# Chapter 1

# Introduction

Recently, there has been an upsurge of research interests in radio frequency (RF) energy harvesting/scavenging technique [1] , or RF harvesting in short, which is the capability of converting the received RF signals into electricity. This technique becomes a promising solution to power energy-constrained wireless networks.

Conventionally, the energy-constrained wireless networks, such as wireless sensor networks, have a limited lifetime which largely confines the network performance. In contrast, an RF energy harvesting network (RF-EHN) has a sustainable power supply from a radio environment. Therefore, the RF energy harvesting capability allows the wireless devices to harvest energy from RF signals for their information processing and transmission.

Consequently, RF-EHNs have found their applications quickly in various forms, such as wireless sensor networks [2], wireless body networks [3], and wireless charging systems. With the increasingly emerging applications of RF energy harvesting/charging, the Wireless Power Consortium is also making the efforts of establishing an international standard for the RF energy harvesting technique.

Microwave power transfer (MPT) refers to wirelessly transmitting energy from one place to another. Simultaneous wireless information and power transfer (SWIPT) refers to using the same emitted electromagnetic (EM) wave field to transport both energy that is harvested at the receiver, and information that is decoded by the receiver In the past decades, much research effort has been directed towards developing MPT for replacing cables in long-distance power transfer either terrestrially [1] or from solar satellites to the earth [2].

This has led to a series of breakthroughs in microwave technology including high-power microwave generators and, more importantly in the current context, the invention of rectennas (rectifying antennas) for efficient RF to DC conversion [1]. This technology has been applied to the design of helicopters and airplanes powered solely by microwaves [3].

Most prior research on MPT focuses on the design of compact and efficient rectennas or similar energy harvesters [1], [4]. More recently there has been interest in the powering of low-power devices and even trickle-recharging of certain personal communications devices. There is already equipment available that does this [5], by broadcasting omni-directionally with an RF power of about 1 W, and harvesting several mW. With a massive transmitter array, power could be focused so that the harvested power is increased hundreds of times. The power levels involved are still small, much smaller than the emitted RF power by some cell phones (up to 2 W for GSM), so absorption by the human body does not appear to be a fundamental technological problem. Moreover, various safety precautions could be applied if deemed important.

With SWIPT, one and the same wave-field is used to transmit energy and information. This has several advantages. First, separate transmission of power and information by time division is suboptimal in terms of efficiently using the available power and bandwidth. SWIPT, by contrast, may exploit integrated transceiver designs. Second, with SWIPT, interference to the communication systems can be kept under control. This is especially important in multi-user systems with many potential receivers who would suffer from interference. By contrast, traditional microwave power transfer (MPT) relies on transmission of a single tone (and its unintended harmonics), which can interfere with communication links. Furthermore, MPT does not have any dedicated spectrum. Hence, as such, for use in existing bands, it must be integrated with communication solutions.

A key application of SWIPT that we foresee is to provide power to, and communicate with, sensors for which battery replacement is difficult or even impossible [6]. Radio-frequency identification (RFID) tags are one important example. RFID is already a very widely used technology, but its full potential is probably not fully exploited. A major limitation is the small range of RFID readers with constrained power. Another limitation is the ability of readers to correctly resolve different RFID tag returns that arrive at the receiver superimposed on one another. Many other applications, for example, in the chemical process industry, in environmental monitoring, in oil platforms and pipelines and in surveillance and national security applications require sensors with extreme reliability. Often these sensors transmit rather modest amounts of data, in some applications, only a few bits per hour.

Typically the sensors are hard to access and therefore their batteries require long lifetimes and very low failure rates. Making SWIPT work will require integration between multi-antenna transmission, efficient energy harvesting, resource management and signal processing.

In RF energy harvesting, radio signals with frequency range from 300GHz to as low as 3kHz are used as a medium to carry energy in a form of electromagnetic radiation. RF energy transfer and harvesting is one of the wireless energy transfer techniques. The other techniques are inductive coupling and magnetic resonance coupling.

Inductive coupling [5] is based on magnetic coupling that delivers electrical energy between two coils tuned to resonate at the same frequency. The electric power is carried through the magnetic field between two coils.

Magnetic resonance coupling [6] utilizes evanescent-wave coupling to generate and transfer electrical energy between two resonators. The resonator is formed by adding a capacitance on an induction coil.

Both of the above two techniques are near-field wireless transmission featured with high power density and conversion efficiency. The power transmission efficiency depends on the coupling coefficient, which depends on the distance between two coils/resonators.

The power strength is attenuated according to the cube of the reciprocal of the distance [7], [8], specifically, 60 dB per decade of the distance, which results in limited power transfer distance. Besides, both inductive coupling and resonance coupling require calibration and alignment of coils/resonators at transmitters and receivers. Therefore, they are not suitable for mobile and remote replenishment/charging. In contrast, RF energy transfer has no such limitation. As the radiative electromagnetic wave cannot retroact upon the antenna that generated it (by capacitive or inductive coupling) at a distance of above $\lambda/(2\pi)$ [9], RF energy transfer can be regarded as a far-field energy transfer technique. Thus, RF energy transfer is suitable for powering a larger number of devices distributed in a wide area. The signal strength of far-field RF transmission is attenuated according to the reciprocal of the distance between transmitter and receiver, specifically, 20 dB per decade of the distance. Table I shows the comparison between the three major wireless energy transfer techniques. We can see that RF energy transfer technique has clear advantages in effective energy transfer distance. However, it has low RF-to-DC energy conversion efficiency especially when the harvested RF power is small. The readers can refer to [11], [12] for more detailed introduction of wireless energy transfer techniques.

Wireless power transfer has caught research attention since long ago, as a separate problem with wireless information transmission. Traditionally, free-space beaming and antennas with large apertures were used to overcome propagation loss for large power transfer.

For example, in 1960's, the authors in [14] demonstrate a small helicopter hovering at an height of 50-feet, powered by an RF source with a DC power supply of 270W operating on 2.45GHz on the ground. In [15], the authors demonstrate a space-to-earth power transfer system using gigantic transmit antenna arrays at a satellite and receive antenna arrays at a ground station. For transmit power of 2.7GW, the power transfer efficiency is estimated to be 45% over a transfer distance of 36000km.

During the past decade, with the development in RF energy harvesting circuit, low power transfer for powering mobile terminals in wireless communication systems began to attract increasing attention [16], [17]. The authors in [16] propose a network architecture for RF charging stations, overlaying with an uplink cellular network. In [17], a harvest-then-transmit protocol is introduced for power transfer in wireless broadcast system.

Moreover, various modern beamforming techniques are employed to improve power transfer efficiency [17]–[19] for mobile applications. It is until recently that the dual use of RF signals for delivering energy as well as for transporting information has been advocated [20], [21].

Simultaneous wireless information and power transfer (SWIPT) [22] is proposed for delivering RF energy, usually in a low power region (e.g., for sensor networks). SWIPT provides the advantage of delivering controllable and efficient on-demand wireless information and energy concurrently, which offers a low-cost option for sustainable operations of wireless systems without hardware modification on the transmitter side. However, recent research has recognized that optimizing wireless information and energy transfer simultaneously brings tradeoff on the design of a wireless system [20], [23].

# Chapter2

**Design Issues in RF Energy Harvesting Networks**

- **CIRCUIT DESIGN**
  - Antenna
  - Matching Network
  - Rectifier
  - Receiver Architecture
- **Single-Hop Network with RF Energy Harvesting**
  - Multi-user Scheduling
  - Receiver Operation Policy
- **Multi-Antenna Network with RF Energy Harvesting**
  - SWIPT Beamforming Optimization without Secure Communication Requirement
  - SWIPT beamforming for Secure Communication
  - Energy Beamforming
  - Information Feedback Mechanism
- **Relay Networks with RF Energy Harvesting**
  - Relay Operation Policy
  - Relay Selection
  - Power Allocation
- **RF-powered Cognitive Radio Networks**
  - Spectrum Sensing
  - Spectrum Access
  - Spectrum Management
  - Spectrum Handoff
- **COMMUNICATION PROTOCOLS**
  - MAC Protocol
  - Routing Protocol

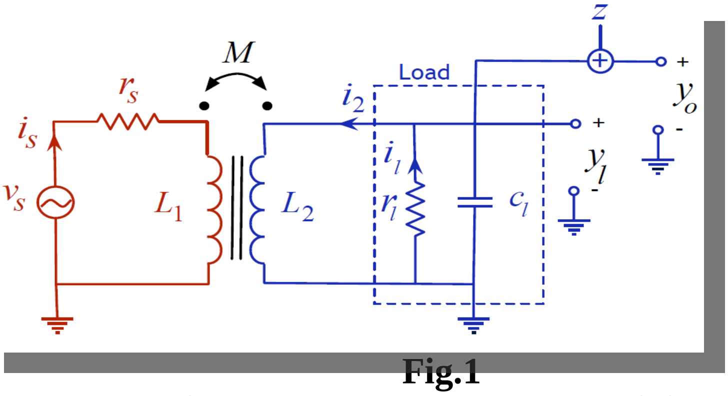
# Chapter 3

## Hypothesis

Ignoring the practical motivations for a moment, consider a hypothetical meeting of Claude Shannon and Nikola Tesla. They are both looking at the circuit in Fig. 1. While Tesla designed it to deliver power wirelessly to the load, Shannon wants to use it to send information. Tesla observes the relation between the total available power $P^{avail}$ and the delivered power $P^{del}$ across frequency. Noticing that the efficiency function,

$$\eta(f) = P^{del}(f) \,/\, P^{avail}(f)$$

has a peak (see Fig. 2) at frequency of $f_{peak}$ ( ≈5 MHz for the choice of circuit parameters in Fig. 2), Tesla wants to use just the one sinusoid at the max-efficiency frequency as the input




This would not work for Shannon, since a sinusoid of fixed frequency has zero-bandwidth, and therefore zero communication rate. Shannon looks at the noisy output $y_o(t) = y_l(t) + z(t)$ (where z(t) is additive white Gaussian noise of intensity $N_0$) and views the circuit as a frequency selective channel1, with the fading parameter h($f$) satisfying

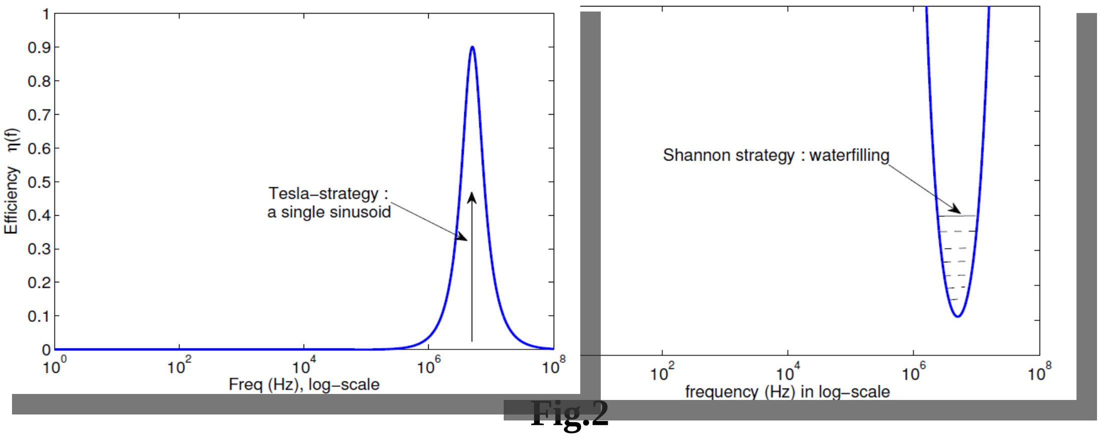



Fig.2

$|h(f)|^2$ = h(f). Therefore, Shannon wants to use the "waterfilling" allocation of Fig. 2.

This Hypothesis could simply be a fanciful investigation about how Shannon and Tesla would have arrived at a compromise. However, it has a much more practical interpretation as well. The coupled-inductor circuit shown in Fig. 1 is also the most common implementation of wireless power-transfer used, for example in many medical implants (e.g. the cochlear implant) [2, Ch. 16], futuristic wireless memories, electronic toothbrushes [3], and even Tesla's famous Wardenclyff tower.

Most such applications require, or can be enhanced, by simultaneous data-transfer as well. An understanding of the tradeoff between information and power transfer may therefore find utility in all these applications. There is reason why many current implementations do not use the same link for information and power transfer. Sarpeshkar notes in his recent book [2], "… power efficiency is maximized for narrowband links that operate at low frequencies," whereas "data signals : : : require larger link bandwidths, which are more easily obtained at higher operating frequencies." A separate coil for data transfer may therefore appear to be a good strategy.

However, provisioning for an additional communication channel may be unnecessary, or even unwise because the infrastructure for this extra channel occupies chip-area and also consumes power. Further, recent progress in wireless power transfer for medical implants by Poon et al [6] shows that the optimal transmit frequency for human body is several hundreds of megahertz, increasing the available bandwidth significantly (though the motivation in [6] is reduction in the antenna size).

Even without taking the results of [6] into account, consider the current implementation of cochlear implants: even at small distances of a few millimeters (the coils are separated merely by the skin), the available (3-dB) bandwidth is on the order of a few MHz. The required data rate is about 1 Mbps, or smaller. Our example circuit (though for much lower frequencies and bandwidth, see Fig. 3) suggests that with less than 2% loss in power efficiency, communication rates of about half the waterfilling capacity can be attained in some cases. The power link may well suffice for transferring information as well.

But cochlear implants require very small data rates as compared to wireless memories. At the same time (as noted in [2, Fig. 16.7]), the bandwidth of a coupled-inductor circuit increases rapidly with the gap between the two coils. Therefore, while the required data rates will be much larger for wireless memories, so will be the available bandwidth. We believe that a deeper investigation is required to conclude if a separate data transfer link is required in all coupled inductor- based implementations.

A related problem was considered by Gastpar [8], where received power constraints are imposed on devices so that the interference they cause is limited. While in Gastpar's case there is a limit on how large the received power can be (i.e. the power is constrained from above), here there is a required received power that is constrained from below.

## Chapter 4

# Architecture of RF Energy Harvesting Network.

A typical centralized architecture of an RF-EHN, as shown in Fig.3, 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 equipments that communicate 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.

The information gateway has an energy harvesting zone and an information transmission zone represented by the dashed circles in Fig.3. 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. Note that the decentralized RFEHN also has a similar architecture to that shown in except that the network nodes communicate among each other directly. Fig.4 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 an 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.

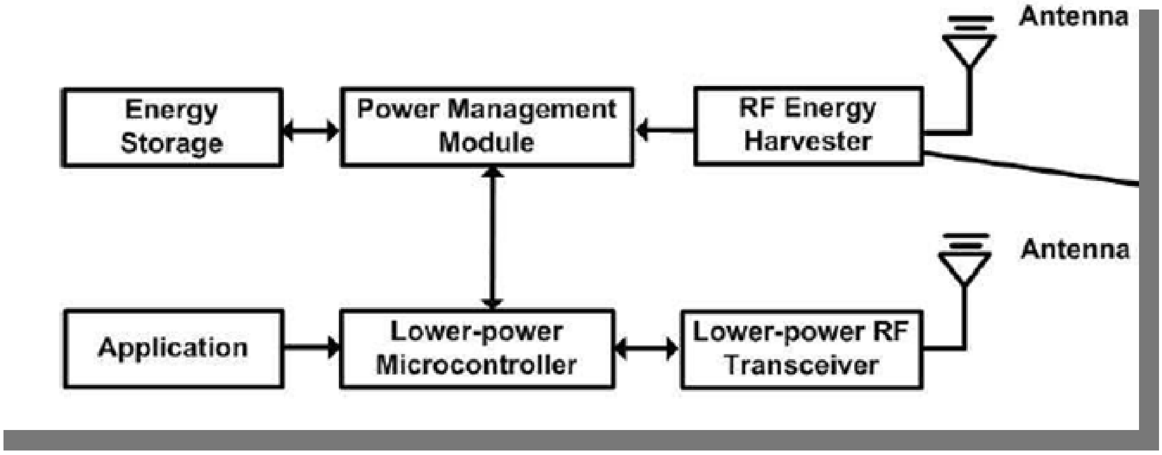



**Fig.3**

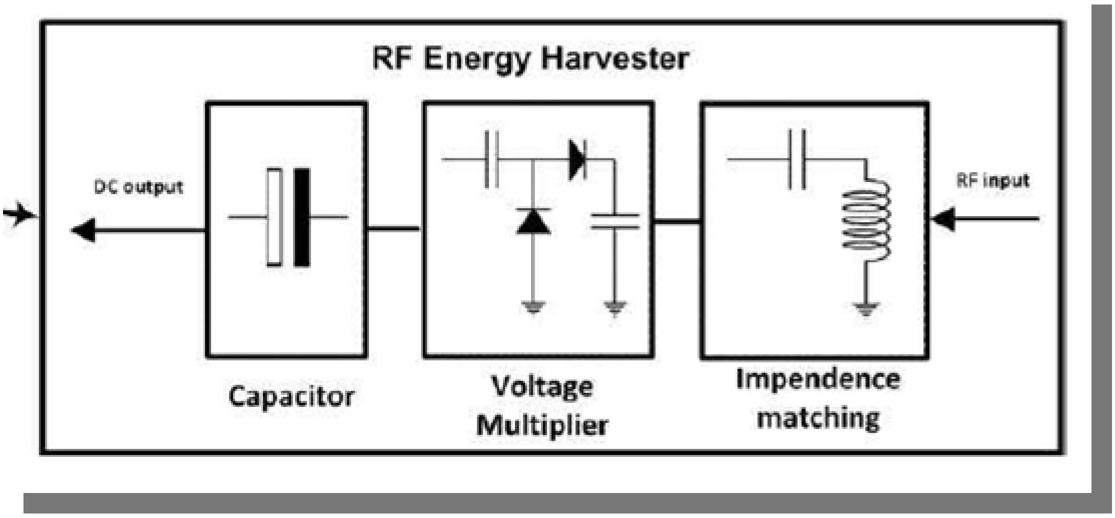



**Fig.4**

Fig.4 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 hand 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) [22] concept. This concept allows the information receiver and RF energy harvester to share the same antenna or antenna array.

# Chapter 5

## 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 [24] as follows:

$$P_R = P_T G_T G_R \lambda^2 / (4\pi d)^2 L$$

where $P_R$ is the received power, $P_T$ is the transmit 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

$$P_R = P_T G_T G_R h_t^2 h_r^2 / d^4 L$$

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 modelling. A practical and widely adopted probabilistic model is a Rayleigh model [25], which represents the situation when there is no line-of-sight channel between a transmitter and receiver.

In the Rayleigh model, we have

$$P_R = P^{det}{}_R \times 10^L \times \log(1 - \mathrm{unif}(0, 1))$$

R represents the received RF power calculated by a deterministic model. The path loss factor L is defined as $L = -\alpha \log_{10}(d/d_0)$, where $d_0$ is a reference distance.
unif(0, 1) denotes a random number generated following uniform distribution between 0 and 1.

The above has presented three common RF propagation models. The aggregated harvested RF energy can be calculated based on the adoption of the network model and RF propagation model. Readers can refer to [26] for more detailed survey of RF propagation models in different environments.

## Chapter 6

# 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 Powercaster transmitter [27] 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 [28]. 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. Note that the dedicated RF sources could be mobile, which can periodically move and transfer RF energy to network nodes. In [29]–[31], different RF energy transmission schemes for mobile power transmitters to replenish wireless sensor networks are investigated.

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.

- 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. In [32], the performance analysis of a sensor powered by static ambient RF sources is performed using a stochastic geometry approach. An interesting finding is that when the distribution of ambient RF sources exhibits stronger repulsion, larger RF energy harvesting rate can be achieved at the sensor.

- 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. The study in [33] is an example of 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.

## Chapter 7

# CIRCUIT DESIGN

This section introduces some background related to the hardware circuit designs of RF energy harvesting devices. Here, the purpose is to introduce some basic knowledge of circuit design required to understand the communication aspects of the RF-EHN. Again, the comprehensive survey of the works related to circuit design and electronics for RF energy harvesting is beyond the scope of this paper.

### A. 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, as shown in [101], 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 [102].

### B. Antenna Design

An antenna is responsible for capturing RF signals. Miniaturised size and high antenna gain are the main aims of antenna technology. The authors in [97] report a comparative study of several antenna designs for RF energy harvesting. Several antenna topologies for RF energy harvesting have been reported in [110]. In [111], the authors perform a comparison of existing antenna structures. Antenna array design has also been studied for effective RF energy harvesting in [112], [113]. Antenna arrays are effective in increasing the capability for low input power. However, a tradeoff exists between antenna size and performance. For hardware implementations, research efforts have been made for narrow-band antenna (typically from several to tens of MHz) designs in a single band [73], [108], [114], [115], and dual bands [112], [116]–[118] as well as triple bands [119]– [121]. Moreover, broadband antenna designs (typical on order of 1GHz) have been the focus of some recent work [122]– [129].

### C. 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 [130]. To this end, a matching network is usually made with reactive components such as coils and capacitors that are not dissipative [131]. 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. The detailed introduction of these circuits can be found in [131].

## D. 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 [132], a bridge of diodes [133] and a voltage rectifier multiplier [134]. 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(s) [131]. 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 [135].

In [136], a model is developed to characterize the RF-to- DC rectification with low input power. Based on the model, the authors derive closed-form solutions for the equilibrium voltage and the input resistance of the rectifier. A quasi-static model is further developed to describe the dynamic charging of the capacitor of the rectifier.

## E. Receiver Architecture Design

The traditional information receiver architecture designed for information reception may not be optimal for SWIPT. 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) [22]. This inspires the research efforts in devising the receivers for RF-power information receivers. Currently, there are four typical types of receiver architectures.

- **Separated Receiver Architecture**: Separated receiver architecture, also known as antenna-switching [22], equips an energy harvester and information receiver with independent antenna(s) so that they observe different channels. Figure 4a 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 to perform energy harvesting and information decoding independently and concurrently. The antenna-switching scheme [22] can be used to optimize the performance of the separated receiver architecture.
- **Co-located Receiver Architecture:** The co-located receiver architecture let an energy harvester and an information receiver share the same antenna(s) so that they observe the same channel(s). 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. 4b, 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 working in the energy harvesting mode, the power harvested from source i can be calculated as follows:

$$P_{j,i} = \eta P_i |h_{i,j}|^2$$

where $\eta$ denotes the energy harvesting efficiency factor, $P_i$ is the transmit power at source i, and $h_{i,j}$ denotes the channel gain between source i and receiver j. Let W and $\sigma^2$ 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

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

In the power-splitting architecture, as shown in Fig. 4c, the received RF signals are split into two streams for the information receiver and RF energy harvester with different power levels. Let $\theta_j$ € [0, 1] denote the power splitting coefficient for receiver j, i.e., $\theta_j$ 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:

$$P_{j,i} = \_P_i|h_{i,j}|^2\theta_j.$$

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

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

In practice, power splitting is based on a power splitter and time switching requires a simpler switcher. It has been recognized that theoretically power-splitting achieves better tradeoffs between information rate and amount of RF energy transferred [22], [137]

- **Integrated Receiver Architecture:** In the integrated receiver architecture proposed in [137], 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 4d demonstrates the model for integrated receiver architecture. Note that 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.
- **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. Any energy carried by received RF signals sent for an information receiver is lost during the information decoding processing. Existing works that consider ideal receiver architecture, such as [20], [23], [138], [139], generally analyze the theoretical upper bound of receiver performance. The studies in [137] show that 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. It is also shown that 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 introduced in [141] can be adopted. Illustrated in Fig. 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.

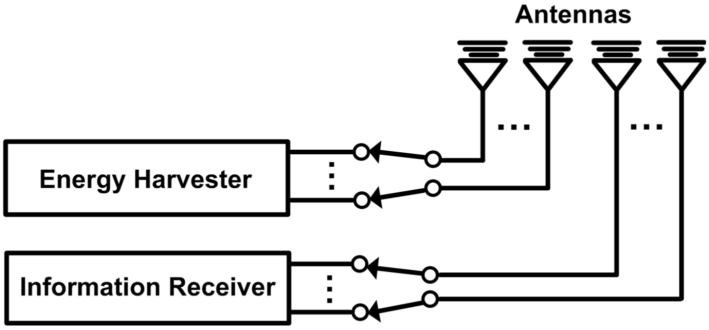



**Fig.4a**

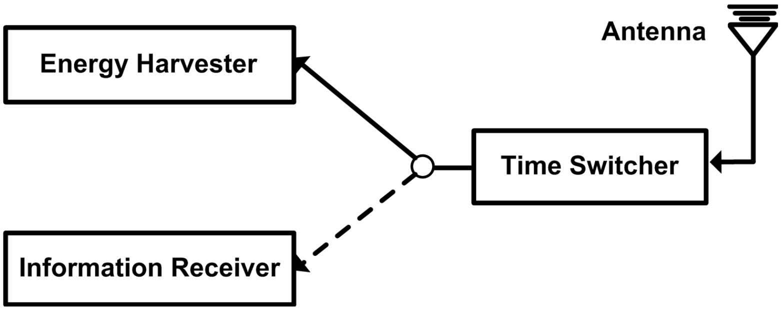



**Fig.4b**

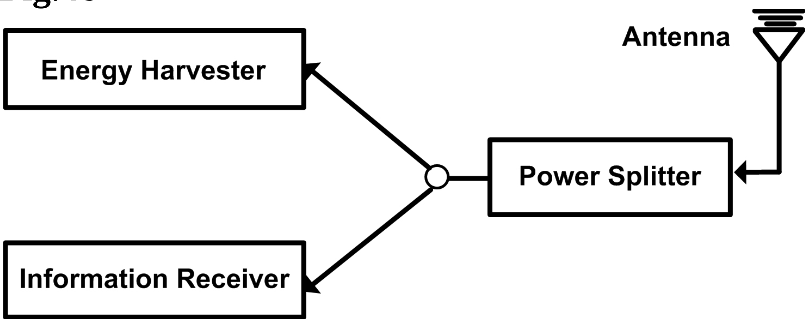



**Fig.4c**

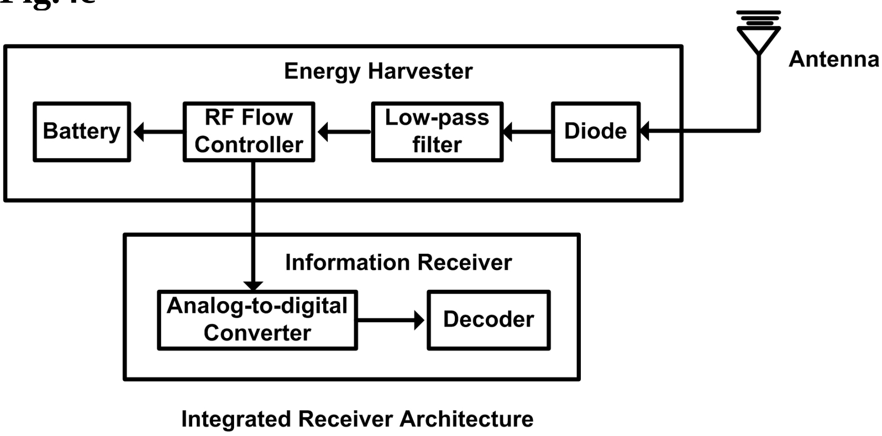



**Fig.4d**

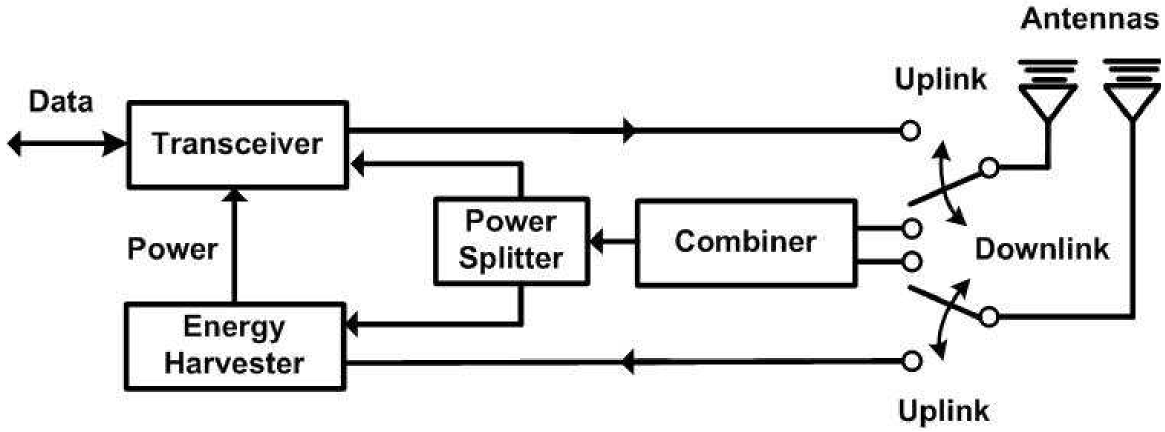
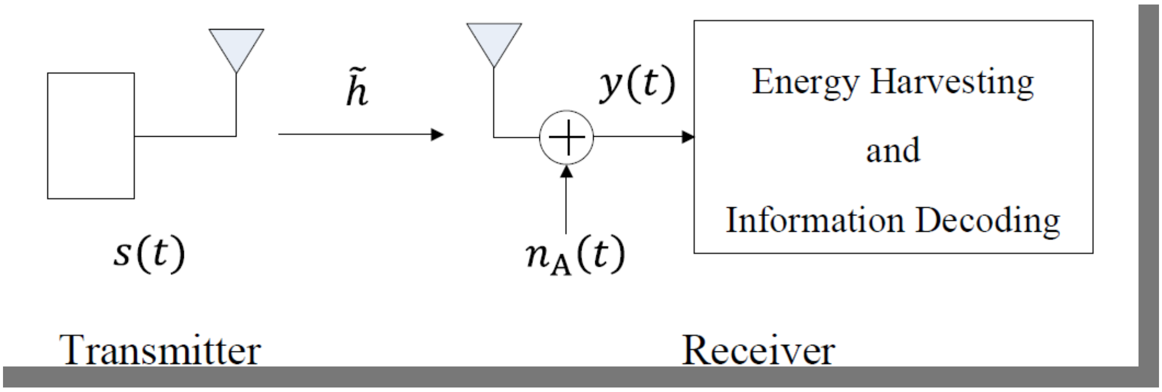

Antennas
Uplink
Data
Transceiver
Power
Splitter
Combiner
Downlink
Power
Energy
Harvester
Uplink

**Fig.5**

# Chapter 8

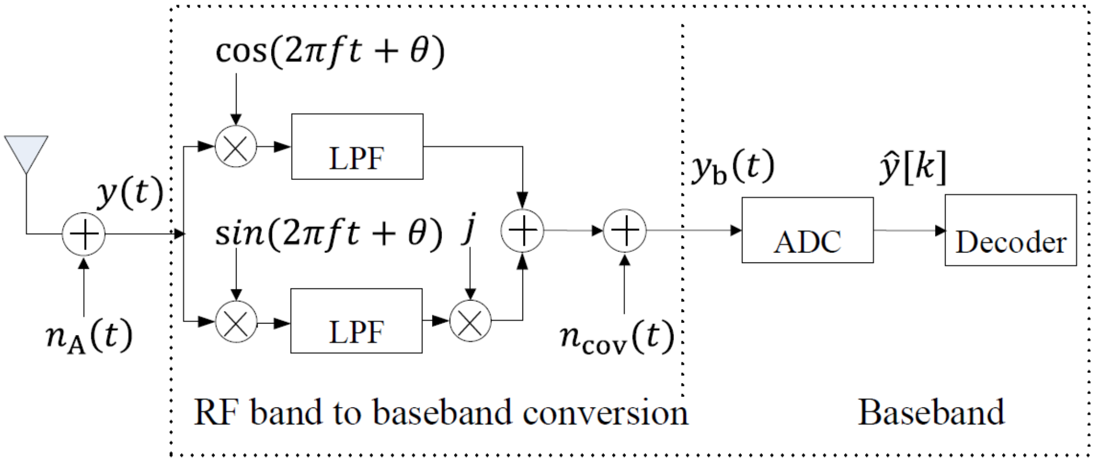
## System Model




- Baseband signal: $x(t) = A(t)e^{j\phi(t)}$ with $\mathbb{E}[|x(t)|^2] = 1$
- Transmitted signal: $s(t) = \sqrt{2P}\mathcal{R}\{x(t)e^{j2\pi ft}\}$
- Complex channel: $\tilde{h} = \sqrt{h}e^{j\theta}$
- Antenna noise is modeled as narrow-band Gaussian noise:
  - $n_A(t) = \sqrt{2}\mathcal{R}\{\tilde{n}_A(t)e^{j2\pi ft}\} = \sqrt{2}\left(n_I(t)\cos 2\pi ft - n_Q(t)\sin 2\pi ft\right)$

# Chapter 9

## Information Receiver




- RF to baseband conversion by mixers, which are active devices.
- Equivalent baseband channel (AWGN):

$$Y = \sqrt{hP}X + Z$$

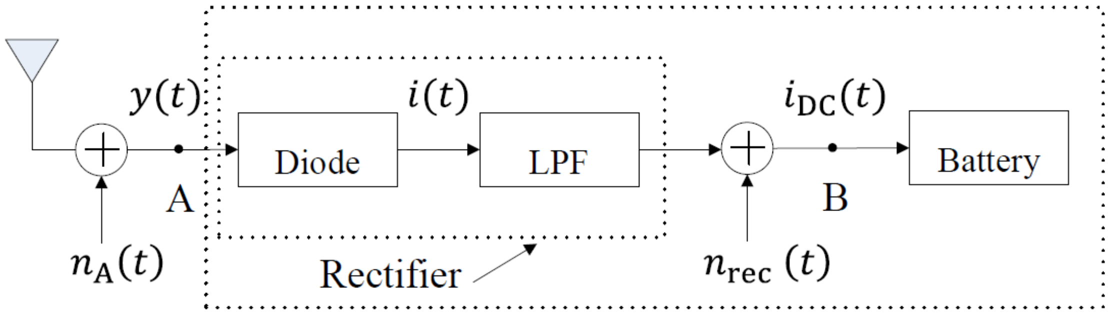
where $Z \sim \mathcal{CN}(0, \sigma_A^2 + \sigma_{cov}^2)$.

- Maximum achievable rate:

$$R = \log_2\left(1 + \frac{hP}{\sigma_A^2 + \sigma_{cov}^2}\right).$$

# Chapter 10

## Energy Receiver




The received RF band signal $y(t)$ is converted to a DC signal $i_{\mathrm{DC}}(t)$ by a rectifier.

- Diode:

$$i(t) = I_s\left(e^{\gamma y(t)} - 1\right) = a_1 y(t) + a_2 y^2(t) + a_3 y^3(t) + \cdots$$

- After LPF, the harmonic components at $f, 2f, \ldots$ are removed:

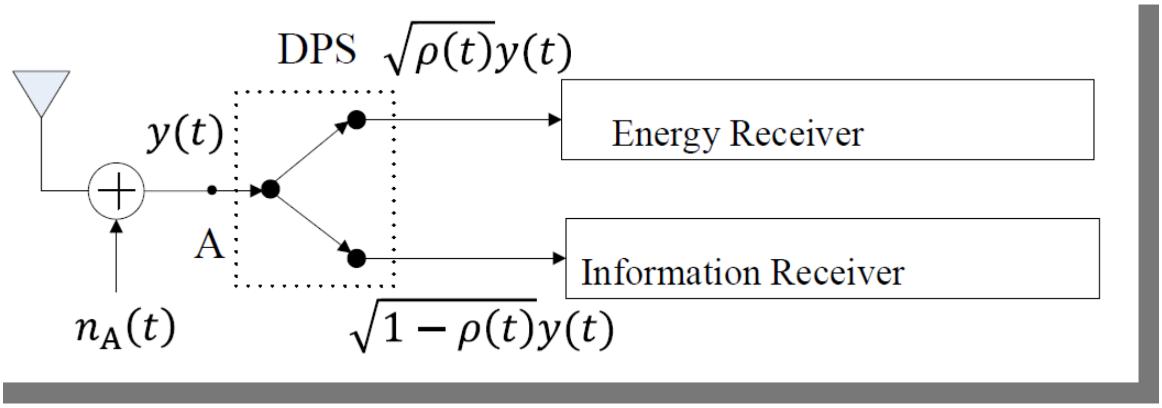
$$i_{\mathrm{DC}}(t) \approx \left(\sqrt{hP}A(t)\cos\left(\phi(t)+\theta\right) + n_{\mathrm{I}}(t)\right)^2 + \left(\sqrt{hP}A(t)\sin\left(\phi(t)+\theta\right) + n_{\mathrm{Q}}(t)\right)^2 + n_{\mathrm{rec}}(t)$$

- With conversion efficiency $\zeta$, the harvested energy is:

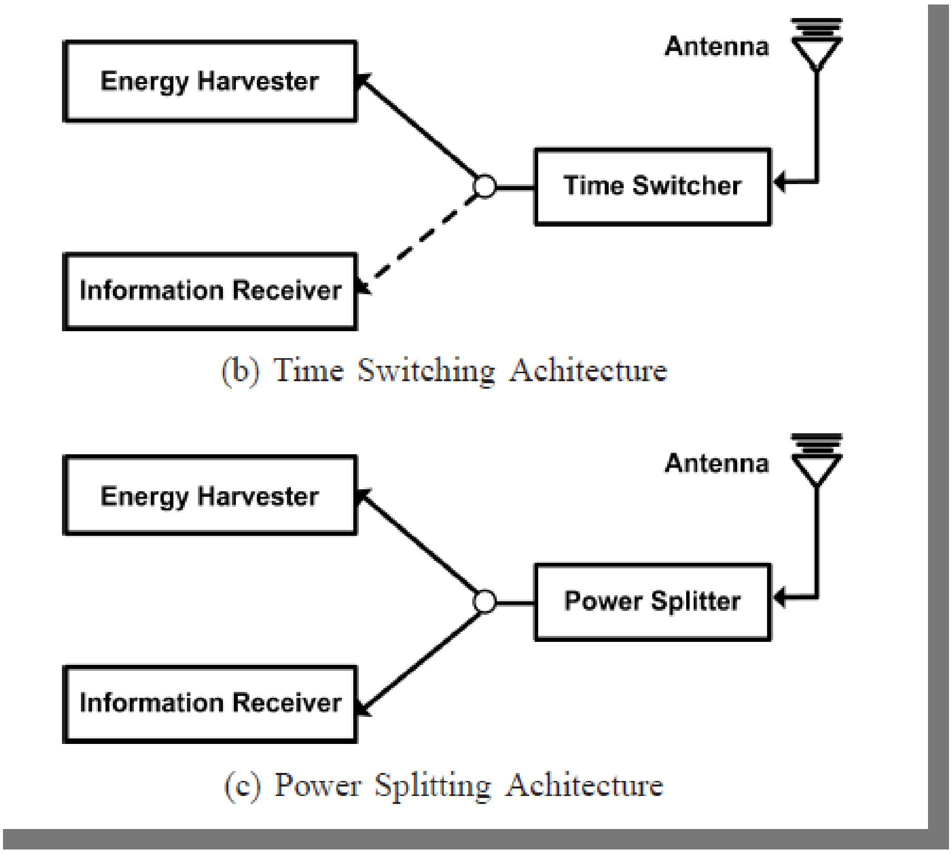
$$Q = \mathbb{E}[i_{\mathrm{DC}}(t)] = \zeta h P$$

## Chapter 11

# Separated Information and Energy Receiver




- Received signal split at RF band (point A)
- Power splitting ratio can be set different over time: Dynamic Power Splitting (DPS)




(b) Time Switching Achitecture



(c) Power Splitting Achitecture

## Chapter 12

# 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, as shown in [34], 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 antenna(s). 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. • 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. As introduced above, 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 tradeoff between the transmission efficiency and power consumption. The scheme to optimize this tradeoff 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.

# Chapter 13

## References

[1] W. C. Brown, “The history of power transmission by radio waves,” IEEE Trans. on Microwave Theory and Techniques, vol. 32, pp. 1230–1242, Sep. 1984.
[2] J. O. Mcspadden and J. C. Mankins, “Space solar power programs and microwave wireless power transmission technology,” IEEE Microwave Magazine, vol. 3, pp. 46–57, Apr. 2002.
[3] J. J. Schlesak, A. Alden, and T. Ohno, “A microwave powered high altitude platform,” IEEE MTT-S Digest, pp. 283–286, 1988.
[4] T. Le, K. Mayaram, and T. Fiez, “Efficient far-field radio frequency energy harvesting for passively powered sensor networks,” IEEE Journal of Solid-State Circuits, vol. 43, pp. 1287–1302, May 2008.
[5] “P2110 - 915MHz RF powerharvester receiver,” Product Datasheet, Powercast Corp., pp. 1–12, 2010.
[6] F. Balouchi and B. Gohn, “Wirelss power,” Pike Research Report, 2Q 2012.
[7] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, “Scaling up MIMO: Opportunities and challenges with very large arrays,” IEEE Signal Proc. Magazine, vol. 30, pp. 40–60, Jan. 2013.
[8] L. R. Varshney, “Transporting information and energy simultaneously,” in Proc., IEEE Intl. Symposium on Information Theory, pp. 1612–1616, Jul. 2008.
[9] P. Grover and A. Sahai, “Shannon meets Tesla: Wireless information and power transfer,” in Proc., IEEE Intl. Symposium on Information Theory, pp. 2363–2367, Jun. 2010.
[10] H. J. Visser and R. J. M. Vullers, “RF energy harvesting and transport for wireless sensor network applications: principles and requirements,” Proceedings of the IEEE, vol. 101, no. 6, pp. 1410-1423, June 2013.
[11] H. Nishimoto, Y. Kawahara, and T. Asami, “Prototype implementation of ambient RF energy harvesting wireless sensor networks,” in Proceedings of IEEE Sensors, Kona, HI, November 2010.
[12] X. Zhang, H. Jiang, L. Zhang, C. Zhang, Z. Wang, and X. Chen, “An energy-efficient ASIC for wireless body sensor networks in medical applications,” IEEE Transactions on Biomedical Circuits and Systems, vol. 4, no. 1, pp. 11-18, Feb. 2010.
[13] http://www.wirelesspowerconsortium.com/
[14] H. Liu, “Maximizing efficiency of wireless power transfer with resonant Inductive Coupling,” 2011. (Available on-line at http://hxhl95.github.io/media/ib ee.pdf)
[15] J. O. Mcspadden and J. C. Mankins, “Space solar power programs and microwave wireless power transmission technology,” IEEE Microw. Mag., vol. 3, pp. 46-57, Apr. 2002.
[16] K. Huang and V. K. N. Lau, “Enabling wireless power transfer in cellular networks: architecture, modeling and deployment,” IEEE Transactions on Wireless Communications, vol 13, no. 2, pp. 902-912, Feb. 2014. [17] L. Liu, R. Zhang, and K. C. Chua, “Multi-antenna wireless powered communication with energy beamforming.” (available on-line at arXiv:1312.1450)
[18] G. Yang, C. K. Ho, and Y. L. Guan, “Dynamic resource allocation for multiple-antenna wireless power transfe,” IEEE Transactions on Signal Processing, vol. 62, no. 14, pp. 3565-3577, July 2014.
[19] X. Chen, X. Wang, and X. Chen, “Energy-efficient optimization for wireless information and power transfer in large-scale MIMO systems employing energy neamforming,” IEEE Wireless Communications Letters, vol. 2, no. 6, pp. 667-670, Dec. 2013.

[20] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," Science, vol. 317, no. 5834, pp. 83-86, June 2007.
[21] J. O. Mur-Miranda, W. Franklin, G. Fanti, Y. Feng, K. Omanakuttan, R. Ongie, A. Setjoadi, and N. Sharpe, "Wireless power transfer using weakly coupled magnetostatic resonators," in Proc. of IEEE Energy Conversion Congress and Exposition (ECCE), Atlanta, GA, Sept. 2010.
[22] Tutorial Overview of Inductively Coupled RFID Systems, UPM Rafsec, 2003. (available online at: www.rafsec.com/rfidsystems.pdf)
[23] R. C. Johnson, H. A. Ecker, and J. S. Hollis, "Determination of farfield antenna patterns from near-field measurements" Proceedings of the IEEE, vol. 61, no. 12, pp. 1668-1694, Dec. 1973.
[24] C. Mikeka and H. Arai, "Design issues in radio frequency energy harvesting system," Sustainable Energy Harvesting Technologies - Past, Present and Future, December 2011.
[25] N. Shinohara, "The wireless power transmission: inductive coupling, radio wave, and resonance coupling," Wiley Interdisciplinary Reviews: Energy and Environment, vol. 1, no. 3, pp. 337-346, Sept. 2012.
[26] L. Xie, Y. Shi, Y. T. Hou, and W. Lou, "Wireless power transfer and applications to sensor networks," IEEE Wireless Communications Magazine, vol. 20, no. 4, pp. 140-145, August 2013.
[27] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," Science, vol. 317, no. 5834, pp. 8386, July 2007.
[28] W. C. Brown, "Experiments involving a microwave beam to power and position a helicopter," IEEE Trans. on Aerospace and Electronic System, vol. AES-5, pp. 692-702, Sep. 1969.
[110] J. P. Thomas, M. A. Qidwai, and J. C. Kellogg, "Energy scavenging for small-unmanned systems," Journal of Power Sources, vol. 159, no. 2, pp. 1494-1509, September 2006.
[111] A. Aziz, A. Mutalib, and R. Othman, "Current developments of RF energy harvesting system for wireless sensor networks," Advances in information Sciences and Service Sciences (AISS), vol. 5, no. 11, pp. 328-338, June 2013.
[112] X. Shao, B. Li, N. Shahshahan, N. Goldman, T. S. Salter, and G. M. Metze, "A planner dual-band antenna design for RF energy harvesting applications," in Proc. of IEEE International Semiconductor Device Research Symposium (ISDRS), College Park, MD, Dec. 2011.
[113] J. M. Barcak, and H. P. Partal, "Efficient RF energy harvesting by using multiband microstrip antenna arrays with multistage rectifiers," in Proc. of IEEE Subthreshold Microelectronics Conference (SubVT), pp. 1-3, Waltham, MA, Oct. 2012.
[114] M. Arsalan, M.H. Ouda, L. Marnat, T. J. Ahmad, A. Shamim, and K. N. Salama, "A 5.2GHz, 0.5mW RF powered wireless sensor with dual on-chip antennas for implantable intraocular pressure monitoring," in Proc. of IEEE International Microwave Symposium Digest (IMS), pp. 1-4, Seattle, WA, June 2013.
[115] M. Arrawatia, M. S. Baghini, and G. Kumar, "RF energy harvesting system at 2.67 and 5.8GHz," in Proc. of IEEE Microwave Conference Proceedings (APMC), pp. 900-903, Yokohama, Dec. 2010. [116] Z. Zakaria, N. A. Zainuddin, M. Z. A. Abd Aziz, M. N. Husain, and M. A. Mutalib, "A parametric study on dual-band meander line monopole antenna for RF energy harvesting," in Proc. of IEEE International Conference on RFID-Technologies and Applications (RFID-TA), Johor Bahru, Malaysia, Sept. 2013.
[117] B. Li, X. Shao, N. Shahshahan, and N. Goldsman, T. Salter, and G. M.Metze, "An antenna co-design dual band RF energy harvester," IEEE Transactions on Circuits and Systems I, vol. 60, no. 12, pp. 3256-3266, Dec. 2013.
[118] Z. Zakaria, N. A. Zainuddin, M. Z. A. Abd Aziz, M. N. Husain, and M. A. Mutalib, "Dual-band monopole antenna for energy harvesting system," in Proc. of IEEE Symposium on Wireless Technology and Applications (ISWTA), Kuching, Malaysia, Sept. 2013.

[119] B. L. Pham, and A.-V. Pham, “Triple bands antenna and high efficiency rectifier design for RF energy harvesting at 900, 1900 and 2400 MHz,” in Proc. of IEEE MTT-S International Microwave Symposium Digest (IMS), Seattle, WA, June 2013.
[120] D. Masotti, A. Costanzo, and S. Adami, “Design and realization of a wearable multi-frequency RF energy harvesting system,” in Proc. Of IEEE European Conference on Antennas and Propagation (EUCAP), pp. 517-520, Rome, Italy, April 2011.
[121] S. Keyrouz, H. J. Visser, and A. G. Tijhuis, “Multi-band simultaneous radio frequency energy harvesting,” in Proc. of IEEE European Conference on Antennas and Propagation (EuCAP), pp. 3058-3061, Gothenburg, Sweden, April 2013.
[122] D. Yi, and T. Arslan, “Broadband differential antenna for full-wave RF energy scavenging system,” in Proc. of IEEE Antennas and Propagation Conference (LAPC), pp. 325-328, Loughborough, UK, Nov. 2013.
[123] A. Buonanno, M. D’Urso, and D. Pavone, “An ultra wide-band system for RF Energy harvesting,” in Proc. of IEEE European Conference on Antennas and Propagation (EUCAP), pp. 388-389, Rome, Italy, April 2011.
[124] A. Nimo, D. Grgic, and L. M. Reindl, “Ambient electromagnetic wireless energy harvesting using multiband planar antenna,” in Proc. Of IEEE International Multi-Conference on Systems, Signals and Devices (SSD), Chemnitz, German, March 2012.
[125] D. Yi, T. Arslan, and A. Hamilton, “Broadband antenna for RF energy scavenging system,” in Proc. of IEEE Antennas and Propagation Conference (LAPC), pp. 1-4, Loughborough, UK, Nov. 2012.
[126] J. Zhang, Y. Huang, and P. Cao, “Harvesting RF energy with rectenna arrays,” in Proc. of IEEE European Conference on Antennas and Propagation (EUCAP), pp. 365-367, Prague, Czech Republic, March 2012.
[127] J. Zhang, Y. Huang, and P. Cao, “A wideband cross dipole rectenna for RF wireless harvesting,” In Proc. of IEEE European Conference on Antennas and Propagation (EuCAP), pp. 3063-3067, Gothenburg, Sweden, April 2013.
[128] N. A. Zainuddin, Z. Zakaria, M. N. Husain, B. M. Derus, M. Z. A. A. Aziz, M. A. Mutalib, and M. A. Othman, “Design of wideband antenna for RF energy harvesting system,” in Proc. of IEEE International Conference on Instrumentation, Communications, Information Technology