DISTRIBUTION POWER LEVEL BY GSM900 BASE STATION FOR RF ENERGY HARVESTING

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ABSTRACT

A development in nano-technology allows the creation electronic equipment operating at microwave frequency. Rectenna is a high gain antenna receiver that's good in rectifiers able to converse radio frequency (RF) energy to DC (direct current) power is an evidence of achievement in the field of electronic microwave. With the rapid development in the field of wireless communications the density of microwave energy become higher and allows the microwave energy harvesting and thus stronger recommend to wireless power transmission. But with technology rectenna available at present, there is the question of relevancies is used as the ambient energy harvester from the environment. This study examines the extent to which rectenna suitable for use as energy harvester in GSM900 band around Kuala Terengganu. Rectenna used is from the Powercast P2110 with RF- DC conversion efficiency up to 55% at a frequency of 915MHz. The study found rectenna efficiency can reach more than 40% within about 25 meters from the transmitter GSM. It can be concluded that around Kuala Terengganu energy harvesting process is not perfect yet implemented but by collaboration with the provider GSM900 it allows rectenna used as harvester to their customers.

ABSTRAK

Perkembangan dalam teknologi nano membolehkan penciptaan peralatan elektronik yang beroperasi pada frekuensi gelombang mikro. Rectenna adalah antena penerima dengan gandaan yang tinggi yang mana berkeupayaan menukar tenaga yang dibawa oleh frekuensi radio (RF) kepada tenaga elektrik DC (arus terus) adalah bukti pencapaian dalam bidang mikro elektronik. Dengan perkembangan pesat dalam bidang komunikasi tanpa wayar ketumpatan tenaga gelombang mikro menjadi lebih tinggi dan membolehkan penuaian tenaga gelombang mikro dilakukan dan dengan itu mengarah kepada penghantaran kuasa tanpa wayar. Tetapi dengan teknologi yang ada rectenna pada masa ini, terdapat persoalan relevenisasi tenaga ambien dituia dari alam sekitar. Kajian ini meninjau sejauh mana rectenna sesuai untuk digunakan sebagai penuai tenaga dalam pada band GSM900 di sekitar Kuala Terengganu. Rectenna digunakan adalah dari P2110 Powercast dengan kecekapan penukaran RF-DC sehingga 55% pada frekuensi 915MHz. Kajian mendapati kecekapan rectenna boleh mencapai lebih daripada 40% dalam masa kira-kira 25 meter dari pemancar GSM900. Jesteru itu disimpulkan bahawa di sekitar Kuala Terengganu proses penuaian tenaga tidak sempurna lagi dilaksanakan tetapi dengan kerjasama pembekal GSM900 ia membolehkan rectenna digunakan sebagai penuai kepada pelanggan mereka.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

The ever increasing use of wireless devices, such as mobile phones, wireless computing and remote sensing has resulted in an increased demand and reliance on the use of batteries. With semiconductor and other technologies continually striving towards lower operating powers, batteries could be replaced by alternative sources, such as DC power generators employing energy harvesting techniques. In the quest of green energy, scientists have been in the pursuit of converting deep space solar energy into high power microwave energy. This microwave energy is transmitted from place to place by frequency as it transmission line. Solar cell is special devices can harvest solar energy then covert it to electrical energy.

In the modern environment there are multiple wireless sources of different frequencies radiating power in all directions. One of the potentially could be exploited for RF energy harvesting applications. These might be, but not limited to; TV and radio broadcasts, mobile phone base stations, mobile phones, wireless LAN and radar.

1.2 History of microwave power transmission

Tesla was the first person who introduced the idea of wireless power transmission. Tesla was not able to produce power with the RF signal because the transmitted power got diffused in all the direction with 140 KHz radio signal. The problem faced by Tesla was overcome, by the fact that higher RF frequency has greater directivity and so the power can be transmitted in a particular direction. Radar technology used in world-war 2 was also very helpful in advancing the growth of wireless power [1].

The idea of using the solar space satellites to create power is not very new. It was first presented in 1968 by Peter E. Glaser .In the early 1960's W.C. Brown used that latest technology to produce wireless power for the first time. An antenna with a rectifying circuit to produce power and the conversion was very good [1, 31]. Based on Brown's research work, P.E. Glaser in 1968 introduced a solar power satellite. The area of wireless power is not only limited to power generation by satellites but in fact it can be used in daily electronics, such as a wireless headphone, wireless keyboard, wireless mouse and even in wireless small motors. This research will give a glimpse of future technologies that lies ahead of us [2, 32].

Holst Centre, in collaboration with IMEC, the Delft University of Technology and the Eindhoven University of Technology, have designed and fabricated a self-calibrating RF energy harvester. The device is capable of harvesting RF energy at lower input power levels than state-of-the-art solutions. Already, cell phone companies are developing mobile devices charged by harvesting ambient RF power [3]. Likewise, defense companies have been working on systems to power unmanned aerial vehicles (UAVs) while in air by exploiting directed energy from microwave sources [4].

When used in combination with a dedicated or even ambient RF source, the new RF energy harvester has the potential to power small sensor systems. The harvester shows excellent wireless range performance, leading now an increase of area that covered by the RF source that allow a RF energy harvesting applicable to use.

Radio frequency (RF) energy harvesting, also referred to as RF energy scavenging has been proposed and researched in the 1950s [5].By using high power microwave sources, as more of a proof-of-concept rather than a practical energy source, due to the technologies available at the time. However, with modern advances in low power devices the situation has changed with the technique being a viable alternative to batteries in some applications. Particularly, for wireless devices located in sensitive or difficult access environments where battery operated equipment might not have been previously possible [6].

1.3 Problem Statement

Most of the energy radiates from the communication systems (from the electromagnetic field) are wasted into heat energy and lost unused into the atmosphere. Therefore a RF energy harvesting is introduced to overcome the problems by harvesting the emission of RF energy.

As the technology is growing the world is now moving toward wireless power [7]. We can see that now days everyone prefers to use a wireless mouse or a wireless headphone. The use of batteries can make this possible but the problem is that too many batteries are being used and there has to be a way by which these applications can run wirelessly and the best thing would be if the batteries were not used. How can this be possible? The rectenna is a device that used to convert the RF power into dc signal and instead of batteries the application will have a rectenna to produce the power. Therefore we will have a true wireless system, which has no wires and no batteries. However we have to agree that may be high enough power that suit to electronic application will not be produced by these rectenna because of small power detected received at antenna itself[8].

Scientists believe that within the next few decades this method will solve world's energy crisis significantly and become an alternative energy source for developing countries those cannot effort conventional energy sources [9]. Two types of research groups are extending the boundaries of low-power wireless devices, said Brian Otis, an assistant professor of electrical engineering at the University of Washington. Some researchers are working to reduce the power required by the devices; others are learning how to harvest power from the environment. "One day," Professor Otis said, "those two camps will meet, and then we will have devices that can run indefinitely."

Until now there is a lot of module and kit represent a good in efficiency rectenna have been design for harvesting. But the question is there our environments good enough and ready to provide the ambient RF energy for harvesting? The ambient energy is too small when putting in free environments [9, 30]. This project will study the capable of energy harvesting at frequency 915MHz in our surrounding.

1.4 Objectives

The objective of this thesis is to investigate a distributed RF energy around a selected mobile base station is applicable for power harvesting application.

1.5 Scope

In this project the scope of work will be undertaken in following requirement:

i. Mobile base station that operates at band GSM 900 will be used as transmitter in experiment.

ii. The antenna type wills used as RF receiver is 915 MHz PCB patch antenna which has two layers and the RF connector located on the back of the antenna. The front side should be pointed toward the transmitter with the same polarization

    a. Type: directional, vertically polarized
    b. Energy pattern: 122° (azimuth/horizontal), 68° (elevation/vertical)
    c. Antenna gain: Linear gain = 4.1 (6.1 dBi)

iii. A high efficiency rectenna module at 915MHz will be used as a device to harvest the ambient RF energy in surrounding

CHAPTER 2

LITERATURE REVIEW

This chapter will discuss the concepts used in the GSM system. At the same time it touches the antenna and rectenna concept of energy harvesting practices. Constraints in wireless power transmission link budget is discussed in the context of where Friss formula as a model of energy reception.

2.1 GSM

GSM (Global System for Mobile Communications, originally *Groupe Spécial Mobile*), is a standard developed by the European Telecommunications Standards Institute (ETSI) to describe protocols for second generation (2G) digital cellular networks used by mobile phones[10]. It is the factor that global standard for mobile communications with over 90% market share, and is available in over 219 countries and territories.

The GSM standard was developed as a replacement for first generation (1G) analog cellular networks, and originally described a digital, circuit-switched network optimized for full duplex voice telephony. This was expanded over time to include data communications, first by circuit-switched transport, then packet data transport via GPRS (General Packet Radio Services) and EDGE (Enhanced Data rates for GSM Evolution or EGPRS).

Subsequently, the 3GPP developed third generation (3G) UMTS standards followed by fourth generation (4G) LTE Advanced standards, which are not part of the ETSI GSM standard.

The Cellular concept is a system with many low power transmitters, each providing coverage to only a small portion of the service area. Each base station is allocated a portion of the total number of channels available to the entire system, and nearby base station are assigned different group of channels so that the interference between base stations is minimized [11]. The channels assignment in case of GSM900, E-GSM900 and DCS1800 (or GSM1800) is as shown in Figure 2.1 below,

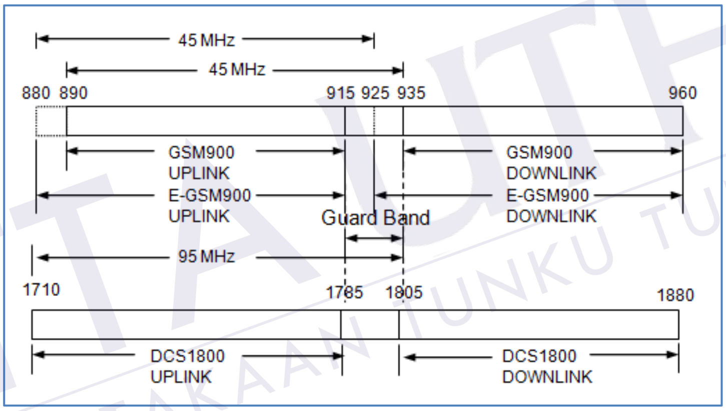

Figure 2.1: GSM Channels Assignment

As shown the Uplink and Downlink band are separated by 20 MHz of guard band in case of GSM and DCS and 10 MHz in case of E-GSM. The channel separation between Uplink and Downlink is 45 MHz in case of GSM and E-GSM and is 95MHz in case of DCS network. Each channel (carrier) in GSM system is of 200 KHz bandwidth, which is designated by Absolute Radio Frequency Channel Number (ARFCN). Table 2.1 is the allocation of ARFCN of GSM Chanel. If we call Fl(n) the frequency value of the carrier ARFCN n in the lower band(Uplink), and Fu(n) the corresponding frequency value in the upper band (Downlink), Hence we have 124 channels in GSM900, 174 channels in E-GSM900 and 374 channels in DCS1800.

GSM 900	Fl(n) = 890 + 0.2*n	1 ≤ n ≤ 124 Fu(n)	Fu(n) = Fl(n) + 45
E-GSM 900	Fl(n) = 890 + 0.2*n Fl(n) = 890 + 0.2*(n-1024)	0 ≤ n ≤ 124 Fu(n) 975 ≤ n ≤ 1023	Fu(n) = Fl(n) + 45
DCS 1800	Fl(n) = 1710.2 + 0.2*(n-512)	512 ≤ n ≤ 885	Fu(n) = Fl(n) + 95

Table 2.1: ARFCN

2.1.1 GSM900 band

Global system for mobile communication (GSM) is a globally accepted standard for digital cellular communication. GSM is the name of a standardization group established in 1982 to create a common European mobile telephone standard that would formulate specifications for a pan-European mobile cellular radio system operating at 900MHz [12].

Although it is possible for the GSM cellular system to work on a variety of frequencies, the GSM standard defines GSM frequency bands and frequencies for the different spectrum allocations that are in use around the globe. For most applications the GSM frequency allocations fall into three or four bands, and therefore it is possible for phones to be used for global roaming.

While the majority of GSM activity falls into just a few bands, for some specialist applications, or in countries where spectrum allocation requirements mean that the standard bands cannot be used, different allocations may be required. Accordingly for most global roaming dual band, tri-band or quad-band phones will operate in most countries, although in some instances phones using other frequencies may be required.

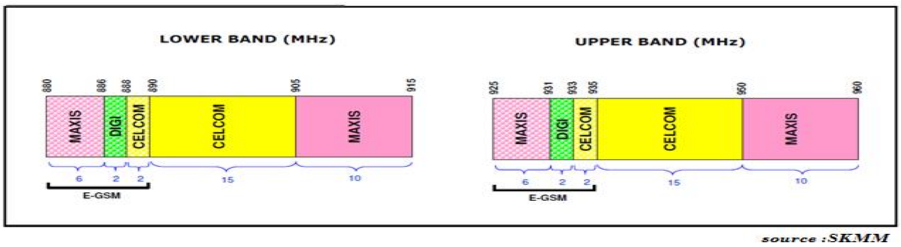

Figure 2.2: Global System for Mobile (GSM900) applied in Malaysia

The usage of the different frequency bands varies around the globe although there is a large degree of standardization. The GSM frequencies available depend upon the regulatory requirements for the particular country and the ITU (International Telecommunications Union) region in which the country is located.

As a rough guide Europe tends to use the GSM 900 and 1800 bands as standard. These bands are also generally used in the Middle East, Africa, Asia include Malaysia and Oceania. In Malaysia the GSM band allocation was controlled by government under responsibility of "*Suruhanjaya Komunikasi dan Multimedia Malaysia"*(SKMM). Figure 2.2 is an allocation band GSM900 applied in Malaysia which were sharing by 3 major provider that Celcom, Maxis and Digi [12] and Table 2.2 describes the standard uplink and downlink channel allocated by SKMM.

Band	Uplink (MHz)	Downlink (MHz)	Comments
380	380.2 - 389.8	390.2 - 399.8	
410	410.2 - 419.8	420.2 - 429.8	
450	450.4 - 457.6	460.4 - 467.6	
480	478.8 - 486.0	488.8 - 496.0	
710	698.0 - 716.0	728.0 - 746.0	
750	747.0 - 762.0	777.0 - 792.0	
810	806.0 - 821.0	851.0 - 866.0	
850	824.0 - 849.0	869.0 - 894.0	
900	890.0 - 915.0	935.0 - 960.0	P-GSM, i.e. Primary or standard GSM allocation
900	880.0 - 915.0	925.0 - 960.0	E-GSM, i.e. Extended GSM allocation
900	876.0 – 915	921.0 - 960.0	R-GSM, i.e. Railway GSM allocation
900	870.4 - 876.0	915.4 - 921.0	T-GSM
1800	1710.0 - 1785.0	1805.0 - 1880.0	
1900	1850.0 - 1910.0	1930.0 - 1990.0	

Table 2.2: The Uplink and Downlink GSM900

For North America the USA uses both 850 and 1900 MHz bands, the actual band used is determined by the regulatory authorities and is dependent upon the area. For Canada the 1900 MHz band is the primary one used, particularly for urban areas with 850 MHz used as a backup in rural areas.

2.1.2 Frequency re-use

One important characteristic of GSM networks is frequency planning wherein given the limited frequency spectrum available, the re-use of frequencies in different cells is to be planned such that high capacity can be achieved keeping the interference under a specific level.

A cell in a GSM system may be omni-directional or sectored represented by hexagons. In GSM system a tri-sectored cell is assumed and the frequency plan is made accordingly [5]. To understand the frequency re-use planning, consider a GSM system having S channels (ARFCN's) allocated, wherein each cell (sector) is allocated k channels, assuming that all three sectors have same number of k channels. If the S channels are divided among N base stations each having three sectored cell, then the total number of available radio channels can be expressed as in equation 2.1 below:

$$S = 3kN \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.1]$$

This explains N base stations each having three sectors and each sector having k channels. The N base stations, which collectively use the complete set of available frequencies, in which each frequency is used exactly once is called a Cluster. If the cluster is replicated M times then the total number of channels, C, can be used as measure of capacity and is given by,

$$C = M3kN \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.2]$$

So, the capacity can be express as equation 2.3 below:

$$C = MS \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.3]$$

The Cluster size N is typically equal to 3, 4, 7, or 12. Deciding a cluster size possess a compromise between capacity, spectrum allocated and interference. A cluster size of 7 or 12 gives least interference frequency plan but as the cluster size is big enough hence re-use at far away distance hence lesser capacity and would also require bigger frequency spectrum. Consider an example where k equals 1 that is one frequency per sector. With a cluster size of 7 would require minimum spectrum of,

$$S = 3\ x\ 1\ x\ 7 = 21\ ARFCN \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.4]$$

Or, 21 x 0.2 MHz = 4.2 MHz of spectrum that is about 16% of total available spectrum in GSM900. Adding one more frequency per sector would take the requirement to 42 ARFCN or 33% of total spectrum. On the other hand a cluster size of 3 would require (k = 1),

$$S = 3\ x\ 1\ x\ 3 = 9\ ARFCN \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.5]$$

Or, 9 x 0.2 MHz = 1.8 MHz that is about 7% of total spectrum available.

An addition of one more frequency still results in about only 14% of spectrum required. But here a big compromise is made on interference, as the cells are quite closely located hence re-use would pose a major problem. Studies have revealed that cluster size of 4 gives the best balance between capacity & interference, with k equal to 2 meaning two frequencies per sector gives,

$$S = 3\ x\ 2\ x\ 4 = 24 \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.6]$$

Or, 24 x 0.2 MHz = 4.8 MHz that is about 19% of total spectrum available.

Figure 2.3 is illustrates the frequency reuse for cluster size of 4, where cells labelled with the same letter use the same group of channels.

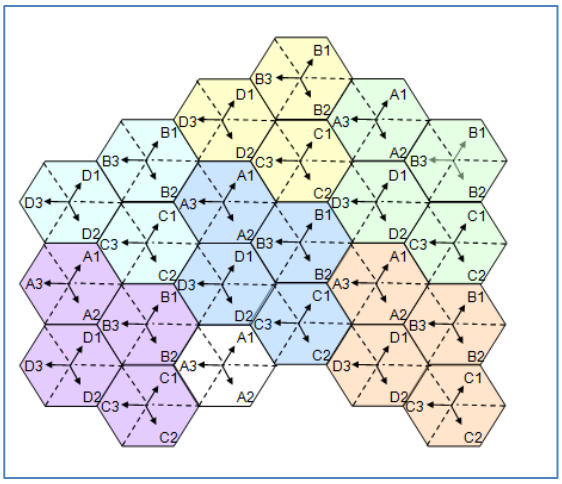

Figure 2.3: Illustrates the Frequency Reuse for Cluster Size of 4

2.1.3 Co-channel interference and system capacity

Frequency re-use implies that in a given coverage area there is several cells that use the same set of frequencies. These cells are called co-channel cells and the interference between signals from these cells is called co-channel interference. Unlike thermal noise which, can be overcome by increasing the S/N ratio, co-channel interference cannot be combated by simple increase in carrier power. This is because an increase in carrier power increases the interference to neighboring co-channel cells. To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance in order to provide sufficient isolation due to propagation.

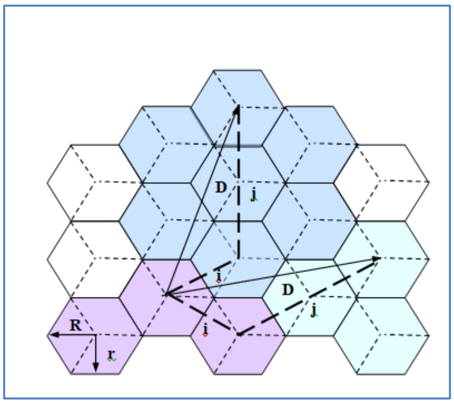

Figure 2.3: Re-use distance calculation.

In a cellular system where the size of each cell is approximately the same, co-channel interference is independent of the transmitted power and becomes the function of the radius of the cell (R), and the distance to the center of the nearest co-channel cell (D).

Figure- 2.3 explains the relation between the cell radius R or always knows as outer cell radius, cluster size N and the re-use distance D, Here, when the Outer Cell radius is R so, Inner Cell radius can be explain as equation 2.7.

$$r = 0.5\ x\ (3)1/2\ x\ R \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.7]$$

Then, the Re-use distance explained by equation 2.8 or the ration between outer per inner (D/R) explained by equation 2.9:

$$D = R\ x\ (3\ x\ (i2 + j2 + ij))^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.8]$$

$$D/R = (3\ x\ N)1/2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.9]$$

Since the cluster size can define by the equation 2.10.

$$N = (i2 + j2 + ij) \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.10]$$

Where i and j are non-negative numbers, to find the nearest co-channel neighbour of a particular cell, one must do the following: (1) move i cells along any chain of hexagons and then (2) turn 60 degrees counter-clockwise and move j cells. This is illustrated in the figure above for i = 1 & j = 2 for a cluster size of 7.

By increasing the ratio of D/R, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased. Thus interference is reduced due to improved isolation from the co-channel cells. The relation between the re-use distance ratio D/R and the co-channel interference ratio C/I is in equation 2.11 as below,

$$(D/R)\gamma = 6\ (C/I) \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.11]$$

(Note: C/I is in dB and should be converted to numeric values for calculation)

Here, γ is the propagation index or attenuation constant with values ranging between 2 to 4.

2.1.4 Coverage Area

A cellular network is a radio network distributed over land areas called cells, each served by at least one fixed-location transceiver known as a cell site or base station. These cells joined together provide radio coverage over a large geographic area. This radio network enables a large number of portable transceivers example mobile phones, pagers, and so on to communicate with each other and with fixed transceivers and telephones anywhere in the network, via base stations, even if some of the transceivers are moving through more than one cell during transmission [13].

The cell and network coverage depend mainly on natural factors such as geographical aspect/propagation conditions, and on human factors such as the landscape either in urban, suburban, or rural, subscriber behavior. The ultimate quality of the coverage in the mobile network is measured in terms of location probability. For that, the radio propagation conditions have to be predicted as accurately as possible for the region.

Three main mechanisms that impact the signal propagation are depicted. Those mechanisms are:

i. Reflection.
   It occurs when the electromagnetic wave strikes against a smooth surface, whose dimensions are large compared with the signal wavelength.

ii. Diffraction.
   It occurs when the electromagnetic wave strikes a surface whose dimensions are larger than the signal wavelength, new secondary waves are generated. This phenomenon is often called shadowing, because the diffracted field can reach the receiver even when shadowed by an impenetrable obstruction (no line of sight).

iii. Scattering.

It happens when a radio wave strikes against a rough surface whose dimensions are equal to or smaller than the signal wavelength.

2.2 Antenna

In the 1890s, there were only a few antennas in the world. These rudimentary devices were primary a part of experiments that demonstrated the transmission of electromagnetic waves. By World War II, antennas had become so ubiquitous that their use had transformed the lives of the average person via radio and television reception. The number of antennas in the United States was on the order of one per household, representing growth rivaling the auto industry during the same period[5,29].

By the early 21st century, thanks in large part to mobile phones, the average person now carries one or more antennas on them wherever they go (cell phones can have multiple antennas, if GPS is used, for instance). This significant rate of growth is not likely to slow, as wireless communication systems become a larger part of everyday life. In addition, the strong growth in RFID devices suggests that the number of antennas in use may increase to one antenna per object in the world (product, container, pet, banana, toy, cd, etc.). This number would dwarf the number of antennas in use today.

2.2.1 Antenna efficiency

The efficiency of an antenna relates the power delivered to the antenna and the power radiated or dissipated within the antenna. A high efficiency antenna has most of the power present at the antenna's input radiated away. A low efficiency antenna has most of the power absorbed as losses within the antenna, or reflected away due to impedance mismatch [14].

The losses associated within an antenna are typically the conduction losses (due to finite conductivity of the antenna) and dielectric losses (due to conduction within a dielectric which may be present within an antenna). The antenna efficiency (or radiation efficiency) can be written as equation 2.12 where the ratio of the radiated power to the input power of the antenna:

$$\varepsilon_r = \frac{P_{radiated}}{P_{input}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.12]$$

Efficiency is ultimately a ratio, giving a number between 0 and 1. Efficiency is very often quoted in terms of a percentage; for example, an efficiency of 0.5 is the same as 50%. Antenna efficiency is also frequently quoted in decibels (dB); an efficiency of 0.1 is 10% or (-10 dB), and an efficiency of 0.5 or 50% is -3 dB. Equation 2.12 is sometimes referred to as the antenna's radiation efficiency.

This distinguishes it from another sometimes-used term, called an antenna's "total efficiency". The total efficiency of an antenna is the radiation efficiency multiplied by the impedance mismatch loss of the antenna, when connected to a transmission line or receiver (radio or transmitter). This can be summarized in Equation 2.13, where $\mathcal{E}_T$ is the antenna's total efficiency, M_L is the antenna's loss due to impedance mismatch, and $\mathcal{E}_R$ is the antenna's radiation efficiency.

$$\varepsilon_T = M_L \bullet \varepsilon_R \ldots\ldots\ldots\ldots\ldots\ldots\ldots [equation\ 2.13]$$

Since M_L is always a number between 0 and 1, the total antenna efficiency is always less than the antenna's radiation efficiency. Said another way, the radiation efficiency is the same as the total antenna efficiency if there was no loss due to impedance mismatch.

Efficiency is one of the most important antenna parameters. It can be very close to 100% (or 0 dB) for dish, horn antennas, or half-wavelength dipoles with no losses materials around them. Mobile phone antennas, or Wi-Fi antennas in consumer electronics products, typically have efficiencies from 20%-70% (-7 to -1.5 dB). The losses are often due to the electronics and materials that surround the antennas; these tend to absorb some of the radiated power (converting the energy to heat), which lowers the efficiency of the antenna. Car radio antennas can have a total antenna efficiency of -20 dB (1% efficiency) at the AM radio frequencies; this is because the antennas are much smaller than a half-wavelength at the operational frequency, which greatly lowers antenna efficiency. The radio link is maintained because the AM Broadcast tower uses a very high transmit power.

2.2.2 Antenna gain

The term antenna gain describes how much power is transmitted in the direction of peak radiation to that of an isotropic source. Antenna gain is more commonly quoted in a real antenna's specification sheet because it takes into account the actual losses that occur [5]. The total gain in wireless transmission can be described in diagram on Figure 2.4.

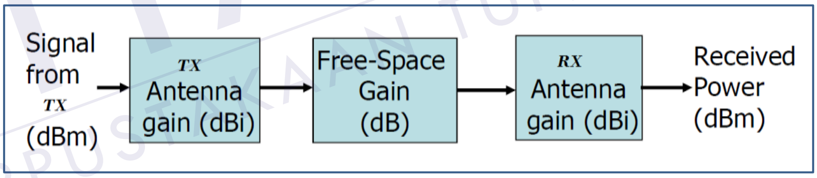

Figure 2.4: Gain in wireless transmission line

An antenna with a gain of 3 dB means that the power received far from the antenna will be 3 dB higher (twice as much) than what would be received from a lossless isotropic antenna with the same input power. Antenna Gain is sometimes discussed as a function of angle, but when a single number is quoted the gain is the 'peak gain' over all directions. Antenna Gain (*G*) can be related to directivity (*D*) by equation 2.14.

$$G = \varepsilon_R D \dots\dots\dots\dots\dots\dots\dots [equation\ 2.14]$$

The gain of a real antenna can be as high as 40-50 dB for very large dish antennas (although this is rare). Directivity can be as low as 1.76 dB for a real antenna (example: short dipole antenna), but can never theoretically be less than 0 dB. However, the peak gain of an antenna can be arbitrarily low because of losses or low efficiency [15]. Electrically small antennas (small relative to the wavelength of the frequency that the antenna operates at) can be very inefficient, with antenna gains lower than -10 dB (even without accounting for impedance mismatch loss)

2.2.3 Smart antenna

Smart antennas and smart antenna technology using an adaptive antenna array are being introduced increasingly with the development of other technologies including the software defined radio, cognitive radio, MIMO and many others.

Smart antenna technology or adaptive antenna array technology enables the performance of the antenna to be altered to provide the performance that may be required to undertake performance under specific or changing conditions.

The smart antennas include signal processing capability that can perform tasks such as analysis of the direction of arrival of a signal and then the smart antenna can adapt the antenna itself using beam-forming techniques to achieve better reception, or transmission [16]. In addition to this, the overall antenna will use some form of adaptive antenna array scheme to enable the antenna to perform is beam formation and signal direction detection.

2.2.3.1 Smart antenna function

While the main purposes of standard antennas are to effectively transmit and receive radio signals, there are two additional functions that smart antennas or adaptive antennas need to fulfill:

i. *Direction of arrival estimation:* In order for the smart antenna to be able provide the required functionality and optimization of the transmission and reception; they need to be able to detect the direction of arrival of the required incoming signal. The information received by the antenna array is passed to the signal processor within the antenna and this provides the required analysis.

ii. *Beam steering:* With the direction of arrival of the required and any interfering signals analyzed, the control circuitry within the antenna is able to optimize the directional beam pattern of the adaptive antenna array to provide the required performance.

2.2.3.2 Types of smart antenna

With considerable levels of functionality being required within smart antennas, two main approaches or types of smart antenna technology have been developed:

i. *Switched beam smart antennas:* The switched beam smart or adaptive antennas are designed so that they have several fixed beam patterns. The control elements within the antenna can then select the most appropriate one for the conditions that have been detected. Although this approach does not provide complete flexibility it simplifies the design and provides sufficient level of adaptively for many applications.

ii. *Adaptive array smart antennas:* Adaptive antenna arrays allow the beam to be continually steered to any direction to allow for the maximum signal to be received and / or the nulling of any interference.

Both types of antenna are able to provide the directivity, although decisions need to be made against cost, complexity and the performance requirements regarding which type should be used [17].

2.3 Rectenna

A rectenna is a rectifying antenna, a special type of antenna that is used to convert microwave energy into direct current electricity. They are used in wireless power transmission systems that transmit power by radio waves [18].

The invention of the rectenna in the 1960s made long distance wireless power transmission feasible. The rectenna was invented in 1964 and patented in 1969 by US electrical engineer William C. Brown, who demonstrated it with a model helicopter powered by microwaves transmitted from the ground, received by an attached rectenna [18]. Since the 1970s, one of the major motivations for rectenna research has been to develop a receiving antenna for proposed solar power satellites, which would harvest energy from sunlight in space with solar cells and beam it down to Earth as microwaves to huge rectenna arrays [19].

A proposed military application is to power drone reconnaissance aircraft with microwaves beamed from the ground, allowing them to stay aloft for long periods[20]. In recent years interest has turned to using rectennas as power sources for small wireless microelectronic devices. The largest current use of rectennas is in RFID tags, proximity cards and contactless smart cards, which contain an integrated circuit (IC) which is powered by a small rectenna element. When the device is brought near an electronic reader unit, radio waves from the reader are received by the rectenna, powering up the IC, which transmits its data back to the reader.

Over the past two decades, many wireless systems have been developed and widely used around the world. The most important examples are cellular mobile radio and Wi-Fi systems. Just like radio and television broadcasting systems, they radiate electromagnetic waves/energy into the air but a large amount of the energy is actually wasted, thus how to harvest and recycle the ambient wireless electromagnetic energy has become an increasingly interesting topic.

One of the most promising methods to harvest the wireless energy is to use a rectenna which is a combination of a rectifier and an antenna. A typical block diagram is shown in Figure 2.5. The wireless energy can be collected by the antenna attached to rectifying diodes through filters and matching circuit. The rectifying diodes convert the received wireless energy into DC power. The low-pass filter will match the load with the rectifier and block the high order harmonics generated by the diode in order to achieve high energy conversion efficiency which is the most important parameter of such a device.

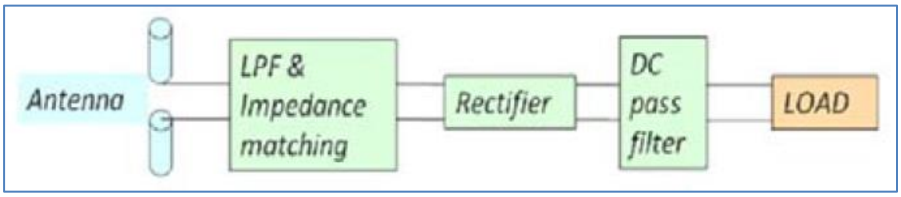

Figure 2.5: Block diagram of a rectenna with a load

A simple rectenna element consists of a dipole antenna with an RF diode connected across the dipole elements. The diode rectifies the AC current induced in the antenna by the microwaves, to produce DC power, which powers a load connected across the diode. Schottky diodes are usually used because they have the lowest voltage drop and highest speed and therefore have the lowest power losses due to conduction and switching. Large rectennas consist of an array of many such dipole elements [18].

There are at least two advantages for rectenna: First, the life time of the rectenna is almost unlimited and it does not need replacement (unlike batteries)and the second it is "green" for the environment unlike batteries, no deposition to pollute the environment.

2.4 Energy harvesting

Over 100 years ago, the concept of wireless power transmission was introduced and demonstrated by Tesla [7], he described a method of "utilizing effects transmitted through natural media". This method has been brought particularly into prominence in recent years. In fact, Tesla was unsuccessful to implement his wireless power transmission systems for commercial use but he transmitted power from his oscillators which operated at 150 kHz to light two light bulbs. The reason for his unsuccessful attempt was that the transmitted power was radiated to all directions at 150 kHz radio wave whose wave length was 20 km and the efficiency was too low.

Based on the development of the microwave tubes during the World War II, rectification of microwave signals for supplying DC power through wireless transmission was proposed and researched in the context of high power beaming since 1950s. B. C. Brown started the modern era of wireless power transmission with the advancement of high-power microwave tube at Raytheon Company [1]. By 1958, a 15 kW average power-band cross-field amplifying tube was developed that had a measured overall DC to RF conversion efficiency of 81%. The first receiving device for efficient reception and rectification of microwave power emerged in the early 1960's.

A rectifying antenna or rectenna was developed by Raytheon. The structure consisted of a half-wave dipole antenna with a balanced bridge or single semiconductor diode placed above a reflecting plane. The output of the rectenna element is then connected to a resistive load. 2.45 GHz is widely used as the transmitting frequency because of its advanced and efficient technology base, location at the center of an industrial, scientific, and medical (ISM) band and its minimal attenuation through the atmosphere even in heavy rainstorms.

From the 1960's to the 1970's the conversion efficiency of the rectenna was increased at this frequency [6]. Conversion efficiency is closely linked to the microwave power that is converted into DC power by a rectenna element, the greatest conversion efficiency ever recorded by a rectenna element occurred in 1977 by Brown in Raytheon Company using a GaAsPt Schottky barrier diode, a 90.6% conversion efficiency was recorded with an input microwave-power level of 8 W.

This rectenna element used aluminum bars to construct the dipole and transmission line [20]. Later, a printed rectenna design was developed at 2.45 GHz with efficiencies around 85% [21]. More recently, McSpadden and Chang used the rectenna as a receiving antenna attached to a rectifying circuit that efficiently converts microwave energy into DC power. [14].

As an essential element of the rectenna, the antenna of rectenna can be any type such as a dipole [22], Yagi-Uda antenna [23], microstrip antenna [24], monopole [25], coplanar patch [15], spiral antenna [26], or even parabolic antenna [27].

The rectenna can also take any type of rectifying circuit such as single shunt full-wave rectifier [25], full-wave bridge rectifier [N. Shinohara, S. Kunimi, 1998], or other hybrid rectifiers [23]. The circuit, especially the diode, mainly determines the RF to DC conversion efficiency, rectennas with FET [25] or HEMT [15] appeared in recent years. The world record of the RF-DC conversion efficiency among developed rectennas is approximately 90% at 8 W inputs of 2.45 GHz [22].

The RF-DC conversion efficiency of the rectenna with a diode depends on the microwave power input intensity and the optimum connected load. When the power is small or the load is not matched, the efficiency becomes quite low. The efficiency is also determined by the characteristic of the diode which has its own junction voltage and breakdown voltage, if the input voltage to the diode is lower than the junction voltage or is higher than the breakdown voltage the diode does not show a rectifying characteristic. As a result, the RF-DC conversion efficiency drops with a lower or higher input than the optimum.

It is worth noticing that all the recorded high conversion efficiencies were generated from high power incident level due to the reason we mentioned above. For low power incident level, a measured conversion efficiency of 21% was achieved at a power incident of 250 μW/cm^2 [28], of course, in principle a high efficiency should be achievable. There are basically two approaches to increase the efficiency at the low microwave power density. The one is to increase the antenna aperture as shown in [27]. There are two problems for this approach. It produces a high directivity and this is only applied for exclusive applications as SPS satellite experiment and not for low power applications like RFID or microwave energy recycling. The other approach is to develop a new rectifying circuit to increase the efficiency at a weak microwave input.

2.5 Link Budget

A link budget is the accounting of all of the gains and losses from the transmitter, through the medium like free space, cable, waveguide, fiber and so on to the receiver in a telecommunication system. It accounts for the attenuation of the transmitted signal due to propagation, as well as the antenna gains, feedline and miscellaneous losses.

Randomly varying channel gains such as fading are taken into account by adding some margin depending on the anticipated severity of its effects. The amount of margin required can be reduced by the use of mitigating techniques such as antenna diversity or frequency hopping.

As the name implies, a link budget is an accounting of all the gains and losses in a transmission system. The link budget looks at the elements that will determine the signal strength arriving at the receiver. The link budget may include the following items; transmitter power, Antenna gains (receiver and transmitter), antenna feeder losses (receiver and transmitter), path losses, and receiver sensitivity which although this is not part of the actual link budget, it is necessary to know this to enable any pass fail criteria to be applied [5].

Where the losses may vary with time, such a fading, and allowance must be made within the link budget for this - often the worst case may be taken, or alternatively an acceptance of periods of increased bit error rate for digital signals or degraded signal to noise ratio for analogue systems. In essence the link budget will take the form of the equation 2.15 where P_r is received power, P_t, G is transmitter and receiver antenna gain and L is total losses. Usually the transmitted power and the receiver power are specified in terms of dBm (Power in decibels with respect to 1mW) and the antenna gains in dBi (Gain in decibels with respect to an isotropic antenna)[5]. Therefore, it is often convenient to work in log domain instead of linear domain. Another alternative form of Friis Free space equation in log domain is given by:

$$P_r(dBm) = P_t(dBm) + G(dB) - L(dB) \dots\dots\dots\dots\dots\dots\dots [equation\ 2.15]$$

The basic calculation to determine the link budget is quite straightforward. It is mainly a matter of accounting for all the different losses and gains between the transmitter and the receiver.

2.5.1 Friis transmission formula

The Friis transmission equation is used to calculate the power received from one antenna (with gain *G1*), when transmitted from another antenna (with gain *G2*), separated by a distance *R*, and operating at frequency *f* or wavelength lambda[5]. To begin the derivation of the Friis Equation, consider two antennas in free space (no obstructions nearby) separated by a distance R as illustrated by Figure 2.6:

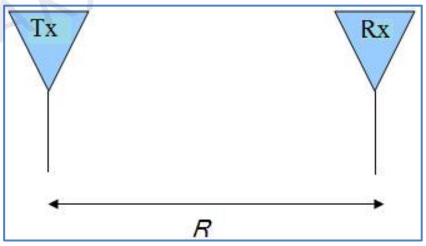

Figure 2.6: Transmit (Tx) and Receive (Rx) Antennas separated by *R*.

Assume that P_t Watts of total power are delivered to the transmit antenna. For the moment, assume that the transmit antenna is omnidirectional, lossless, and that the receive antenna is in the far field of the transmit antenna. Then the power density *P* (in Watts per square meter) of the plane wave incident on the receive antenna a distance *R* from the transmit antenna is given by equation 2.16.

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