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Wireless Charging in the Context of Sensor Networks

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Abstract
Breakthroughs in wireless communications have given rise to low-cost sensor networks, which are being used in a wide range of sectors such as household, health and military sectors. The rising popularity and demand for wireless sensor networks mandate efficient methods for powering them. In most cases, it may not be feasible to replace battery sources for the networks. Hence it is highly desirable to build smart systems that can locally generate and provide sensor nodes with power thus increasing the network's life span. In this paper, we discuss the idea of charging sensor nodes wirelessly. We start by providing a background about wireless sensor networks, wireless power transfer and then we study wireless charging and the power management systems involved in the context of wireless sensor networks. We also show through simulations the applicability of the wireless charging in wireless sensor networks.

Keywords: Wireless charging, power transfer, sensor networks, inductive coupling, energy transfer.

INTRODUCTION

Sensor nodes are small-size devices that have enabled un-tethered communication over short distances. They generally have three components-sensing, data processing and communication elements. A large number of sensor nodes combine together to form sensor networks. These sensor nodes are usually densely deployed within the network, which is either inside or close to the phenomenon under consideration [1].

Sensor networks offer significant advantages over traditional sensors. For instance, the position of sensor nodes need not be considered in their design. This means that they can be used even in disaster relief operations in inaccessible terrains. However, this also means that they need self-organizing capabilities, which generally implies making use of complex algorithms and sensor network protocols. Another example of sensor networks' advantages over traditional sensors lies in the 'cooperative effort' feature of sensor nodes, which have an on-board processor. This enables nodes to carry out partial computations, before sending data to other recipient nodes. This is in contrast to traditional sensors which do not possess processing capabilities, and hence can only transmit raw data. This particular feature of 'cooperative effort' thus results in many application possibilities for sensor networks and help save transmission bandwidth [1].

The sensor nodes are generally scattered within a sensor field, and each scattered node is capable of collecting data, as well as to transmit data back to the sink, which in turn can communicate with the central node that performs the role of task manager. The latter is carried out by using a multi-hop, infrastructure-less architecture. The design of a sensor network considers many factors such as fault tolerance, production costs, scalability, sensor network topology, operating environment, transmission media, hardware constraints, power consumption, etc. [1, 2].

A wireless sensor node is a microelectronic device. Hence in terms of power consumption, it can be equipped with only a limited power source (usually < 0.5 Ahr, and 1.2 V). In quite a few applications, it may not be possible to replace power sources. This means that the lifetime of sensor nodes is strongly determined by the lifetime of the power source it uses [1].

In the case of a multi-hop and hoc sensor network, every node takes two different roles-data originator and data router. The nodes being closely related, any malfunctioning even in a few of them can cause serious problems in the network – they may alter its topology and overall functionality. This may result in a necessity to reroute packets, if not reorganize the entire network. Therefore, power management and conservation are two factors that must be given the utmost importance in the design of sensor networks. Just as the functionality of any node in a sensor network is three-fold, power consumed by the system can also be accordingly classified as-sensing power, processing power, and communication power [2]. The communication mode is the most energy hungry [3]. Fortunately, sensors rarely communicate with each other and only transmit processed information to reduce the communication time and the required bandwidth. However, they should keep monitoring the channel and not completely sleep or switched off. This listening process significantly contribute to the overall power consumption of the sensor node [4]. In order to reduce the power consumed during the idle mode and functionally operating the WSN, switching between the sleep state and the listening state using the concept of duty cycling has been suggested in [5].

Whichever mode the node maybe in, it should be capable of minimizing the amount of respective power consumed. At the micro-systems level, power saved even for a short period of time makes a huge difference in the overall performance of the system. In a sensor network, not all nodes are functioning at all times. In fact, taking any specific node, it generally is in only one phase of operation. So it makes sense to make sure that the other two phases are switched off when not in use. However, designing power-saving schemes in a sensor network is not straightforward. An elaborate dynamic power management scheme specifically for using in wireless sensor networks has been discussed in [2].

Keeping the importance of power consumption in mind, most of the research has focused on designing power-aware algorithms and protocols that achieve high energy efficiency, such as using lightweight communication protocols [4, 6] or adopting low-power radio transceivers [4, 7]. Recently, energy harvesting, which is also known as energy scavenging, has received a great deal of attention in wireless sensor networks and internet of things literature [4]. It has been presented as a promising fundamental source for recharging sensor nodes' batteries and prolonging the network life [8]. Basically, energy from different environmental sources such as, thermal, solar, vibration, and / or wireless RF energy sources is converted to electrical energy and then stored in the battery [9]. A comparison of the amount of power harvested per unit area produced by the aforementioned sources is provided under different outdoor and indoor scenarios [10].

In this article we provide an extensive overview of wireless energy harvesting concept (wireless charging concept). In the context of Internet of Things (IoT) and wireless sensor networks (WSNs) wireless energy sources can be classified into dedicated sources and Ambient sources [11]. In the case of dedicated wireless sources, dedicated RF sources are deployed to provide a predictable energy supply to the device. These sources are optimized in terms of frequency and maximum power to meet the requirements of the sensor devices [4]. On the other hand, energy harvested from ambient sources such as mobile base stations, radio and TV broadcasting and WiFi access points are usually not optimized in terms of frequency and transmitted power. Some of these sources might not always be available and can transmit on different frequency bands. This complicates the antenna geometry requirements and demands a sophisticated power converter [4]. Therefore, we approach the problem assuming that a dedicated energy source is used and the power is wirelessly transferred to the sensor nodes.

The paper is organized as follows: in section 2 we thoroughly discuss the concept of wireless power transfer and analytically show how effective it is in charging the sensor nodes. We go through the current research efforts addressing wireless charging in the context of wireless sensor networks in section 3. In section 4 we study the factors affecting the efficiency of wireless charging through simulations. We then conclude by outlining future research direction in field.

WIRELESS CHARGING

Ever since Marconi invented long distance radio transmission, wireless telecommunications has changed the lifestyle of almost everyone on the planet. As far as innovation in wireless technology is concerned, it is closely related with improvements in energy storage technologies. There is an ever demand for better performance from electronics, and researchers are trying to catch up to it [5].

Wireless-power-transfer is not a new concept as far as technology is concerned. However, in the past, wireless power transfer has been associated with a very small portion of electronic devices. This trend has been changing, and this field has now become a very popular field of research [5].

Concepts in Power Transfer

In general, electric power is transmitted when electrons move in conductors and semiconductors, during the time when the receiver and the transmitter are electrically connected. This is the wired form of power transfer. If one needs to achieve this even when the transmitter and receiver are not electrically connected, then electromagnetic fields need to be utilized as the medium of transmission which means that they should be magnetically connected [12].

As per Maxwell's equations, wave dependence is defined as the ratio of electric field to magnetic field. Time varying electric field gives rise to magnetic field, and time varying magnetic field produces electric field. The nature of the source, the media surrounding it, and the distance between the source and the observation point determine the characteristics of a field. At points relatively close to the source, field characteristics are more strongly dependent on source properties, and at points away from the source, the propagation media's properties have a stringer influence.

Both electric field and magnetic field may be used for wireless power transmission. However, most applications prefer adopting magnetic field transmission because it offers the advantages of less attenuation and reflection due to strong dielectric materials since it is less influenced by permittivity. Further, magnetic coupling structure is simpler in terms of implementation, when compared to electric field coupling [12].

Inductive Coupling and Resonant Magnetic Coupling

Inductive coupling of two conductors is one way for transferring power between them in the form of magnetic field [12, 13]. Wireless power transfer using induction in the form of electric toothbrushes has been a popular technique which has been in use for a long time. Since the electric toothbrushes are constantly exposed to water, they are required to use inductive technology to recharge their batteries. This kind of a wireless charging system can be termed inductive coupling. Inductive coupling generally means that the wireless power transfer occurs at a distance of a few millimetres between the transmitter and receiver coils. Since the coils have short lengths, the amount of leakage magnetic field is also small. Further, efficiency is in the range of 60%-90% which is quite reasonable. However, the distance cannot be easily increased, and the alignment of the receiver and transmitter must be accurate – these are two major drawbacks of inductive coupling. These can however be overcome by using resonant magnetic coupling wherein the resonance circuit of the transmitter and receiver are applied [13].

Topology and Design

The core of any wireless charging system comprises of a power source, transmitter and receiver coils, and load, as can be seen in Figure 1. The design of each element is very important in implementing wireless energy transfer since the coils are closely related to the circuit design, dimensions, transfer power and magnetic field shape.

Transmitter and receiver coils of feeding type indicate indirectly fed coils in which the transmitter and receiver coils are separated. In such a case, the coils have high Q-factor values since the load and source resistance are not included, which means the distance of the wireless energy transfer can be increased. However, just like other systems that offer high Q-factors, this system can also be very sensitive to design parameters like resonance frequency and inductor value.

Therefore, directly fed wireless charging systems are preferred however stability is the main concern, and the transmission distance is not that important [12].

Q-factor affects power transfer efficiency appreciably. Coils with higher Q-factor values can result in better efficiency provided the frequency of power transmission and the resonance frequency exactly match. Figure 2 which is quoted from [12] shows an indirect-fed wireless power transfer scheme.

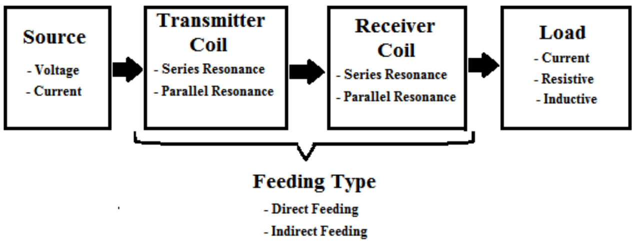

Figure 1: Overall block diagram

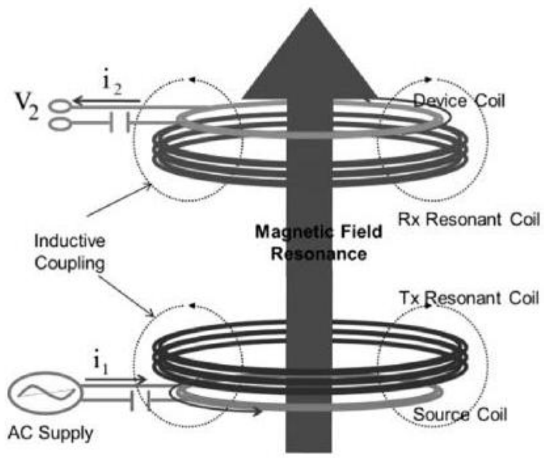

Figure 2: Indirect-fed wireless power transfer scheme [12].

An important factor in a wireless system is the maximum possible distance between the receiver and transmitter to ensure normal operating conditions. The following equations describe the mathematical relationships governing this factor:

Received power = Tx power + gains – losses (1)

Max path loss = Tx power + gains – Rx sensitivity – losses-fade margin (2)

where fade margin is based on the surrounding environment then:

$$Max\ Distance\ (km) = 10^{(maximum\ path\ loss\ -\ 32.44\ -\ 20\log(f))/20} \quad (3)$$

with *f* denoting frequency in MHz.

CURRENT RESEARCH

Conventional wireless sensors are restricted by limited battery energy. Therefore, the network finite lifetime, as explained earlier is regarded as basic performance bottleneck. Recent research in the field of wireless energy transfer is indeed a technological breakthrough that offers the possibility to remove such an undesirable performance bottleneck. In other words, it has enabled the possibility for sensor networks to be operational for very long time.

In [14] the case of a mobile charging vehicle that periodically travels inside the sensor network has been considered. A new concept of renewable energy cycle has been introduced that is used to study and solve an optimization problem. The main objective is to maximize the WCV's (wireless charging vehicle) vacation time to cycle time ratio. Analysis of this problem shows that the optimal traveling path for the wireless charging vehicle is the smallest Hamilton cycle, and also provides a number of important properties. This analysis is used to come up with and test a near optimal solution.

As for prolonging sensor network lifetime it is emphasized in [18] that mobile charging is a key component in a wireless sensory system. Depending on the distance of the mobile charger, the effectiveness of the amount of power a receiver can capture varies. An inverse proportionality between the distance and the charging efficiency was concluded in [18] meaning that the efficiency of the mobile charger decreases with the increase in the distance [18].

A good power source for wireless sensor networks that operate at low power can be obtained from environmental energy. Work in [15] presents Prometheus, a smart system that can manage energy transfer for perpetual operation without the need for human intervention or servicing for the associated wireless sensor networks.

Making use of the positive features of different energy storage elements and the intelligence of the micro-processor, an efficient multi-stage energy transfer system was proposed in [16]. Work in [16] claimed that the system reduced the general limitations posed by single energy storage systems, thus achieved almost perpetual operation.

Analysis of implementation results provided there predicted that the system would operate for over 43 years if there was 1% load, 4 years if there was 10% load, and 1 year for 100% load. The implementation covered in details the design of a two stage storage system that comprised super capacitors (which act as primary buffers) and a lithium rechargeable battery (which acts as the secondary source). This was a real-time system that made use of solar energy to power Berkeley's Telos Mote. The system was fully aware of power levels and made intelligent decisions so as to manage energy transfers and to maximize lifetime [16].

Wireless transmission of energy has always been a challenging topic in the recent years, especially with the advent of devices like medical implants where there is need for transferring energy to devices that works in conditions where supplying power is tedious or risky. Wireless electricity or witricity in short, is the advanced method for energy transmission using resonant inductive coupling, which can address this issue. It is based on the principle that resonantly coupled systems can transfer energy more efficiently than weakly coupled systems [13].

Generally in a conventional wireless energy transfer system, the coupling depends on physical separation and this leads to increase in leakage inductances and a negligible mutual inductance. But using witricity based system, coupling efficiency can be improved up to 500% than the conventional system because of resonant coupling. Since the witricity system depends also on the frequency of the primary and secondary coils, more factors have to be taken into account, which includes the device dimensions and coil turns ratio [13].

There are basically two advantages of witricity based energy transfer method. Firstly, an exceptionally higher coupling coefficient can be achieved if the system is designed for the characteristic resonant frequency. Secondly, the dependence of coupling with distance is more acceptable and follows a gradual curve compared to the conventional method which has an exponential drop with distance [13].

Wireless charging has enormous applications in many areas and one prominent field is in sensor networks where power distribution is a big challenge. Battery-powering the sensor networks which are meant for long term purposes is not practical since it requires regular maintenance for battery replacements which is inefficient and time consuming. Also there are instances where the sensors are placed at positions that are inaccessible to humans (like medical implants). Wireless charging can address this issue by providing energy using coupling coils placed considerable distance apart. In contrast to the battery replacement, this method is more robust and accurate sensor positioning is not a key requirement [18].

Using current technological advancements, sensor networks equipped with power receivers on each node and an effective wireless charging device along with proper control system can be designed and put to work. For the charging system to identify the nodes that are down, a state-of-the-art power monitoring system which senses the node power level is inevitable. Depending on the network implementation, this monitored data is used to give proper control signals to the mobile wireless chargers. Generally, a sink is present in the system to consolidate the energy level data uploaded by each sensor nodes, and this is forwarded to the monitor station which uses various efficient algorithms to determine the pattern in which nodes should be arranged so that the mobile charger can efficiently reach near the node vicinity and supply energy [18]. The monitoring should be done real-time to make sure that the mobile charger is given appropriate instructions continuously thereby saving time. The energy transfer rate between charger and node depends inversely on the distance between them and this also affects the time taken for adequate node charging [13].

More recent research focuses on energy harvesting solutions such as using solar [17], piezo, thermal and wind energies as a source of battery power in sensor networks. In a new scheme developed, a controllable energy source is designed to charge sensor nodes, as a mobile charger. This means that the charging pattern can be used dynamically rather than be dependent on environmental availability of energy. The specific scheme of node reclamation and replacement strategy uses a mobile repairman for the purpose of periodically replacing almost dead sensors with fully recharged ones [18].

SIMULATION RESULTS

Based on the above discussion of the wireless power transferring, it can be seen that many factors affect the amount of received power. These factors are the resonance frequency of the circuit, the distance between transmitter and receiver and the value of transmitted power. The value of transmitted power also depends on resonance of the parallel LC at the transmitter side as well as the power parameters of the transmitter such as the primary current and primary voltage [19]. The values of inductor and capacitor at the transmitting and receiving circuit are chosen to have resonance at the transmission frequency thus satisfying equation (4) below.

$$f_r = \frac{1}{\sqrt{LC}} \qquad (4)$$

where f_r is the resonance frequency, L is the inductor, and C is the capacitor. Figure 3 shows a parallel LC circuit simulating the equivalent resonance circuit used for transferring power wirelessly. Figure 4 shows the setting values of the resonance frequency and the input and output voltages waveforms. Figure 5 shows the behavior of the parallel LC for a frequency range that includes the resonance frequency.

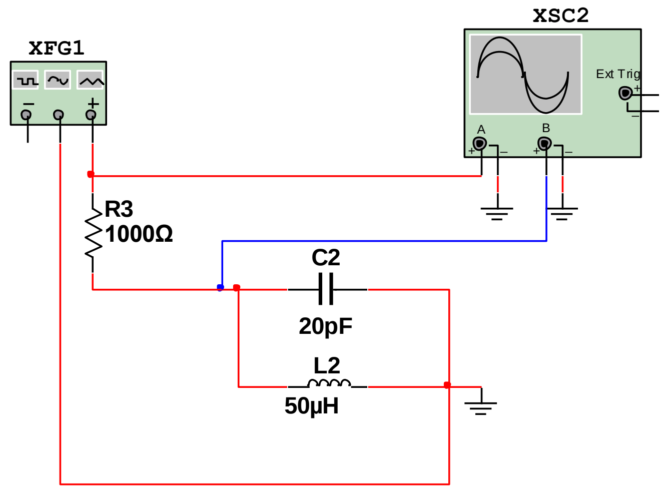

Figure 3: Designed LC circuit with resonance frequency 5 MHz

The work in this research focuses on studying the effect of varying the DC input voltage on the transmitted power and the received power and on how to improve the received power. Firstly, the circuit is designed and simulated assuming that the distance between the transmitting and receiving sides is normalized and that resonance is obtained at 5 MHz in both the transmitting and receiving circuits.

As for the case of many research studies which proposed the use of DC power supply for mobile phones wireless charging [20-23], we propose the circuit in figure 6 for charging sensor nodes batteries wirelessly. The results of changing the DC input voltage value on the transmitted voltage, received voltage, output DC voltage, and Zener voltage are listed in table I.

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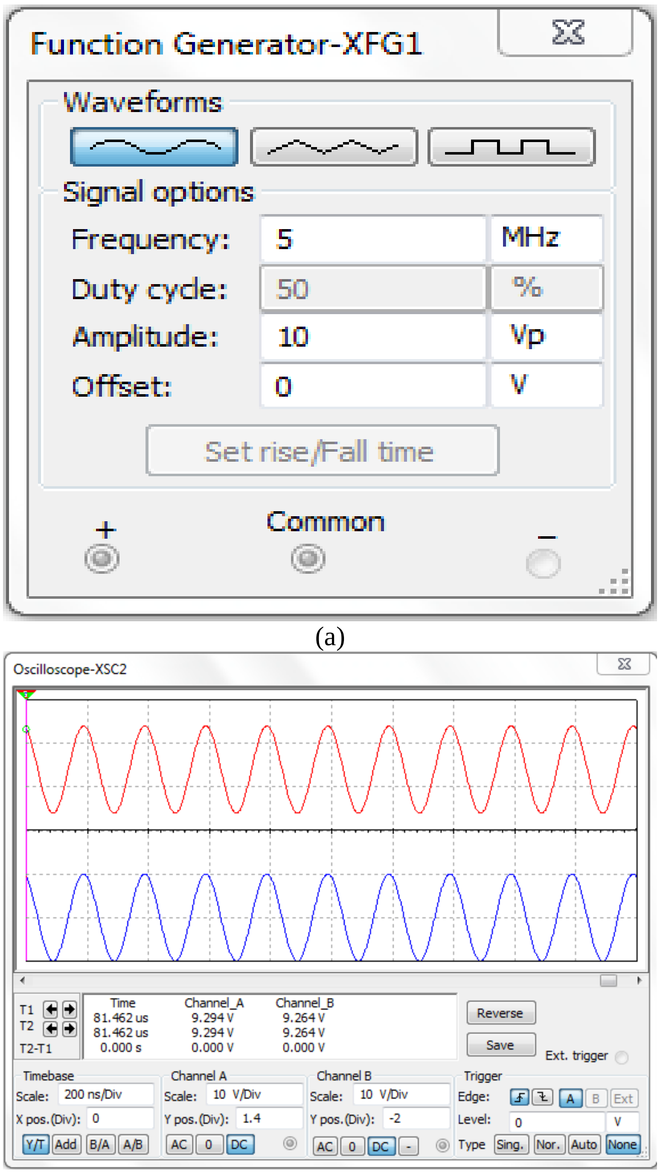

(a)

(b)

Figure 4: Input and output voltage through LC circuit with setting of resonance frequency

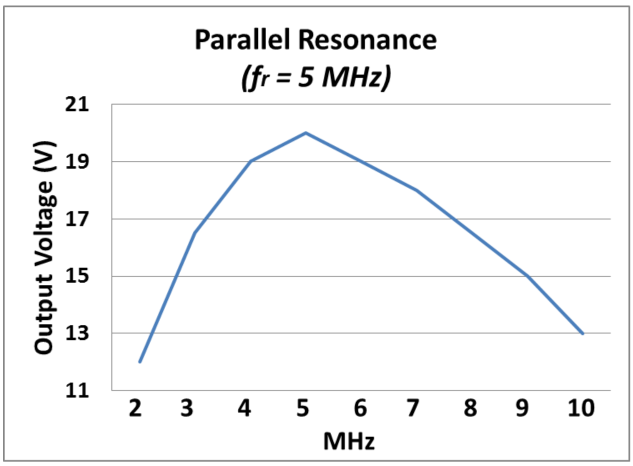

Figure 5: Behaviour of the parallel resonance LC Circuit

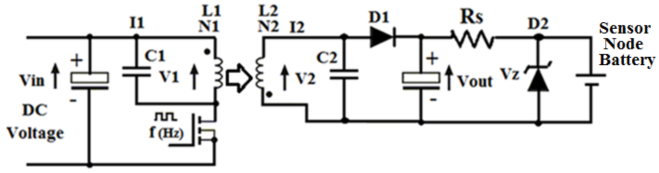

Figure 6: Proposed electronic design

Table I: Details of voltage values for transmission with attenuation (50%)

Input DC Voltage (V)	Transmitted (5 MHz) Voltage (V)	Received (5 MHz) Voltage (V)	Output DC Voltage (V)	Zener Voltage (V)
10 V	9.949	4.975	4.978	4.526
12 V	11.931	5.966	5.962	5.129
14 V	13.784	6.821	6.93	5.179
16 V	15.774	7.819	7.903	5.205
18 V	17.853	8.926	8.88	5.228
20 V	19.77	9.823	9.861	5.248

Table I list the voltage values at different points in figure 6 with the assumption of transmission attenuation of 50% for a fixed normalized distance between transmitter and receiver. Figure 7 depicts the data of table 1. The effect of attenuation and the variation of the input voltage on the output voltage can be seen in figure 7. It can also be noticed that the Zener voltage remains almost constant in spite of the variation of transmitter side voltage.

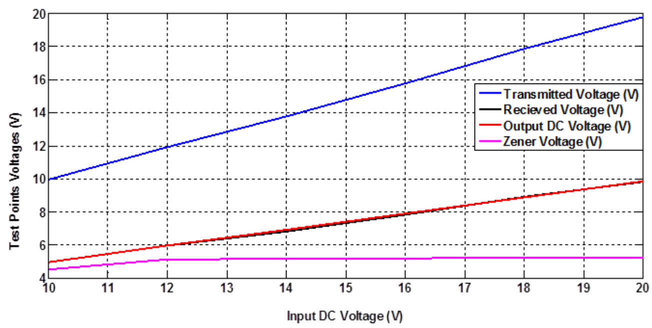

Figure 7: Stable Zener voltage during changing transmitted voltage value.

CONCLUSION

Building smart systems that can manage power transfer and maintenance in wireless sensor networks can increase their life span. Wireless charging is one solution that can take care of continuous monitoring and management of power transfer in these networks. This paper has discussed various wireless charging techniques and energy management systems in the context of wireless sensor networks. Through simulations it has been shown that inductive coupling under resonance conditions can be a good alternative for wireless charging.

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