. A practical and widely adopted probabilistic model is a Rayleigh model, which represents the situation when there is no line-of-sight channel between a transmitter and receiver. In the Rayleigh model, we have

$$P_R = P_R^{det} * 10^L * \log(1 - \mathrm{unif}(0,1)) \qquad (2.3)$$

Where P_R^{det} represents the received RF power calculated by a deterministic model. The path loss factor L is defined as L = −α log 10(d/d0), where d0 is a reference distance. unif(0, 1) denotes a random number generated following uniform distribution between 0 and 1.

The aggregated harvested RF energy can be calculated based on the adoption of the network model and RF propagation model.

2.3 RF Energy Harvesting Technique:

Unlike energy harvesting from other sources, such as solar, wind and vibrations, RF energy harvesting has the following characteristics:

- RF sources can provide controllable and constant energy transfer over distance for RF energy harvesters.
- In a fixed RF-EHN, the harvested energy is predictable and relatively stable over time due to fixed distance.
- Since the amount of harvested RF energy depends on the distance from the RF source, the network nodes in the different locations can have significant difference in harvested RF energy.

The RF sources can mainly be classified into two types, i.e. dedicated RF sources and ambient RF sources.

1) Dedicated RF sources: Dedicated RF sources can be deployed to provide energy to network nodes when more predictable energy supply is needed. The dedicated RF sources can use the license-free ISM frequency bands for RF energy transfer. The Power caster transmitter operating on 915MHz with 1W or 3W transmit power is an example of a dedicated RF source, which has been commercialized. However, deploying the dedicated RF sources can incur high cost for the network. Moreover, the output power of RF sources must be limited by regulations, such as Federal Communications Commission (FCC) due to safety and health concern of RF radiations. For example, in the 900MHz band, the maximum threshold is 4W. Even at this highest setting, the received power at a moderate distance of 20m is attenuated down to only 10 μW. Due to this limitation, many dedicated RF sources may need to be deployed to meet the user demand. As the RF energy harvesting process with dedicated RF sources is fully controllable, it is more suitable to support applications with QoS constraints. The dedicated RF sources could be mobile, which can periodically move and transfer RF energy to network nodes.

2) Ambient RF sources: Ambient RF sources refer to the RF transmitters that are not intended for RF energy transfer. This RF energy is essentially free. The transmit power of ambient RF sources varies significantly, from around 106W for TV tower, to about 10W for cellular and RFID systems, to roughly 0.1W for mobile communication devices and WiFi systems. Ambient RF sources can be further classified into static and dynamic ambient RF sources [2].

• ***Static ambient RF sources:*** Static ambient RF sources are the transmitters which release relatively stable power over time, such as TV and radio towers. Although the static ambient RF sources can provide predictable RF energy, there could be long-term and short-term fluctuations due to service schedule (e.g., TV and radio) and fading, respectively. Normally, the power density of ambient RF sources at different frequency bands is small. As a result, a high gain antenna for all frequency bands is required. Moreover, the rectifier must also be designed for wideband spectrum. When the distribution of ambient RF sources exhibits stronger repulsion, larger RF energy harvesting rate can be achieved at the sensor [2].

• ***Dynamic ambient RF sources:*** Dynamic ambient RF sources are the RF transmitters that work periodically or use time-varying transmit power (e.g., a WiFi access point and licensed users in a cognitive radio network). The RF energy harvesting from the dynamic ambient RF sources has to be adaptive and possibly intelligent to search for energy harvesting opportunities in a certain frequency range. An example is the energy harvesting from dynamic ambient RF sources in a cognitive radio network. A secondary user can harvest RF energy from nearby transmitting primary users, and can transmit data when it is sufficiently far from primary users or when the nearby primary users are idle [2].

The energy harvesting rate varies significantly depending on the source power and distance. Typically, the amount of harvested energy is in order of micro-watts, which is sufficient for powering small devices [10].

2.4 Applications of RF Energy Harvesting:

Wireless sensor networks have become one of the most widely applied applications of RF-EHNs. An RF energy harvester can be used in a sensor node to supply energy. The RF-powered devices also have attractive healthcare and medical applications such as wireless body network. Benefiting from RF energy harvesting, low-power medical devices can achieve real-time work-on-demand power from dedicated RF sources, which further enables a battery-free circuit with reduced size [11]. The antenna of a body device circuit dual-band operating at GSM 900 and GSM 1800 achieves gains of the order 1.8-2.06 dBi and efficiency of 77.6−84%. Another RF energy harvesting application that has caught intensive research investigation is RFID, widely used for identification, tracking, and inventory management. Recent developments in low-power circuit and RF energy harvesting technology can extend the lifetime and operation range of conventional RFID tags. In particular, RFID tags, instead of relying on the readers to activate their circuits passively, can harvest RF energy and perform communication actively. Consequently, RFID technology has evolved from simple passive tags to smart tags with newly introduced features such as sensing, on-tag data processing and intelligent power management. Other than these applications, devices powered by ambient RF energy are attracting increasingly research attention. For example, an information rate of 1 kbps can be achieved between two prototype devices powered by ambient RF signals, at the distance of up to 2.5 feet and 1.5 feet for outdoors and indoors, respectively. Many implementations of battery-free devices can be powered by ambient energy from WiFi, GSM and DTV bands as well as ambient mobile electronic devices.

Additionally, RF energy harvesting can be used to provide charging capability for a wide variety of low-power mobile devices such as electronic watches, hearing aids, and MP3 players, wireless keyboard and mouse, as most of them consume only micro-watts to milli-watts range of power [11].

V. CIRCUIT DESIGNS OF RF ENERGY HARVESTING DEVICES

This section introduces some background related to the hardware circuit designs of RF energy harvesting devices.

3.1. Circuitry Implementations

There have been a large number RF energy harvester implementations based on various different technologies such as CMOS, HSMS and SMS. Most of the implementations are based on the CMOS technology. Generally, to achieve 1V DC output, -22 dBm to -14 dBm harvested RF power is required. Though CMOS technology allows a lower minimum RF input power, the peak RF-to-DC conversion efficiency is usually inferior to that of HSMS technology. The efficiency above 70% can be achieved when the harvested power is above -10 dBm. For RF energy harvesting at a relatively high power (e.g., 40 dBm/10W), SMS technology can be adopted. In particular, 30V output voltage is achieved at 40 dBm input RF power with 85% conversion efficiency. However, when the harvested RF power is low, the conversion efficiency is low. For example, only 10% as input power is -10 dBm [15].

3.2. Antenna Design

An antenna is responsible for capturing RF signals. Miniaturised size and high antenna gain are the main aims of antenna technology. Antenna arrays are effective in increasing the capability for low input power. However, a tradeoff exists between antenna size and performance [4].

3.3. Matching Network

The crucial task of matching network is to reduce the transmission loss from an antenna to a rectifier circuit and increase the input voltage of a rectifier circuit. To this end, a matching network is usually made with reactive components such as coils and capacitors that are not dissipative. Maximum power transfer can be realized when the impedance at the antenna output and the impedance of the load are conjugates of each other. This procedure is known as impedance matching. Currently, there exist three main matching network circuits designed for RF energy harvesting, i.e., transformer, shunt inductor, LC network [4].

3.4. Rectifier

The function of a rectifier is to convert the input RF signals (AC type) captured by an antenna into DC voltage. A major challenge of the rectifier design is to generate a battery-like voltage from very low input RF power. Generally, there are three main options for a rectifier, which are a diode, a bridge of diodes and a voltage rectifier multiplier.

The diode is the main component of a rectifier circuit. The rectification performance of a rectifier mainly depends on the saturation current, junction capacitance and its conduction resistance of the diode. The circuit of a rectifier, especially the diode, determines the RF-to-DC conversion efficiency. The most commonly used diode for rectennas is silicon Schottky barrier diodes. Generally, a diode with a lower built-in voltage can achieve a higher rectifying efficiency. This is because larger voltage will result in significantly more harmonic signals due to the nonlinear characteristics of the diode, thus notably decreasing the rectifying efficiency [15].

3.5. Receiver Architecture Design

The traditional information receiver architecture designed for information reception may not be optimal for SWIPT [6]. The reason is because information reception and RF energy harvesting works on very different power sensitivity (e.g., -10 dBm for energy harvesters versus -60 dBm for information receivers). Currently, there are four typical types of receiver architectures.

• *Separated Receiver Architecture*: Separated receiver architecture, also known as antenna-switching, equips an energy harvester and information receiver with independent antennas so that they observe different channels.

Figure 3.1 shows the model for the separated receiver architecture. The antenna array is divided into two sets with each connected to the energy harvester or the information receiver. Consequently, the architecture allows performing energy harvesting and information decoding independently and concurrently. The antenna-switching scheme can be used to optimize the performance of the separated receiver architecture.

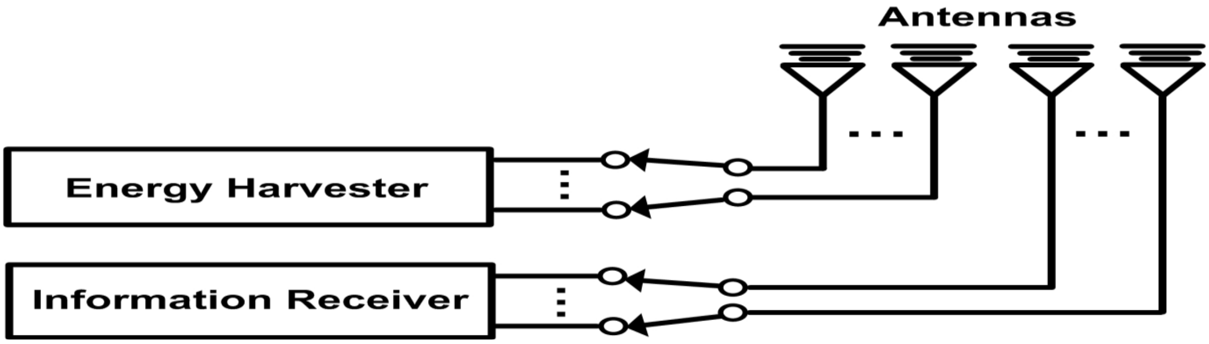

Fig. 3.1. Seperated Receiver Architecture

***• Co-located Receiver Architecture*:** The co-located receiver architecture lets an energy harvester and an information receiver share the same antenna so that they observe the same channel. As a single antenna can be adopted, the co-located receiver architecture is able to enable a smaller size compared to the separated receiver architecture. This architecture can be categorized into two models, i.e., time-switching and power-splitting architectures. The time-switching architecture, as shown in Fig. 3.2, allows the network node to switch and use either the information receiver or the RF energy harvester for the received RF signals at a time. When a time switching receiver j is working in the energy harvesting mode, the power harvested from source i can be calculated as follows:

$$P_{j,i} = \eta Pi \left| h_{i,j} \right|^2 \tag{3.1}$$

where η denotes the energy harvesting efficiency factor, Pi is the transmit power at source i, and $h_{i,j}$ denotes the channel gain between the source i and receiver j. Let W and σ^2 denote the transmission bandwidth and noise power, respectively. When the time-switching receiver j working in the information decoding mode, the maximum information decoding rate from source i is

$$R_{j,i} = W \log(1 + P_i|h_{i,j}|^2/\sigma^2) \tag{3.2}$$

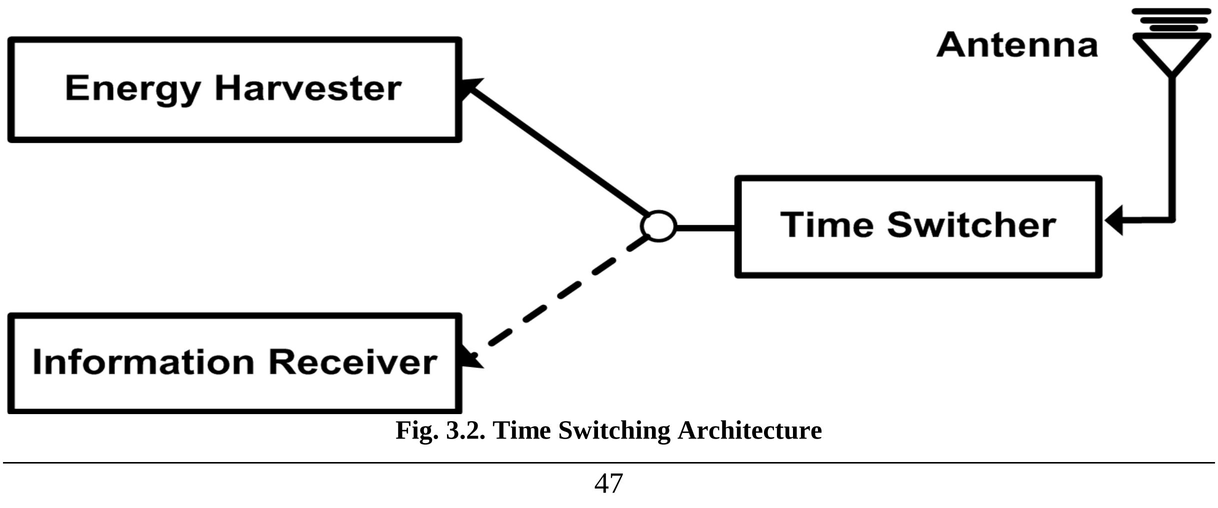

Fig. 3.2. Time Switching Architecture

In the power-splitting architecture, as shown in Fig. 3.3, the received RF signals are split into two streams for the information receiver and RF energy harvester with different power levels [7]. Let $\theta_j \in [0, 1]$ denote the power-splitting coefficient for receiver j, i.e., θ_j is the fraction of RF signals used for energy harvesting. Similarly, the power of harvested RF energy at a power-splitting receiver j from source i can be calculated as follows:

$$P_{j,i} = \_P_i|h_{i,j}|^2\theta_j \quad (3.3)$$

Let σ^2_{sp} denote the power of signal processing noise. The maximum information decoding rate at the power splitting receiver j decoded from source i is

$$R_{j,i} = W \log(1 + (1 - \theta_i)P_i|h_{i,j}|^2/(\sigma^2 + \sigma^2_{sp})) \quad (3.4)$$

In practice, *power splitting* is based on a power splitter and *time switching* requires a simpler switcher. Power-splitting achieves better tradeoffs between information rate and amount of RF energy transferred.

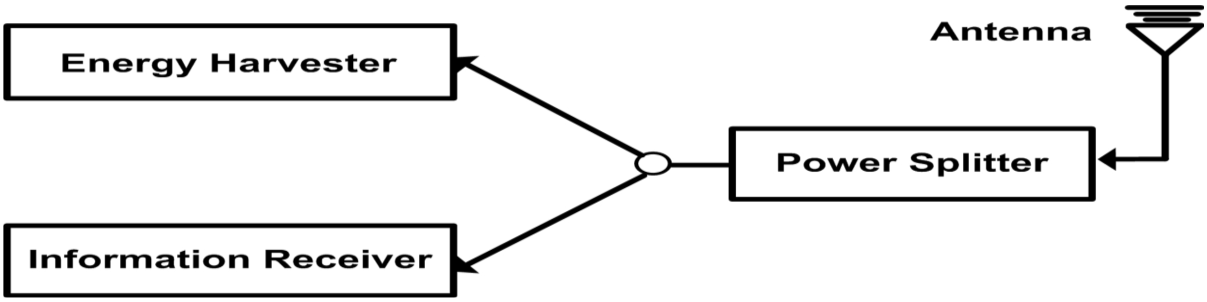

Fig. 3.3. Power Splitting Architecture

• ***Integrated Receiver Architecture*:** In the integrated receiver architecture, the implementation of RF-to-baseband conversion for information decoding, is integrated with the energy harvester via the rectifier. Therefore, this architecture allows a smaller form factor. Figure 3.4 demonstrates the model for integrated receiver architecture. The RF flow controller can also adopt a switcher or power splitter, like in the co-located receiver architecture. However, the difference is that the switcher and power splitter are adopted in the integrated receiver architecture.

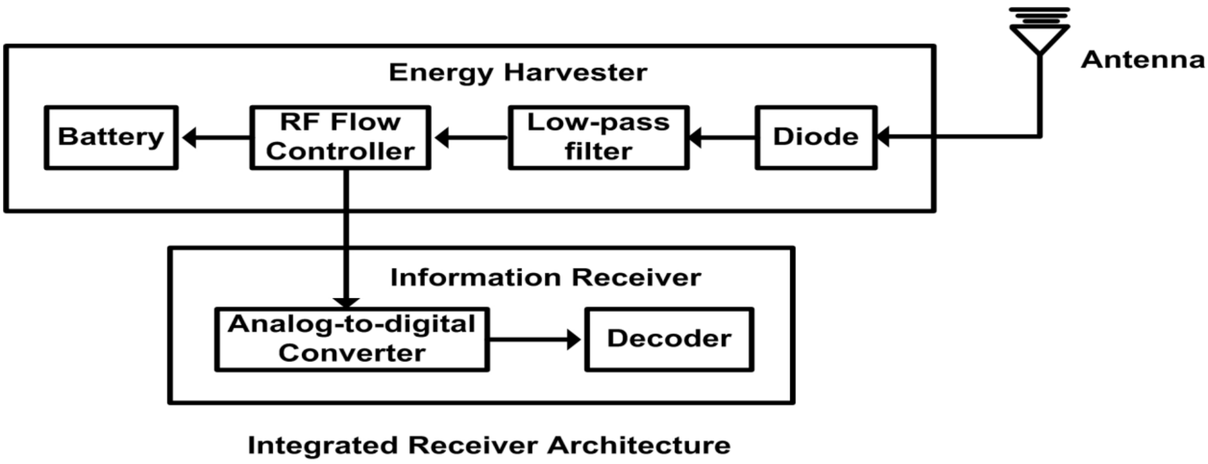

Fig. 3.4. Integrated Receiver Architecture

• ***Ideal Receiver Architecture*:** The ideal receiver architecture assumes that the receiver is able to extract the RF energy from the same signals used for information decoding. However, this assumption is not realistic in practice. The current circuit designs are not yet able to extract RF energy directly from the decoded information carrier. In other words, any energy carried by received RF signals sent for an information receiver is lost during the information decoding processing. When the circuit power consumptions are relatively small compared with the received signal power, the integrated receiver architecture outperforms the co-located receiver architecture at high harvested energy region, whereas the co-located receiver architecture is superior at low harvested energy region. When the circuit power consumption is high, the integrated receiver architecture performs better. For a system without minimum harvested energy requirement, the integrated receiver achieves higher information rate than that of the separated receiver at short transmission distances.

With an antenna array, the dual-antenna receiver architecture can be adopted. As shown in Fig.3.5, a combiner is adopted to coherently combine the input RF signals for enhancement of the received power. This architecture can be easily extended to the case with a larger number of antennas and the case with time-switching operation.

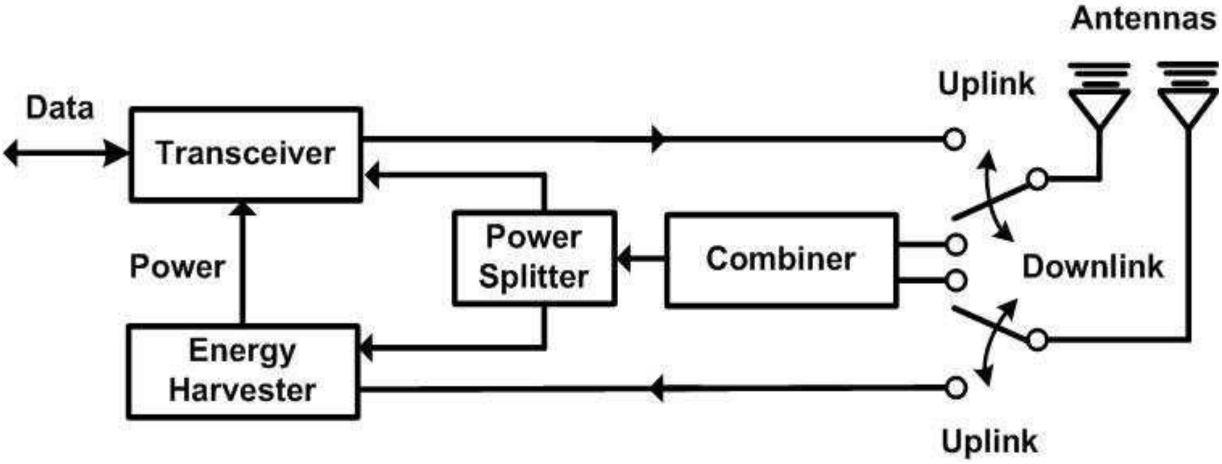

Fig. 3.5. An architecture for Dual antenna Receiver

VI. FUTURE DIRECTIONS AND PRACTICAL CHALLENGES

A. Distributed Energy Beamforming

Distributed energy beamforming enables a cluster of distributed energy sources to cooperatively emulate an antenna array by transmitting RF energy simultaneously in the same direction to an intended energy harvester for better diversity gains. The potential energy gains at the receiver from distributed energy beamforming are expected to be the same as that from the well-known information beamforming. However, challenges arise in the implementation, e.g., time synchronization among energy sources and coordination of distributed carriers in phase and frequency so that RF signals can be combined constructively at the receiver [20].

B. Interference Management

Some of the existing interference management techniques are interference alignment and interference cancellation, attempt to avoid or mitigate interference through spectrum scheduling. However, with RF energy harvesting, harmful interference can be turned into useful energy through a scheduling policy. In this context, how to mitigate interference as well as facilitate energy transfer, which may be conflicting, is the problem to be addressed. Furthermore, the scheduling policy can be combined with power management schemes for further improvement in energy efficiency.

C. Energy Trading

In RF-EHNs, RF energy becomes a valuable resource. The RF energy market can be established to economically manage this energy resource jointly with radio resource. For example, wireless charging service providers may act as RF energy suppliers to meet the energy demand from network nodes. The wireless energy service providers can decide on pricing and guarantee the quality of charging service. One of the efficient approaches in this dynamic market is to develop demand side management, which allows the service providers and network nodes to interact like in smart grid, to guarantee energy efficiency and reliability. However, the issues related to the amount of RF energy and price at which they are willing to trade while optimizing the trade-off between the revenue and cost must be investigated.

D. Effect of Mobility

Network nodes, RF sources, and information gateway can be mobile. Therefore, mobility becomes an important factor for RF energy harvesting and information transmission. The major issue is due to the fact that the energy harvesting and information transmission performances become time-varying, and resource allocation has to be dynamic and adaptive.

When compared, impact of mobile RF source under two different mobility models, namely *center-tocenter mobility (CM) model* and *around edges moving (EM) model* with the focus on the energy gain at receivers. The trade-off between transmit power and distance is explored, taking the energy loss during movement into account. It is found that CM yields better network performance in small networks with high node density. By contrast, EM yields better performance in large networks with low node density.

E. Network Coding

Network coding is well-known to be energy efficient in information transmission. With network coding, senders are allowed to transmit information simultaneously. This property, especially in large-scale network, increases the amount of RF energy that can be harvested. During the time slots when relays or senders are not transmitting, they can harvest ambient RF signals. The lifetime of the network for a two-way relay network with network coding can be increased up to 70% by enabling RF energy harvesting. From the perspective of network lifetime, more diverse network models and network coding schemes, such as physical-layer network coding and analogy network coding, are worth to be explored. Intuitively, taking advantage of the broadcast nature of RF signals to reuse some of the dissipated energy can lead to energy saving. However, theoretically, whether RF energy harvesting will increase the upper bound of energy gain or not and how much exactly the bound will increase still require further investigation.

F. Impact on Health

It has long been recognized that intense RF exposure can cause heating of materials with finite conductivity, including biological tissues. Some effects to genes are noticed when the RF power reaches the upper bound of international security levels. Although there are many existing studies on the health risks of mobile phones, little effort has been made for investigation on health effect caused by a dedicated RF charger, which can release much higher power. Thus, there is a need to address the safety concerns on deploying RF chargers [18].

G. Practical Challenges

Due to the inverse-square law that the power density of RF waves decreases proportionally to the inverse of the square of the propagation distance, practical RF energy transfer and harvesting that complies to FCC regulations is limited to a local area. For example, the FCC allows operation up to 4W equivalent isotropically radiated power. However, to realize 5.5μW energy transfer rate with a 4W power source, only the distance of 15 meters is possible.

Other than transfer distance, RF energy harvesting rate is also largely affected by the direction and gain of the receive antennas. Therefore, to improve the energy harvesting efficiency, devising a high gain antenna (e.g., based on materials and geometry) for a wide range of frequency is an important research issue [19].

Impedance mismatching occurs when the input resistance and reactance of the rectifier do not equal to that of the antenna. In this context, the antenna is not able to deliver all the harvested power to the rectifier. Thus, impedance variations (e.g., introduced by on-body antennas) can severely degrade the energy conversion efficiency. There is a need to develop circuit design techniques that automatically tune the parameters to minimize impedance mismatch.

The RF-to-DC conversion efficiency depends on the density of harvested RF power. Improving the RF-to-DC conversion efficiency at low harvested power input is important. Moreover, realizing a high-efficient low power DC-to-DC converter, which converts a source of DC from a voltage level to another would be another effort to achieve highly efficient RF energy harvesting.

RF energy harvesting components need to be small enough to be embedded in low-power devices. For example, the size of an RF-powered sensor should be smaller than or comparable to that of a battery-power sensor. An RF energy harvesting component may require an independent antenna, matching network and rectifier. The antenna size has a crucial impact on an energy harvesting rate. Additionally, high voltage at the output of a rectifier requires very high impedance loads (e.g., 5M), which is a function of the length of the impedance. Thus, it is challenging to reduce the size of embedded devices while maintaining high energy harvesting efficiency.

Without line-of-sight for RF waves from an RF source to an energy harvester, the considerable energy transfer loss is expected. Therefore, the RF energy source must be optimally placed to support multiple receivers to be charged. Moreover, in a mobile environment, the mobility of receivers and energy sources can affect the RF energy transfer significantly.

The sensitivity of an information receiver is typically much higher than that of an RF energy harvester. Consequently, a receiver located at a distance away from an RF transmitter may be able only to decode information and fail to extract energy from the RF signals. In this case, any SWIPT scheme cannot be used efficiently. Therefore, improving the sensitivity of RF energy harvesting circuit is crucial.

For RF-powered devices, as the transmit power is typical low, multiple antennas can be adopted to improve the transmission efficiency. However, larger power consumption comes along when the number of antennas increases. Thus, there exists a trade off between the transmission efficiency and power consumption. The scheme to optimize this trade-off needs to be developed. This issue becomes more complicated in a dynamic environment, e.g., with varying energy harvesting rate.

As RF-powered devices typically have a strict operation power constraint, it is not practical to support high computation algorithms. Any schemes, such as modulation and coding, receiver operation policy and routing protocol, to be adopted need to be energy-efficient and low-power. Hence, power consumption is always a serious concern in RF-powered devices, which may require the re-design of existing schemes and algorithms for conventional networks.

VII. CONCLUSIONS

The RF-EHNs is a far field or radiative technique which uses harvest-use or harvest-store-use method for managing the power. The RF Sources for energy harvesting are dedicated RF Sources and dynamic ambient RF sources. Different receiver architectures like separated receiver, co-located receivers, integrated receiver architectures can be used for receiving the power depending on the application. Some of the applications of RF-EHNs are Wireless sensor networks, wireless body network, RFID tags and charging for a wide variety of low power mobile devices. Some of the open design issues are Distributed Energy beamforming, interference management, network coding etc. Impedance matching, Sensitivity of the receiver, transmission efficiency are the practical challenges that are to be looked up on when designing RF energy harvester.

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