

RF Energy Harvesting for Hybrid Application: Review and Analysis

Rajiv Dahiya, A. K. Arora, V. R. Singh

Abstract—Wireless Sensor node is one of the important technologies for the recent world applications like military, agriculture, health etc. But the major problem associated with these nodes is their battery dependence. The Battery Dependence for such nodes responds to the life time of the complete node. Failure of network due to node failure occurs when the battery completely depleted. To beware from such conditions for critical conditions there is one more option of Energy harvesting. In this paper we have discussed about many kinds of energy harvesting procedures. RF energy harvesting and related work discussion are the major issues which we have discussed in this paper. The Power transmitted and received, DC power output, efficiency enhancement due to multipliers or charge pumps are the areas which have been discussed in this paper. Some protocols and routing techniques are also discussed in this paper.

Keywords— WSN, RF Energy harvesting, Energy harvesting techniques, Ambient energy harvesting.

I. INTRODUCTION

The greatest problem in case of WSN is the energy. If the energy is depleted the nodes no longer can provide the information and also the routing is effected seriously [2]. Therefore, it is generally accepted that the usefulness of a wireless sensor expires when its battery runs out. Much of the research on wireless sensor networks has assumed the use of a portable and limited energy source, namely batteries, to power sensors and focused on extending the lifetime of the network by minimizing energy usage [3],[5],[7],[8]. Portable energy sources like batteries will experience current leakages that drain the resource even when they are not used; furthermore, any flaws in the packaging due to long term wear and tear can result in environmental problems [2]. A wireless sensor network that is not dependent on a limited power source (like a battery) essentially has infinite lifetime. Failure due to other causes (like structural hardware damage) can be overcome by self-organization and network re-configuration [4]. This has motivated the search for an alternative source of energy to power WSNs especially for applications that require sensors to be installed for long durations (up to decades) or embedded in structures where battery replacement is impractical. In this paper, we have discussed about the ambient energy source and compared them, although our main area of interest is RF energy harvesting.

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Let's discuss the WSN node for more understanding the concept. Fig 1 shows the block diagram of node. Node is associated with three main units: RF Section, Microcontroller unit, and Sensor transducer. All these units need power and power is provided by means of Energy Source. Energy Source is the battery no doubt. But we need a power management unit as well as an Energy harvesting technique [3], [5] to enhance the capability of the node or shortly we can say to enhance the life time of the node. When the point of the life time came in picture then there is a major issue come on which the life time depends when we exclude the energy harvesting architecture. And this issue is its Application. The WSN node having variety of application for which the life time for one kind of battery is different. So let's discuss about key points of the applications. We will not discuss the application in details but it's important because of lifetime dependence.

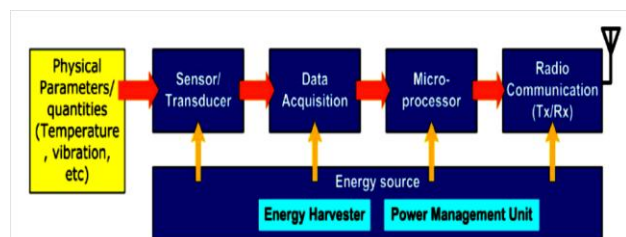


Figure 1: RF Energy Harvesting and power management [3]

Ambient energy sources are discussed and analyzed. On the base of the analysis we have developed the comparison between all types of harvesting techniques. Than RF energy harvesting is taken at priority [3].

For RF energy harvesting many things are important like antenna transmitted power and antenna received power. Conversion efficiency and conversion circuit analysis. Protocols defined for RF energy harvesting. Study and review of Routing technologies and MAC layer optimization for RF energy harvesting have been also done in this paper.

Let's discuss the organization of the paper. In Section II the applications are discussed. Section III is designed for the discussion of ambient energy sources for WSN. Design challenges and operations are discussed in Section III. The antenna transmitted power and received power is discussed in section IV, the discussion is important for different types of antenna associated with RF energy harvesting. Section V is discussed for multipliers charge pumps design for conversion of RF energy into DC energy. Section VI discussed about the enhancement of technology for the RF energy harvesting.

II. APPLICATIONS FOR WSN

A large number of potential applications of sensor networks have been reported ranging from early research investigations to commercial systems [5]. A review of a broad range of applications is given in [8] as the basis for the proposal of a design space model. The applications of the WSN nodes are as follows:

A. Environmental monitoring

A widely considered area for the application of sensor networks is in environmental monitoring. Measurement of glacier dynamics using nodes capable of measuring location, temperature, pressure, and orientation at points inside the glacier over a period of several years was described in [4]. The research described in [5] used nodes on the seabed to monitor pressure, temperature, conductivity, current, and turbidity. These nodes were connected to buoys on the surface to allow radio communication through self-organizing ad-hoc wireless networks. The Argo project [6] uses a sensor network to observe the temperature, salinity, and current profile of the upper ocean. Nodes are attached to free-drifting carriers which cyclically sink to a depth of 2000m and then resurface to allow communication with a satellite. WSNs have been considered for precision agricultural applications such as monitoring grape growing conditions [11]. Here, nodes with temperature, soil moisture, light, and humidity sensors are deployed on a 20m grid across a vineyard to provide information to guide the adaptation of water/fertilizer/pesticide supply to the needs of individual plants and to optimize harvesting.

B. Animal tracking and control

Tracking and controlling the movements of domestic and wild animals presents interesting challenges in WSNs. The breeding behavior of birds was considered by Mainwaring et al. [12] using sensor nodes installed inside burrows. Clusters of nodes, each capable of measuring humidity, pressure, temperature, and ambient light level, along with infrared sensors to detect the presence of the birds, form local networks and each cluster has a node fitted with a long-range directional antenna to pass cluster data to a base station. Nodes fitted to wild animals (e.g., wild horses, zebras, and lions) are capable of roaming over a very large area as considered in [13]. Each node logs the animal's behavior and environment and passes data to any other node which comes within range. At regular intervals, a mobile base station (e.g., a car or a plane) moves through the observation area and collects the recorded data from the animals it passes. In the case of [14], the WSN is used both to monitor behavior and to control it. In this case, the positions of cattle are monitored and "virtual fences" created by using an acoustic stimulus to discourage an animal from crossing a defined line. The network of nodes is connected to a base station so that feeding behavior can be monitored and virtual fences adjusted to improve usage of the feedstock.

C. Safety, security, and military applications

WSNs have been developed to assist rescue teams in saving people buried in avalanches [15]. By monitoring heart rate, respiration activity, orientation, and blood oxygen level, it is possible to automate the prioritization of

victims and to guide rescuers to their location. Tracking of military vehicles using networks of nodes deployed by an unmanned aerial vehicle (UAV) was considered in [16]. Data collected from the nodes by a UAV was used to identify the path and velocity of ground vehicles. Anti-tank landmines capable of self-monitoring for signs of tampering have been formed into networks so that, if an individual mine is disabled, a neighboring device is able to take its place using rocket thrusters to effect the necessary movement [17]. Combining data from a network of acoustic sensors in order to determine the location of a sniper and the direction of the bullet based on the time of flight of muzzle blast was considered by Simon et al. [17]. Monitoring of buildings and emergency response personnel has been considered by Yang and Frederick [18] with the aim of improving safety in dealing with fires and other life-threatening situations in the built environment.

D. Built environment

Monitoring of the internal environmental conditions and adaptation of heating, lighting, etc. in response to human occupancy and activity is a major potential application for sensor networks, whether based on wireless communications or on wired connections. In [19], a WSN was developed to monitor power consumption in large and dispersed office buildings with the aim of detecting locations or devices that are consuming a lot of electrical power.

E. Health

Health applications for WSNs include patient monitoring, drug administration, tracking of patients at home [17, 18] and doctors in hospitals. Body sensor networks [20] are used in the medical sector; implanted medical devices with integrated wireless technology are used for therapeutic and diagnostic applications. Physicians can use this technology to monitor device performance and patient response without the need for invasive surgery. Drug manufacturers are also interested in this technology to reduce their costs when introducing a new drug. The patients can be monitored wirelessly and data about the patient's internal chemistry can be analyzed for abnormal reaction and side effects over a secure link. Yang [20] undertook a thorough analysis of the wireless technologies available and concluded that the IEEE 802.15.4 wireless standard with provisions for body sensor networks (BSN) in the ZigBee application layer was the most appropriate for the body sensor networks. An analysis of the performance of medical sensor body area networking [21] also endorsed the advantage of using IEEE 802.15.4 and ZigBee for medical sensor technologies.

F. Hybrid Networks

In general, complete application scenarios contain aspects of all three categories. For example, in a network designed to track vehicles that pass through it, the network may switch between being an alarm monitoring network and a data collection network. During the long periods of inactivity when no vehicles are present, the network will simply perform an alarm monitoring function. Each node will monitor its sensors waiting to detect a vehicle.

Once an alarm event is detected, all or part of the network will switch into a data collection network and periodically report sensor readings up to a base station that track the vehicles progress. Because of this multi-modal network behavior, it is important to develop a single architecture that can handle all three of these application scenarios.

III. AMBIENT ENERGY SOURCES

In order for a sensor network to operate, it requires electrical power and given that it is frequently desirable to install nodes in inaccessible locations, it can be difficult to provide a sufficiently large store of energy for long term operation or to replace the power source at appropriate intervals. Although the performance of non-renewable energy sources, such as batteries and fuel cells, has improved over the years [23], this improvement is fairly gradual compared with other areas of electronics [24] and cannot satisfy all of the simultaneous demands for long life, low volume, low weight and limited environmental impact. There are a great many sources of energy and conversion devices which have been considered for energy harvesting [25, 26] and in order to compare different approaches, it is useful to consider the criteria for comparison.

Clearly, a key consideration is whether the energy harvesting device can provide the level of power required by the sensor node but it is also important that the electrical power is at a suitable voltage and current level since conversion between voltage levels implies some dissipation of energy and, in general, the greater the ratio between input and output voltage, the greater the power losses.

In order to achieve a desired power level, some conversion devices can be appropriately scaled. Thus, for instance, if a photovoltaic (PV) cell is considered then an increase in power demand can be accommodated by an increase in cell area. However, other sources/converters cannot be so readily scaled. For instance, energy derived from human activity cannot generally be scaled up without either increasing the effect on the person concerned or increasing the number of people involved. While it may be possible to scale up a conversion device, many applications of sensor networks require nodes which are small and light weight. Thus, an important consideration is the power density (in either W/m³ or W/kg) which can be achieved. In assessing power density, the volume and weight of associated energy storage may also be important.

A number of authors have proposed classification systems to categorize energy sources suitable for harvesting which, while broadly similar, do exhibit some differences. In [22], sources are grouped as human and environmental with kinetic and thermal considered as sub classes. Buren [27] uses a similar classification of thermal energy, radiant energy, and mechanical energy sources when considering wearable micro-generators. This classification will be adopted here although mechanical source will be subdivided between those which are continuously present over long periods, such as air flow, those which involve vibration and those which involve short periods of energy availability such as footfall during walking.

A. Electromagnetic radiation

Although radio frequency signals can be used to power passive electronic devices such as radio frequency identification (RFID) tags, these must be carefully tuned to

the frequency of the radio source and are typically only capable of transmitting power over a distance of a few meters [31]. Without the use of such a dedicated source of radio frequency (RF) energy, the ambient levels are very low and are spread over a wide spectrum. Harvesting useful levels of electrical energy in these ambient conditions would require large broadband antennas.

B. Thermal Energy

Extraction of energy from a thermal source requires a thermal gradient. The efficiency of conversion from a thermal source is limited by the Carnot efficiency to

$$\text{Efficiency} \leq \frac{T_h - T_c}{T_h}$$

where T_h is the absolute temperature on the "hot" side of the device, and T_c is the absolute temperature on the "cold" side. Thus, the greater the temperature difference the greater the efficiency of the energy conversion. A potential heat source in many environments would be a room heater. A domestic hot water radiator typically delivers approximately 1.4 kW·m⁻² when heated to 50°C above ambient and so a relatively small section of such a radiator could provide a useable power source.

C. Mechanical Energy Sources

Sources of mechanical energy may usefully be grouped as those dependent on motion which is essentially constant over extended periods of time, such as air flow used in a turbine, those dependent on intermittent motion, such as human footfall and those where the motion is cyclic, as in vibration sources. These different types of sources will be considered separately.

1. Steady state mechanical sources

Sources of ambient energy which are essentially steady state are based around fluid flow, as in wind and air currents and water flow either in natural channels or through pipes, or around continuous motion of an object such as a rotating shaft. Fluid flow based sources of energy are widespread and used on the macro scale for electrical power generation as in wind turbines and hydroelectric plants but have also been considered for smaller scale harvesting applications. Starner [32] considered the potential for energy harvesting from blood flow and breathing in human subjects and determined that significant power was available but that these might not be acceptable to subjects.

2. Intermittent mechanical sources

Energy is available from motion which may be cyclic in nature but in which the energy is only available for a short part of the cycle. Examples of this type include energy available from vehicles passing over an energy harvesting device [33] and intermittent human activity such as walking or typing where, for instance, footfall occurs over a period of milliseconds during a gait cycle of around one second. Harvesting of energy from these intermittent sources was also considered by Starner [32] who concluded that available energy ranged from around 7 mW from finger motion during typing to 67 W for lower limb movement. This paper also considered the effect that extracting this energy would have on the subject and concluded that inconvenience to the subject could only be avoided if significantly lower power levels were extracted.

A particularly attractive source of energy in this context is footfall or heel strike since normal walking involves dissipation of significant energy in the shoe and walking surface, so the user might be unaware if some of this energy were converted to electrical energy. It may readily be calculated that a subject weighing 60 kg must apply a force of at least 588 N through the foot during walking (the peak force is typically 25% above body weight during walking and up to 2.75 – 3 times body weight during running [34]). If this is accompanied by a 10 mm deflection of the floor or shoe, then the available energy is 5.88 J and assuming two steps per second, an available power of 5.88 W per foot. Similar calculations may be carried out for the case of vehicles passing over a deflection device and, given the far greater weight, a significantly greater energy level is found (for example, a single 40 t vehicle causing a 10 mm deflection could provide 4 kJ), although clearly the frequency of vehicle passage will affect the average power level achievable.

3. **Vibration**

Vibration energy is available in most built environments. The energy that can be extracted from a vibration source depends on the amplitude of the vibration and its frequency. It also depends on the extent to which the presence of an energy harvesting device affects the vibration. This, in turn, depends on the mass of the harvesting device relative to that of the vibrating mass. Vibration sources vary considerably in amplitude and dominant frequency. Roundy et al. [42] presents measurement for a number of vibration sources that indicate that the amplitude and frequency varies from $12 \text{ m}\cdot\text{s}^{-2}$ at 200 Hz for a car engine compartment to $0.2 \text{ m}\cdot\text{s}^{-2}$ at 100 Hz for the floor in an office building with the majority of sources measured having a fundamental frequency in the range 60–200 Hz. Vibration present in most environments is not made up of a single frequency but is typically made up of a number of fundamental frequencies and their harmonics. For instance, the vibration data shown in Fig. 2, which is taken from a domestic freezer, indicates a fundamental frequency of 50 Hz with an acceleration amplitude of $0.1 \text{ m}\cdot\text{s}^{-2}$ with the 2nd and higher harmonics present at lower amplitudes. The energy that can be extracted from a vibration source depends on the frequency and amplitude and, since the majority of vibration based conversion devices have a relatively narrow range of operating frequencies, it is important that the nature of the source be understood. It is difficult to establish a strong relationship between the amplitude and fundamental frequency of ambient sources because of the limited frequency range typically found. However, if a harvesting device is tuned to a frequency above about 200 Hz, it may be necessary to use harmonics rather than the fundamental frequency of the source. The amplitude of these harmonics tends to be of significantly lower amplitude than the fundamental.

Table 1: Comparison of various ambient energy harvesting

Technology	Power Density {29} (w/cm^2)	Energy Harvesting Rate (Mw)	Duty Cycle (%)
Vibration-electromagnetic	4.0	0.04	0.05
Vibration-piezoelectric	500	5	6

Vibration-electrostatic	3.8	0.038	0.05
Thermoelectric	60	0.6	0.72
Solar-direct sunlight	3700	37	45
Solar-Indoor	3.2	0.032	0.04

III. DESIGN CHALLENGES AND RF ENERGY LAYOUT

So the overall thing is that we want to generate some energy. Obviously we have different kind of sources but because our main point of interest is energy harvesting by means of RF power sources. So first we will discuss about the design challenges of the WSN node and then we will discuss about the design metrics of WSN-Node which is powered with RF energy harvesting. Instead of focusing on energy-efficient networking protocols to maximize the lifetime of sensor networks, the main objective is to maximize the information or data collected from the sensor network given the rate of energy that can be harvested from the environment. In the following subsections, we briefly discuss the networking-related research issues.

A. Topology Control

Topology control schemes can exploit transmission power control to increase the probability of successfully delivering the data to the next hop [36]. Larger transmission power means that more energy is required to be harvested before the node can receive or transmit data packets, thereby decreasing the duty cycles of the node. This may be necessary if a node's neighbours have not harvested sufficient energy to operate. This also influences the logical topology and deployment strategies [37].

B. MAC

Typically, MAC protocols designed for WSNs aim to reduce energy usage and prolong network lifetime at the expense of longer delays. It makes more sense to find a means of efficiently using the harvested energy to maximize throughput and minimize delays. Furthermore, unnecessary waiting (to synchronize with time slots) or retransmissions can be counter-productive; it has been shown in [38] that a slotted CSMA MAC performs worse than an un-slotted scheme because energy is consumed during the slot synchronization process, resulting in longer harvesting periods thereby reducing throughput.

C. Routing

Since the wakeup time of any sensor cannot be estimated accurately because the exact rate of energy harvested fluctuates with time and other environmental factors, it is very difficult to ensure that the next-hop node is awake to receive a packet. The uncertainty in how long it takes a node to harvest enough energy before it can function again makes existing sleep-wake scheduling schemes for WSNs unusable since a node may not have harvested sufficient energy at the scheduled wakeup time. Furthermore, if it has depleted all its energy in its previous cycle, it may lose its timing reference when it wakes up again. However, broadcasting may result in many duplicates if many nodes are awake; therefore, some form of duplication-suppression is needed so that the harvested energy is not wasted on delivering duplicates.



The ideal situation would be anycast where exactly one node (among those awake and heard the packet transmission) will forward data packets towards the sink. This ensures that the sink receives exactly one copy of each packet from the source.

If there are insufficient awake forwarding nodes, either because the density of the nodes deployed is too low or the average energy harvesting period is too long, then it becomes an intermittently connected mobile network, where the use of delay-tolerant network (DTN) techniques may be appropriate.

D. Reliable Data Delivery

Reliable data delivery may be required for some applications.

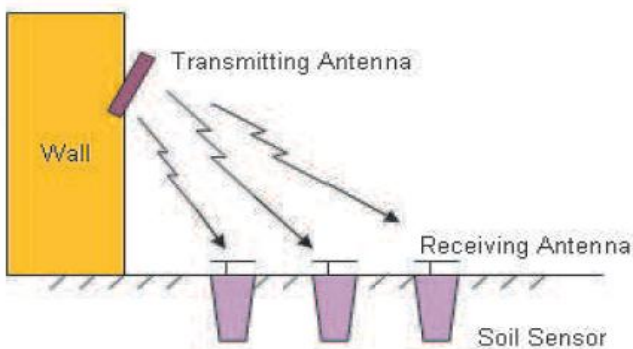
Since the source node is not awake all the time, it is a challenge to design reliable transport protocols as many reliable transport protocols need to make use of positive feedback for retransmissions. Another requirement to ensure each flow gets its fair share of bandwidth given the amount of energy that can be harvested from the environment. Since energy is free because it is renewable, nodes further away from the sink may starve the nodes nearer the sink if forwarding packets have higher priority than the node's own packets. Therefore, there is a need for a transport protocol to regulate the data flow such that any source will get its fair share of bandwidth no matter where it is located in the network.

Here we can conclude from the discussion in this section that not only the hardware issues but also some software algorithm like routing schemes, definition of MAC layer and topology control can also define some key concept for the case of max RF energy harvesting. The RF energy harvesting also declares the individual node hardware specification. In the rest of the paper we will see the individual node only because the RF energy harvesting is our main point of discussion.

The Concept of RF energy Harvesting has many aspects like Transmitting antenna, receiving antenna or received power, efficiency, Multiplier, Algorithm specialized for Energy harvesting. In the next section let us define the professionally available hardware like transmitting antenna, receiving antenna, high frequency diode for energy conversion.

IV. ANTENNA ANALYSIS: TRANSMITTING ANTENNA AND RECEIVING ANTENNA

Before discussion the facts let us discuss about an important picture 2.



A. Transmission Antenna:

Selection of a proper operating frequency band for the proposed RF energy harvesting system is crucial since it will affect the overall size of the receiving antenna and operating range of the system. Two unlicensed UHF bands 867 MHz and 2.45 GHz were evaluated. 867 MHz was chosen due to its lower free space attenuation (as the free space path loss at 2.45 GHz is about 9 dB higher than at 867 MHz). Table 1 shows the frequency allocation for the selected UHF band in various countries with its permitted radiated power level. For this system to be used worldwide, the receiving antenna has to be designed to resonate over a frequency range of 860 MHz to 960 MHz, with an impedance bandwidth ($S_{11} \leq -10$ dB) covering the chosen band.

Table 2: Permitted radio power and frequency

Country	Frequency band	Power
USA	902-928 MHz	4W EIRP
UK	865.6-867.6 MHz	2W ERP/ 3.28 EIRP
Japan	952-954 MHz	4W EIRP
ASIA/EUROPE	2.4-2.5 GHz	4W EIRP

When we want to include some patch antenna in our experiments then we can consider some commercially available antennas and also some of the transmitting antenna which is mainly designed for energy harvesting. Let us include some important pictures for that case.

Let us see Table 2, which shows many important aspects regarding a transmitting antenna.

Table 3: Important parameter of Patch Antenna (902-928 MHz)

902-928 MHz flat panel antenna series specifications		
Model	ZDAFP928-8	ZDAFP928-11
Frequency Range	902-928 MHz	902-928 MHz
Gain	8 dBi	10.5 dBi
Polarization	Vertical or Horizontal	Vertical or Horizontal
Horizontal Beam Width	90 °	60 °
Vertical Beam Width	70 °	55 °
F/B Ratio	>15	>15
VSWR	<1.5	<1.5
Input Impedance	50 ohm	50 ohm
Input Maximum Power	200 W	50 W
Lightning Protection	DC Ground	DC Ground
Connector	N female or customized	N female or customized
Size	8.6x8.6x1 in (216x216x25mm)	12x12x1 in (306x306x25mm)
Radome Material	ABS	ABS
Operating Temperature	-40°C to 85°C (-40°F to 185°F)	-40°C to 85°C (-40°F to 185°F)
Diameter of Installation Pole	1.2-2 in. (30-50 mm)	1.2-2 in. (30-50 mm)
Weight	3.08 Lbs (1.4 Kg)	3.96 Lbs (1.8 Kg)
Wind Loading:	8 lb.	11 lb.
100MPH	16 lb.	21 lb.
125MPH		

Another frequency rating which we have considered is 2.4-2.5 GHz. The antenna whatever we have taken in table 2 or table 3 is designed by commercial industry. The tables included from the “ZDA Communication Company”.

The main challenge faced in harvesting RF energy is the free space path loss of the transmitted signal with distance. The Friis transmission equation relates the received (P_r) and transmitted (P_t) powers with the distance R as

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \dots\dots\dots 1$$

Where, G_t and G_r are antenna gains, and λ is the wavelength of the transmitted signal. The received signal strength, diminishes with the square of the distance, requires special sensitivity considerations in the circuit design. Moreover, FCC regulations limit the maximum transmission power in specific frequency bands. For example, in the 900-MHz band, this maximum threshold is 4W EIRP [39]. Even at this highest setting, the received power at a moderate distance of 20 m is attenuated down to only 10. We describe a new circuit design in this section that is capable of scavenging energy with high efficiency, beginning with the selection of the circuit components.

Table 4 : Important parameter of Patch Antenna (902-928MHz)

2400-2500MHz flat panel antenna series specifications				
Model	ZDAFP2400-16-30	ZDAFP2400-17-25	ZDAFP2400-18-20	ZDAFP2400-21-15
Frequency Range	2400-2500MHz	2400-2500MHz	2400-2500MHz	2400-2500MHz
Gain	16dBi	17dBi	18dBi	21dBi
Polarization	Vertical or Horizontal	Vertical or Horizontal	Vertical or Horizontal	Diamond
Horizontal Beam Width	30 °	25 °	20 °	15°
Vertical Beam Width	30 °	25°	20 °	15°
F/B Ratio	>25	>25	>28	>28
VSWR	<1.5	<1.5	<1.5	<1.5
Input Impedance	50 ohm	50 ohm	50 ohm	50 ohm
Input Maximum Power	100 W	100 W	100 W	100 W
Lightning Protection	DC Ground	DC Ground	DC Ground	DC Ground
Connector	N female or customized	N female or customized	N female or customized	N female or customized
Size	8.6x8.6x1 in (216x216x25 mm)	11x11x1 in (268x268x22mm)	12x12x1 in (306x306x25mm)	17.72x17.72x1 in (450x450x25mm)
Radome Material	ABS	ABS	ABS	ABS
Operating Temperature	-40 to 85°C (-40 to 185°F)	-40 to 85°C (-40 to 185°F)	-40 to 85°C (-40 to 185°F)	-40 to 85°C (-40 to 185°F)
Diameter of Installation Pole	1.2-2 in. (30-50 mm)	1.2-2 in. (30-50 mm)	1.2-2 in. (30-50 mm)	1.2-2 in. (30-50 mm)
Weight	3.04 Lbs (1.2Kg)	3.08 Lbs (1.4 Kg)	3.96 Lbs (1.8 Kg)	6.2 Lbs (2.8 Kg)

Wind Loading: 100MPH 125MPH	8 lb. 16 lb.	10lb. 18lb.	11lb. 21lb.	23lb. 46lb.
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B. Receiving Antenna

Wireless technology is one of the main areas of research in the world of communication systems today. Wireless provides no connectors, safe/flexible connectivity, improves resources sharing, ease of installation, mobility etc.

Antennas are dual, metallic devices which are designed for radiating and receiving electromagnetic energy. An antenna acts as a transitional structure between the guiding device (e.g. waveguide, transmission line) and free space.

In radio communication, an **Omni-directional antenna** is an antenna which radiates radio wave power uniformly in all directions in one plane, with the radiated power decreasing with elevation angle above or below the plane, dropping to zero on the antenna's axis. This radiation pattern is often described as "doughnut shaped". Omni-directional antennas oriented vertically are widely used for non-directional antennas on the surface of the Earth because they radiate equally in all horizontal directions, while the power radiated drops off with elevation angle so little radio energy is aimed into the sky or down toward the earth and wasted. Omni-directional antennas are widely used for radio broadcasting antennas, and in mobile devices that use radio such as cell phones, FM radios, walkie-talkies, wireless computer networks, cordless phones, GPS as well as for base stations that communicate with mobile radios, such as police and taxi dispatchers and aircraft communications.

A **dipole antenna** is a very basic type of radio antenna. It comes in various geometries with different feeding mechanisms and radiating elements. This antenna is the simplest practical antenna from a theoretical point of view. Hertzian dipole is a small length of conductor $\delta\ell$ (small compared to the wavelength λ) carrying an alternating current:

$$I = I_0 e^{j\omega t} \dots\dots\dots A$$

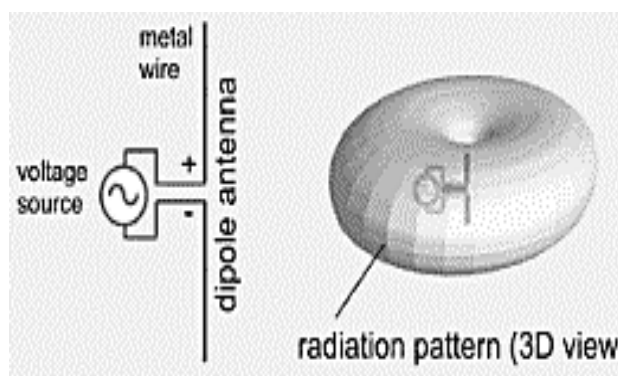


Fig 3. Radiation pattern of Antenna

Here $\omega = 2\pi f$ is the angular frequency (and f the frequency), and $i = \sqrt{-1}$ is the imaginary unit, so that I is a phasor.

It is used in analytical calculation on more complex antenna geometries. This small length of conductor will be just one of the multiple segments into which we must divide a real antenna, in order to calculate its properties.

The closed-form expressions for electric field, \mathbf{E} , and magnetic field, \mathbf{H} (In spherical coordinates) are:-



$$E_r = \frac{ZI_0\delta l}{2\pi} \left(\frac{1}{r^2} - \frac{i}{kr^3} \right) e^{i(\omega t - kr)} \cos\theta \dots\dots 2$$

$$E_\theta = i \frac{ZI_0\delta l}{4\pi} \left(\frac{k}{r} - \frac{i}{r^2} - \frac{1}{kr^3} \right) e^{i(\omega t - kr)} \sin(\theta) \dots\dots 3$$

$$H_\phi = i \frac{I_0\delta l}{4\pi} \left(\frac{k}{r} - \frac{i}{r^2} \right) e^{i(\omega t - kr)} \sin(\theta) \dots\dots 4$$

$$E_\phi = H_r = H_\theta = 0 \dots\dots 5$$

Where r is the distance from the doublet to the point where the fields are evaluated, $k = 2\pi/\lambda$ is the wavenumber, and $Z = \sqrt{\mu/\epsilon} = 1/\epsilon c = \mu c$ is the wave impedance of the surrounding medium (usually air or vacuum).

Some of the researchers also developed a four side patch antenna for better directivity and gain. We have borrowed one figure[4].

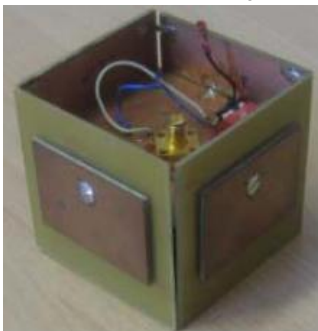


Figure 4: 4 side patch Antenna [40]

The antenna produces a truly omnidirectional pattern in both E-plane and H-plane, which allows for non-intermittent communication that is orientation independent. The frequency of operation lies in the UHF RFID band, 902MHz–928 MHz (centered at 915 MHz). The ultra-compact cubic antenna has dimensions of 3cm x 3cm x 3cm (27 cm³), which features a length dimension of $\lambda/11$. The cubic shape of the antenna allows for “smart” packaging, as sensor equipment may be easily integrated inside the cube’s hollow (or Styrofoam-filled) interior. The prototype fabrication was performed on six (planar) sides on liquid crystal polymer (LCP) substrate, and then folded into the cubic structure. The geometry of the design is inspired by the RFID inductively coupled meander line structures, which are folded around the sides of the cube. Due to the large number of freedom degrees, this antenna concept may be easily reconfigured for many values of impedances and design parameters. Experimental data verify the simulation results.

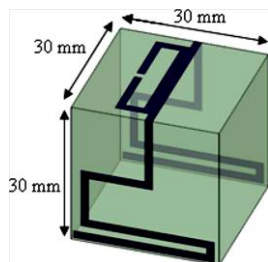


Figure.5 : Node Antenna

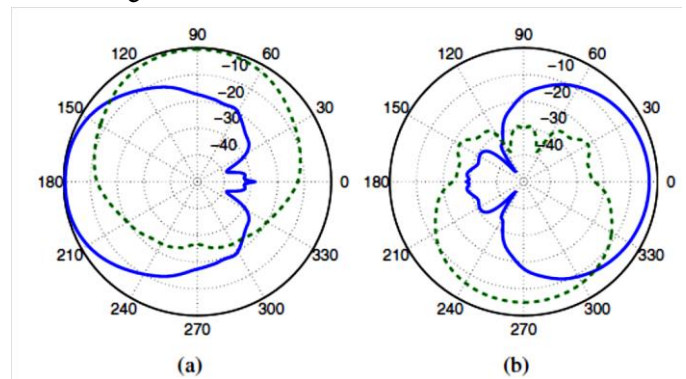


Fig. 6. Radiation pattern of the four antenna faces. a) Patch 1 (solid) &

Patch 2 (dashed); b) Patch 3 (solid) & Patch 4 (dashed).

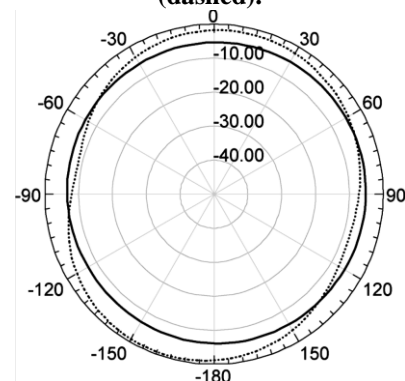


Fig. 7. Radiation pattern of the four antenna faces. a) Patch 1 (solid) &

Patch 2 (dashed); b) Patch 3 (solid) & Patch 4 (dashed).

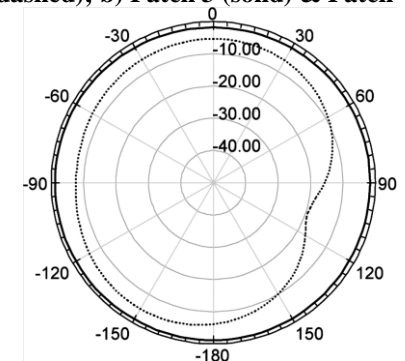


Fig. 8. E-phi (solid) and E-theta (dashed) in dB, $\Phi=90$ deg for cubic antenna fabricated with Styrofoam.

A Four-Beam Patch Antenna (FBPA) designed to meet the size, cost and complexity constraints of sensor nodes [40]. We use in-field experiments with COTS motes to demonstrate substantial benefits to WSN applications. Used outdoors, the FBPA extends the communication range from 140m to more than 350m, while indoors it suppresses the interference due to multipath fading by reducing the signal variability of more than 70%. We also show interference suppression from IEEE 802.11g systems and discuss the use of the antenna as a form of angular diversity useful to cope with the variability of the radio signal.

Experimental data are analyzed to derive model parameters intended for use in future network simulations

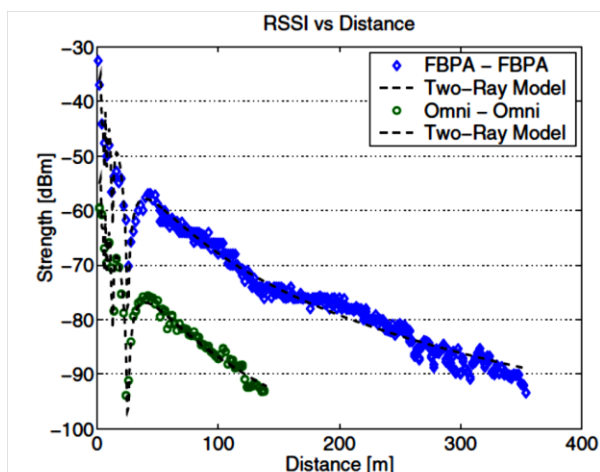


Fig 9: Received signal strength as function of the distance. Transmission power is 0 dBm; values are averaged over 200 radio packets.

V. OTHER PARTS FOR RF ENERGY HARVESTING AND SOME SIMULATION COMPARISON

A. Choice of Diodes

One of the crucial requirements for the energy harvesting circuit is to be able to operate with weak input RF power. For a typical 50dB antenna, the 20 dBm received RF signal power means amplitude of 32 mV. As the peak voltage of the ac signal obtained at the antenna is generally much smaller than the diode threshold [12], diodes with lowest possible turn on voltage are preferable. Moreover, since the energy harvesting circuit is operating in high frequencies, diodes with a very fast switching time need to be used. Schottky diodes use a metal-semiconductor junction instead of a semiconductor-semiconductor junction. This allows the junction to operate much faster, and gives a forward voltage drop of as low as 0.15 V. In this paper, we employ two different diodes from Avago Technologies, HSMS-2822 and HSMS-2852. The former has the turn on voltage of 340 mV while the latter is at

150 mV, measured at 1 and 0.1 mV, respectively. Consequently, HSMS-2852 is suitable for LPD used in the weak RF environment, while HSMS-2822 is preferred for HPD in the strong RF environment. Saturation current is another critical parameter that impacts the efficiency of diodes. It is desirable to have diodes with high saturation current, low junction capacitance, and low equivalent series resistance (ESR). Moreover, diodes with higher saturation current also yield higher forward current, which is beneficial for load driving. However, higher saturation current is usually found in larger diodes, which have higher junction and substrate capacitance. The latter two parameters can introduce increased power loss, where the benefit of higher saturation current is lost.

B. Number of Stages

The number of rectifier stages has a major influence on the output voltage of the energy harvesting circuit. Each stage here is a modified voltage multiplier, arranged in series. The output voltage is directly proportional to the

number of stages used in the energy harvesting circuit. However, practical constraints force a limit on the number of permissible stages, and in turn, the output voltage. Here, the voltage gain decreases as the number of stages increases due to the parasitic effect of the constituent capacitors of each stage, and finally it becomes negligible. Figs. 3 and 4 show the impact of the number of stages on efficiency and output voltage of the energy harvesting circuit, respectively. We have used Agilent ADS with parameters sweep of 20 to 20 dBm for the input RF power and varies the number of circuit stages from 1 to 9 stages. The circuit stage in simulation is a modified voltage multiplier of HSMS-2852, arranged in series. We observe that the circuit yields higher efficiency as the number of stages increases. However, as more stages are introduced, the peak of the efficiency curve also shifts towards the higher power region. The voltage plot shows that higher voltage can be achieved by increasing the number of circuit stages, but a corresponding increase in power loss is also introduced into the low power region.

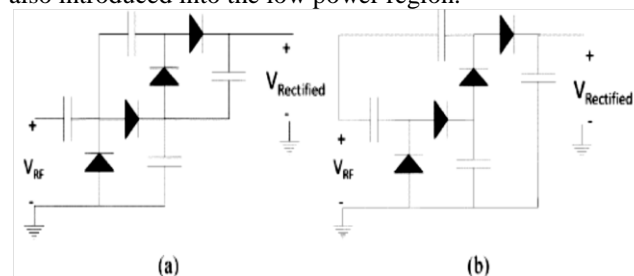


Fig. 10. (a) Villard multiplier and (b) Dickson multiplier.

C. Effect of Load Impedance

It is important that the load impedance be carefully selected for a specific energy harvesting circuit, whose impact on the circuit performance can be seen in Fig. 5. We simulate the effect of load impedance on the efficiency of the energy harvesting circuit using Agilent ADS with parameters sweep of 20 to 20 dBm and 1–181 for input RF power and load value, respectively.

We observe that the circuit yields the optimal efficiency at a particular load value, that is, the circuit's efficiency decreases dramatically if the load value is too low or too high. The energy harvesting in simulation is a five-stage circuit, each stage is a modified voltage multiplier of HSMS-2852, arranged in series. For the particular case of WSNs, the sensor mote draws a different amount of current when it is in the active (all radios operational), low-power (radios shut down for short interval but internal microcontroller active), and deep-sleep (requires external interrupt signal to become active again) states. To correctly identify the impedance in the deep sleep state, where we presume the node harvests energy, we measure the voltage and current of Mica2 sensor mote in deep sleep state to consume 30 at 3.0 V, which translates to a 100-ohm resistive load. A 100-ohm resistive load is further used in our optimization.

D. Effect of RF Input Power

Since the energy harvesting circuit consists of diodes, which are nonlinear devices, the circuit itself exhibits nonlinearity. This implies that the impedance of the energy harvesting circuit varies with the amount of power received from the antenna. Since the maximum power transfer occurs when the circuit is matched with the antenna, the impedance matching is

usually performed at the a particular input power. Fig. 6 depicts the effect of RF input power, ranging from 20 to 20 dBm, on the impedance of the energy harvesting circuit. The nonlinearity in operation is shown by a sharp bend at 5 dBm. This further motivates our approach of a clear separation of two optimized sister-circuits of the LDP and HDP, where each has its own (reasonably) constant impedance.

E. Energy Harvesting Circuit

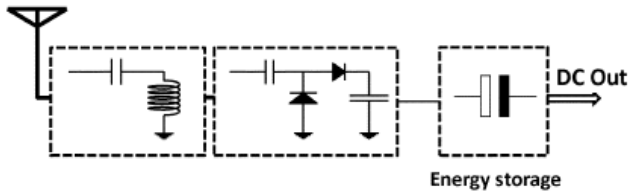


Fig. 11: Energy Harvesting Circuit

The simulation results obtained previously are under an assumption that all components, except Schottky diodes, exhibit an ideal behavior. With non-ideal components and parasitic effects, this is rarely achievable in practice. Consequently, it is imperative that all related parasitic parameters and precise models of components have to be incorporated into the simulation.

This not only yields a closer result to that of the prototype but also provides an upper bound on achievable efficiency with respect to a particular prototype design. For this purpose, Agilent ADS simulation with co-planar waveguide with groundplane (CPWG) is used to observe the effect of the PCB. Moreover, components are modeled with ADS and vendor supplied component libraries. The effect of non-ideal components and PCB becomes clear as the received RF input power goes beyond 16 dBm. This implies that the fabrication method plays an important role on the performance of the energy harvesting circuit. “System on Chip” (SoC) is a highly recommended fabrication method, which however lies beyond the scope of this paper. With the effect of non-ideal components and PCB, it is unlikely that one can achieve the optimal result obtained in the optimization section. We propose the use of multiple antennas in addition to the existing circuit. Antenna collects its own signal, connects to its own matching network and voltage multiplier. However, they all share the energy storage. Note that this concept does not increase conversion efficiency of the circuits since the efficiency of the circuit remains the same. It is obvious that both voltage and efficiency of the circuit can be increased by introducing additional antennas. However, the gain increase is not linear and reduces drastically with additional antennas introduced. This limits the amount of multiple antennas used for the purpose of energy harvesting enhancement. The final fabricated PCB of our proposed energy harvesting module connected to a Mica2 mote. The PCB is fabricated with FR-4 epoxy glass substrate and has two layers, one of which serves as a ground plane. The prototype consists of the design obtained from the proposed optimization.

We select components with values and ratings of their performance parameter as close as possible to ones obtained from the simulation. This data is summarized in Table 5. The energy harvesting circuit prototype is tuned to match simulation parameters using Agilent E5061B vector network analyzer. In order to measure dc power output from the prototype, Agilent N5181 MXG RF signal generator is used to provide a known RF power to the prototype from 20 to 20

dBm. The dc output power from the prototype is obtained from measuring the voltage and current associated with the resistive load of 100K Ohm.

Table 5: Components value

Component	Value
Inductor	3.0, 7.12nH
Capacitor	1.5, 2.9pF
Stage Capacitor	36pF
Diode	HSMS-2852, HSMS-2822

We have more things to optimize the RF Energy harvesting. We can develop some of the energy harvesting specialized protocol for gaining energy from the Power radiator. We have to provide the current information of Energy stored in the nodes.

VI. CONCLUSIONS

From our most of the discussion and analysis of WSN RF Energy harvesting we have defined the hardware design issues. The discussion in the optimized research we included many of the aspects like the RF Antennas: Transmitting and Receiving. Not only this, we have discussed about the high frequency commercially available diodes. The Diodes are used to define the charge pump or multipliers to enhance the efficiency. The efficiency of the circuit can be increased by accurate usage of the diodes and capacitors. We can more optimize the charge pump circuit by parasitic extraction. Another important concept is storage of the converted energy. This can be achieved by super capacitor or by energy storage cells.

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