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Wireless Charging of Embedded Systems: A Review †

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Abstract: Wireless charging technology has become increasingly popular, and demand for its inclusion in embedded systems has also risen. While there are multiple technologies available, each one has unique traits that may make a technology preferable in a given embedded system. This paper will address the prevalent technologies, including radio frequency-based wireless charging and inductive wireless charging, along with their suitability to integrate into embedded systems. This review will also provide a viable option for the most optimal wireless charging technology for small-footprint systems. After reviewing the advantages or limitations of all wireless charging technologies, it is evident that inductive coupling could be the most suitable one to implement in an embedded system when considering size, price, and efficiency. This review also presents the rationale behind this conclusion.

Keywords: inductive coupling; magnetic resonance coupling; radio frequency; energy harvesting; power conversion efficiency

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1. Introduction

The introduction Embedded systems have become an integral part of everyday life for an incredibly large number of people and are being integrated into phones, watches, cars, dishwashers, and many other things. An example of an embedded system is shown in [1] to monitor and control outdoor activity to enable a lighting system. However, one limiting factor for the ubiquitous implementation of embedded systems requires battery power to function. Increasingly, it seems that the sole characteristic holding embedded systems back is the method through which they are charged. Most recently, wireless charging appears to be an all-encompassing solution to this dilemma. With improving transmission efficiency and range, wireless power technology appears to be the trend of the future that can elevate embedded systems to the next level, including smarter watches, glasses, and mobile devices. Embedded applications such as a light sensor would benefit greatly from wireless charging technology because of its positioning on a lamp and the lack of efficient long-distance charging [1]. Another application could be in a medical environment for monitoring patient conditions such as breath patterns [2] through body-worn tiny wearables. The only option for charging embedded systems in the past has been with cables or batteries, for example, through the wire connected to a USB wall socket. As wireless charging continues to be developed and be more efficient and accessible, it becomes an increasingly relevant feature to include in any new systems moving away from wasting countless amounts of non-rechargeable batteries.

There are two primary classes of wireless charging: radio frequency (RF) charging and coupled systems. The coupled systems class can be further divided into two subcategories: tightly coupled inductive charging and loosely coupled magnetic resonance charging. Another modern development in wireless charging is the concept of Qi compliant chargers. Qi standard charging defines a wireless charger that uses resonant inductive coupling between a transmitter and a receiver in close proximity. All of these wireless charging offers their own unique advantages and disadvantages, but they share certain common characteristics: they each reduce hassle by removing the need to interact with cables and charging ports; they each improve durability by removing the need for a charging port that provides the opportunity for dust and detritus to degrade the system; and they each offer potential compatibility between brands and devices, allowing multiple systems to be charged by one universal transmitter module.

Despite these advantages to implementing wireless charging into an embedded system, it is very important to understand which method of wireless charging to use prior to implementation. The motivation of this paper was to provide insight as to what method would best suit a given embedded system.

Thus, the objective of this paper was set to gather and compile information regarding a rapidly developing technology that will likely shape the future of electronics, and specifically embedded systems. This paper will offer information on the foremost of the available technologies to be bought and used in embedded systems. Finally, in the review analysis section, a specific variety of wireless charging technology is recommended.

2. Methodologies

2.1. Inductive Wireless Charging

Inductive wireless charging was one of the initial technologies implemented in the 1960s and has been researched and developed to become a less-intrusive artificial heart [3]. As the technology evolved, it became more powerful, and the coil could sustain more power and tuned out to be one of the predominant types of Wireless Power Technology.

Inductive Wireless Charging is typically used for providing large amounts of power through a short distance. This is done through a method similar to magnetic resonance coupling, which the paper will address shortly. The process involves sending a current through a coil of wire, which generates a magnetic field. This coil can be considered as the transmitter. The transmitter creates a magnetic field, which then goes through another coil. In terms of transmission and reception, the second coil is the receiver. As the magnetic field is flowing through the receiving coil, a current is induced in the wire [4].

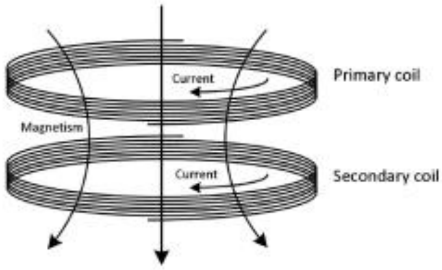

Figure 1. Theory of Inductive Wireless Charging [4].

This system works most efficiently if both coils are attenuated to the same frequency. As can be seen, the distance between these two coils is meant to be very small, "generally less than a wavelength" [4]. While that is the optimal operating range of the paired coils, it is by no means a complete restriction.

As shown in Figure 2, the power transfer of a paired inductive coil can be relatively efficient, including ninety percent efficiency to a range of one hundred centimeters [5].

An additional factor to consider regarding this technology is the quality factor. Quality factor describes the efficiency of the system, specifically relating to "the ratio of the apparent power to the power losses in a device" [6]. Typically, with Inductive Wireless Charging, the quality factor will not exceed ten [4]. This is a very low value, which demonstrates how the weakness in terms of transmission efficiency. That being said, the technology itself is relatively cheap when compared to RF-Based Wireless Charging, which will be addressed later in the paper.

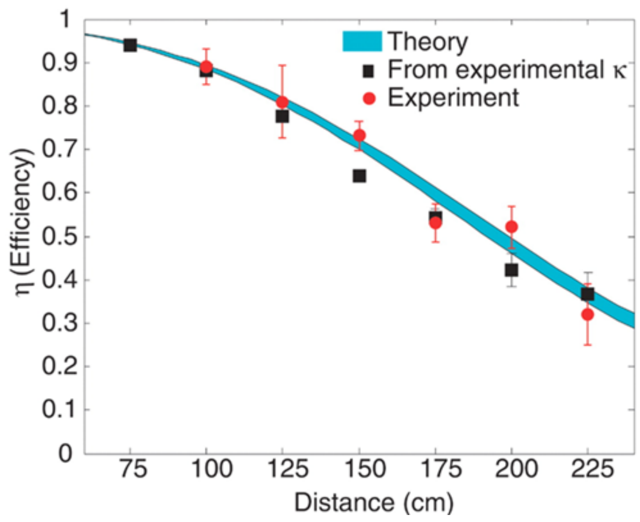

Figure 2. Efficiency of Wireless Power Transfer as a Function of Distance [5].

2.2. Magnetic Resonance Coupling

Another form of wireless charging is magnetic resonance coupling. This works through paired coils generating and transferring energy between oscillating magnetic fields. The primary difference between this magnetic resonance and inductive charging is that magnetic resonance charging occurs between strongly coupled coils operating at the same resonant frequency, which allows for large amounts of energy transfer with high efficiency. Due to the power transfer taking place between two fields at specific frequencies, this also allows for charging multiple devices at once (such as charging a phone and smart watch at the same time), charging at a longer distance than inductive, and charging without line-of-sight.

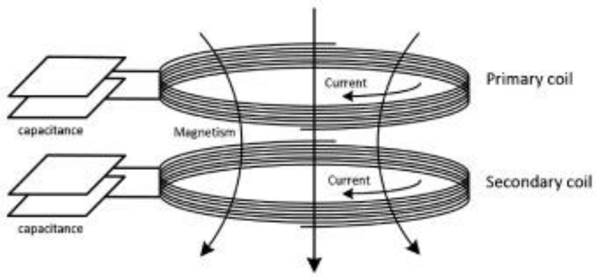

Figure 3. Theory surrounding Magnetic Resonance Coupling [4].

However, these traits do have limitations. The longer the distance between the transmitter and the receivers reduces the efficiency of energy transfer, though it is possible to stay above 90% efficiency at a range of 1 m and at 40% at a range of 2 m [7,8]. For multiple devices tuned to the same frequency, interference can occur, which means that extra precautions need to be taken to ensure that there is no interference [4]. Finally, for all of these, a large capacitive coil is needed, which is a very large obstacle in the face of implementation in small embedded systems.

Coupled systems follow the same structure of using magnetic fields and waves in order to deliver power to a load. Another diagram for how the coupled systems can be applied to a system is shown in Figure 4. A power supply runs through a transmitter that allows for the primary coil to generate a magnetic field. The receiving coil has an induced current from the magnetic field, which powers a battery or a load.

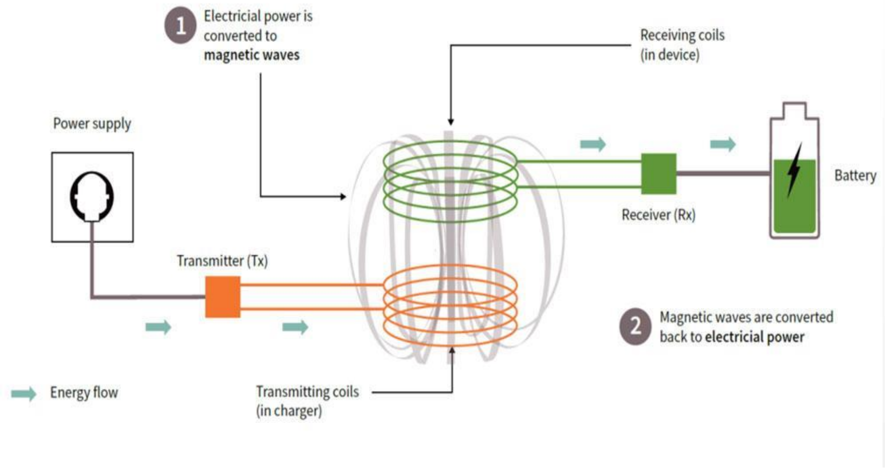

Figure 4. Coupled Wireless System Application in a System [9].

2.3. RF-Based Wireless Charging

Radio waves are typically used to relay frequencies containing information to receivers, and they can be used in RF-based wireless charging systems. They are also able to be a source of wireless power for systems, and radio frequency energy harvesting is favored for low-power applications such as smaller embedded systems [11]. For an RF-based charging system of a smaller embedded system application, the transmitter and receiver of the radio wave would want to be close to each other to reduce loss. Because the focus is to maximize the energy transmission efficiency over a wireless medium, RF-based systems allow another alternative in the list [11]. The conversion of a radio wave to DC power is shown in Figure 5 [12].

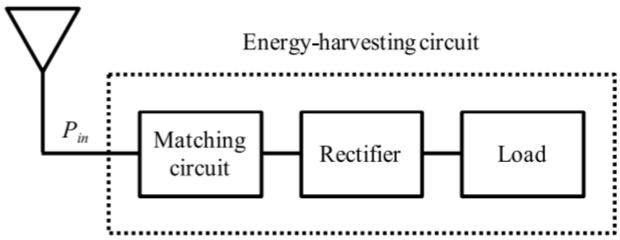

Figure 5. RF-Based Power System Block Diagram [12].

The efficiency of converting radio waves to power also depends on the radio frequency. As the radio frequency is received by the antenna, an AC wave is created that will follow the oscillation of the wave being collected. According to the different frequencies, optimal power conversion efficiencies (PCE) have been tested to convert the radio wave to DC power [12]. As the operational frequency of a radio transmitter increases, the larger input power will be needed to support it and achieve optimal PCE values [12].

The advantage of using an RF-based charging system is that it can have high PCE rates as opposed to other wireless charging systems. The means that achieving proper efficiency takes more testing with frequencies and distances than with other systems.

3. Review Analysis

Table 1 details comparisons between inductive charging, magnetic resonance coupling, and radiofrequency charging, which can be referenced when deciding which type of wireless charging to implement. It is the opinion of the authors that, when considering wireless charging for an embedded system, inductive wireless charging is the most cost-effective system.

Magnetic resonance coupling, while also a good option, occupies space that many embedded systems cannot afford to give. Additionally, the advantages that magnetic resonance coupling offers over inductive wireless charging, such as a longer effective range, is often not even necessary for many applications in embedded systems.

An RF-based system is simply not cost-effective since receivers and transmitters must be purchased separately and are often more expensive individually than a complete set for an inductive charger, a trait that is sometimes shared by magnetic resonance coupling systems. Additional circuitry is also required to rectify the radio signal when implementing RF wireless charging systems.

Inductive charging, on the other hand, offers high efficiency at most ranges required for an embedded system, with a small form factor and minimal additional circuitry to implement. It is also the most cost-effective option of the three. Table 2 shows various vendors that provide inductive charging systems.

STMicroelectronics offers a very efficient receiver/transmitter pair that are Qi compliant and can be implemented in systems at either 3.5 V or 5 V [16]. This is item 5 in Table 2. It is the opinion of the authors that item 5 is the best option for wireless charging in embedded systems. Beyond its technical power characteristics, it is a small unit with a receiver size of 3.265 × 3.674 × 0.6 mm and a transmitter size of 5 × 5 × 1.0 mm that can easily fit within most embedded systems, with little additional circuitry required to implement. Additionally, it is very cost-effective.

Overall, ST's wireless charging solution seems to be the best choice for implementing wireless charging into an embedded system. Figure 6 shows a block diagram/schematic of how the ST's solution can be implemented to wirelessly charge an embedded system.

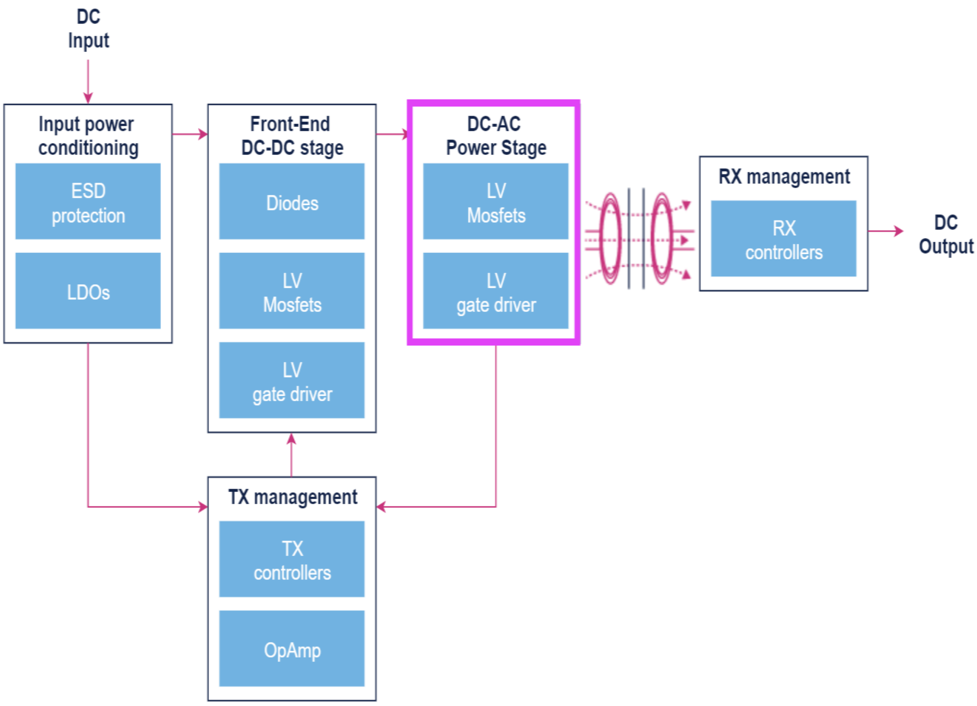

Figure 6. Block Diagram of ST Wireless Charging System [17].

Table 1. Wireless Charging Technology Comparisons [5,7,8,12,19,20].

Technology	Pros	Cons	Distance/Frequency	Efficiency
Inductive Charging	Large Power Transmission (kilowatts) Can be transmitted in a cone shape	Short-range Low quality factor	1. 75 cm 2. 150 cm 3. 225 cm	1. 94% 2. 75% 3. 32%
Magnetic Resonance Coupling	Charging multiple devices at once Moderate distance charging No Line-of-Sight requirement Immunity to neighboring environments	Large size requirement for transmitter Mutual coupling of receivers could cause interference	1. .3 cm 2. 1 m 3. >2 m	1. 92.6% 2. 90% 3. 40%
Radio Frequency Charging	No need for magnetic field induction Radio frequencies can work over larger ranges At short ranges and optimal frequencies, radio charging has efficient PCE rates	Weaker over larger ranges; microWatts from distances of over 1.5 m	1. 900 MHz 2. 1.8 GHz 3. 2.4 GHz 4. 5.8 GHz	1. 95% 2. 86% 3. 65% 4. 40%

Table 2. Commercial Sales of Wireless Charging Units2 [8,16,18].

Vendor[1]	Method	Type/Weight	Size	Efficiency	Unit Price	Additional Details
1. DFRobot	Resonant Magnetic Coupling		Transmitter: 1.3″ × 0.2″ × 0.04″ Receiver: 0.83″ × 0.4″ × 0.03″	Recommended for 2–10 mm operating range	$6.50	-Input Voltage: 5 v -Output Current: 300–600 mA
2. Seeed Technology Co., Ltd.	Inductive Wireless Charger	-	Transmitter: 3.5″ × 3.5″ × 0.05″ Receiver: 3.3″ × 3.3″ × 0.05″	Rated for 2–10 mm usage range	$16.90	-Input Voltage: 5 V -Output Current: 5 A
			Transmitter: 0.87″ × 0.516″ × 0.126″		$8.50	-Input Voltage: 5 V -Output Current: 1.2 A
3. Adafruit		Receiver: 5.5 g Transmitter: 5.7 g	1.5″ diameter	40% for up to 7 mm distance	$9.95	-Input Voltage: 9–12 VDC -Output Voltage: 3.3 VDC -Draw up to 500 mA
4. Newark	RF Receiver—ALPHA-RX433S Model	2.722 g	0.634″ × 0.626″ × 0.17″	Can receive up to 115 Kbps at 300 m range	$7.18	-Max Output Current: 23 mA -Low Standby Current (<0.3 uA) -Wake Up Timer

	RF Transmitter—ALPHA-TRX433S	RF Transmitter 2.722 g	0.634″ × 0.626″ × 0.17″	Transmits up to 115.2 kbps	$12.96	-Input Voltage: 2.2 V-3.6 V -Other models are available in similar sizes and different frequencies
5. STMicroelectronics	Inductive Wireless Charger	Receiver STWLC68JRH	3.265 × 3.674 × 0.6 mm	Up to 80% system efficiency	$5.71	-Max Input Voltage: 5 V -Used for 5 W applications
		Transmitter STWBC-WA	5 × 5 × 1.0 mm		$3.54	-Qi Compliant –2.5 W Output Power -Qi Compatible -Input voltage range: 3 V to 5.5 V -For wearable applications
6. Texas Instruments		Receiver BQ25100YFPR	1.60 × 0.90 mm^2 receiver area	1% Charge Voltage Accuracy 10% Charge Current Accuracy	$1.25	-Less than 75 nA leakage current from the battery -Supports −10 mA to 250 mA Charge Currents

3. Discussion and Conclusions

Wireless charging methods offer an environmentally friendly way of delivering power to devices without needlessly using and wasting non-rechargeable batteries. Battery-based systems result in higher costs and waste due to the number of batteries that would need to be replaced over a device's life. Wireless charging offers the potential for users to get rid of the reliance on batteries, supplying a wire-free charging method [10] [11]. These wireless charging systems also allow for less power leakage from systems because they may be powered only when they need to rather than ones that need to have a battery or a charged connection to run.

As wireless charging technology becomes more advanced, it seems possible that it will make wired chargers nearly completely obsolete, especially when considering embedded systems. An example of this can be seen when this developing technology was used as a monitor for a person's food intake, cigarette smoking, gait locomotion, etc. While the contents of the study are not particularly relevant to this paper, the usage of an embedded system that is powered entirely through wireless power transfer demonstrates the potential stored within this technology [13–15].

There are currently three primary methods of wireless charging: tightly coupled inductive charging, loosely coupled magnetic resonance charging, and radio frequency charging. Based on the specifications, an RF-based wireless charging system is the best in terms of energy efficiency. However, the inductive wireless charging technology is excellent for price and value. The recent expansion of wireless charging technology has made inductive charging more available to developers. With the widespread adoption of inductive systems, they are currently the best option for designing a wireless charging system for a smaller embedded system. As seen with the comparison of the embedded system as applied to a light monitoring system and a breath monitor, the wireless charging method being used will work better for smaller, more mobile systems [1,2]. Furthermore, it has been seen with Qi compliant systems that wireless charging in everyday devices such as smartphones and smartwatches

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Conflicts of Interest:

Appendix A

- DFRobot: https://www.dfrobot.com/product-1283.html (accessed on).
- DFRobot: https://www.dfrobot.com/product-2086.html (accessed on).
- Seeed: https://www.digikey.com/en/products/detail/seeed-technology-co.,-ltd/106990017/5487514# (accessed on).
- Adafruit: https://www.adafruit.com/product/1459?gclid=Cj0KCQjw0oCDBhCPARI-sAII3C_GvOela6qlLTFVkKGt0Wn-PA2AHXJtkok2jWdnT4lB30S6hbkJIetAaAum-QEALw_wcB (accessed on).
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- Newark RF transmitter: https://nz.element14.com/rf-solutions/alpha-trx433s/rf-module-transceiver-fsk-433mhz/dp/1718689?MER=sy-me-pd-mi-acce (accessed on).

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