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Passive Wireless Devices Using Extremely Low to High Frequency Load Modulation

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1. Introduction

Whereas passive wireless communication in the Ultra High Frequency (UHF) domain features long ranges of several meters in free space, systems utilizing lower frequencies in the ELF (Extremely Low Frequency) to HF (High Frequency) domain can be advantageous in environments with conductive materials or where large antennas are not prohibitive. Additionally, the operation range is well defined and can be practically restricted to several centimeters like in Near Field Communication (NFC) *Standard ECMA-340 Near Field Communication Interface and Protocol (NFCIP-2)* (2003), although this does not necessarily mean that communication is secure Hancke (2008).

In this chapter we investigate passive wireless devices in the frequency range from almost DC to tens of Megahertz, i.e. from the ELF to the HF domain. Common abbreviations for the ITU frequency ranges are summarized in Table 1. The most common Radio Frequency Identification (RFID) systems use the LF (@125 kHz) and the HF (@13.56 MHz) bands. This chapter also considers lower frequencies.

Abbreviation	Range	Name
subHz	< 3 Hz	SubHertz
ELF	3 Hz - 30 Hz	Extremely Low Frequency
SLF	20 Hz - 300 Hz	Super Low Frequency
ULF	0.3 kHz-3 kHz	Ultra Low Frequency
VLF	3 kHz - 30 kHz	Very Low Frequency
LF	30 kHz - 300 kHz	Low Frequency
MF	300 kHz - 3 MHz	Medium Frequency
HF	3 MHz - 30 MHz	High Frequency
VHF	30 MHz - 300 MHz	Very High Frequency
UHF	300 MHz - 3 GHz	Ultra High Frequency

Table 1. ITU frequency ranges and abbreviations.

We provide a brief introduction to the technology, performance estimations in terms of powering range with respect to permitted signal levels and human exposure issues, performance considerations in terms of data transmission range with respect to background and man-made noise, and analysis of the impact of conductive/dielectric materials in the vicinity of the passive wireless devices (transponders).

We provide an introduction to the concept of load modulation techniques for passive wireless communication. Usually, RFID systems in the low to high frequency range (LF to HF) are considered as loosely inductively coupled transformers.

The basic principle of such mainly inductively coupled systems is shown in Figure 1. A primary coil of the reader generates an alternating magnetic field and induces a voltage in the coil antenna of the wireless device. The primary coil is connected to a diplexer that carries out frequency separation between the power supply path and the data path. The alternating magnetic field may penetrate layers of air, liquids (e.g. water) or layers of stainless steel and other weak conductors and will then induce a voltage in the coil antenna of the wireless device. A tuning element (e.g. a capacitor) and a power harvesting and storage unit (mainly comprising a rectifier and a storage capacitor) are needed to power the electronic components. A demodulator can extract data sent from the "reader". The transponder itself can transmit data by means of load modulation. This is, e.g., performed by a logic-controlled switch that changes the load of the secondary coil. The control logic can read out a sensor (e.g. a change in resistance or capacitance of a temperature or pressure sensor) and transmit this data back to the reader.

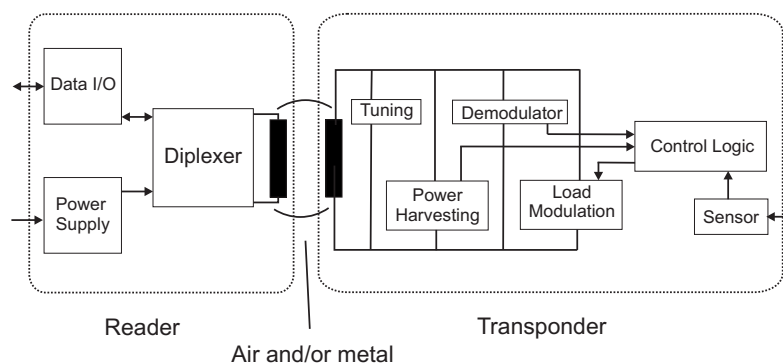


Fig. 1. Principle of passive wireless reader-transponder pair in the ELF to HF bands.

2. Application Examples

Various fields of application can be thought of for passive wireless devices in or behind metal housings powered by low frequent magnetic fields. In this section, we present example applications.

Transmitting measurement data through a double-walled stainless steel vessel can be necessary when extreme temperatures, high pressures, or other harsh environmental conditions (e.g. hazardous substances) are present. This could be a thermally insulated liquid hydrogen storage tank in a car, a whipped cream maker or a chemical reactor. Figure 2(a) shows a simplified block diagram of a setup. Figure 2(b) shows an example experimental setup using a whipped cream maker. The corresponding transponder is immersed in the liquid inside the vessel.

Another interesting application is e.g. for magnetic stirrers, which are standard devices in chemical laboratories. Equipping the magnetic stirring bar (a bar magnet with a protective coating made from either PTFE or stainless steel) with a miniaturized RFID tag that supplies a sensor interface, one could sense and display process parameters directly from the fluid that is stirred and thereby merge multiple devices (e.g. magnetic stirrer, temperature sensor, pH sensor) to a single device, which may need less space and reduce total equipment costs.

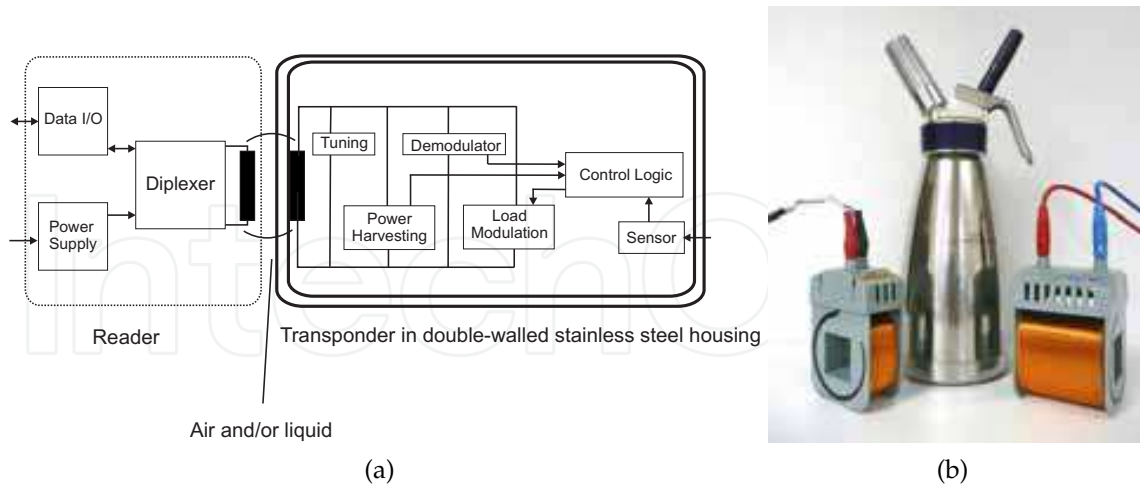


Fig. 2. (a) Schematic of a measurement setup for transmitting measurement data (e.g. pressure or temperature) through a double-walled stainless steel vessel. (b) Photo of an example measurement setup for transmitting temperature data (also other quantities such as pressure could be measured) through a thermally insulated double-walled stainless steel vessel. Here, the passive transponder is placed in a whipped cream maker and could be used, e.g., to monitor the temperature of the liquid.

Figure 3(a) depicts the schematic of such a setup, Figure 3(b) shows an example laboratory setup.

Figure 3(a) depicts the schematic of such a setup, Figure 3(b) shows an example laboratory setup

3. Comparison of Frequency Ranges from ELF to LF

The power that can be transmitted to wireless electronic devices by means of inductive coupling is rather limited by restrictions of the field strength than by technological limits. E.g., power transmissions of up to 60 W have been reported in Kurs et al. (2007). However, in practice we are faced with limitations of the permitted field strength, due to both electromagnetic compatibility and human exposure issues. The investigations in this section are based on the limits provided in *ERC Recommendation 70-03: Relating to the use of short range devices (SRD)* (2007) for limits regarding electromagnetic compatibility and ICNIRP (1998) regarding reference levels with respect to human exposure to alternating magnetic fields for the general public.

Electronic circuitry usually requires DC operating voltage. Therefore, passive devices require a rectifier circuit and an energy storage. Both diodes and transistors can be used for the rectifier, where transistors often offer the advantage of lower voltage drops. For the operation of the circuit it is important to achieve a certain minimum voltage. Consequently, the slew rate of the magnetic field must be high enough. This can be achieved by a high frequency and/or a high field magnitude.

Figure 4 shows Root Mean Square (RMS) reference levels for head, neck and trunk for the general public according to ICNIRP (1998). In the frequency range of up to 100 kHz, the peak values can be $\sqrt{2}$ higher than the RMS values. In the range from 100 kHz to 10 MHz, the permitted peak values increase to 32 times the RMS limit.

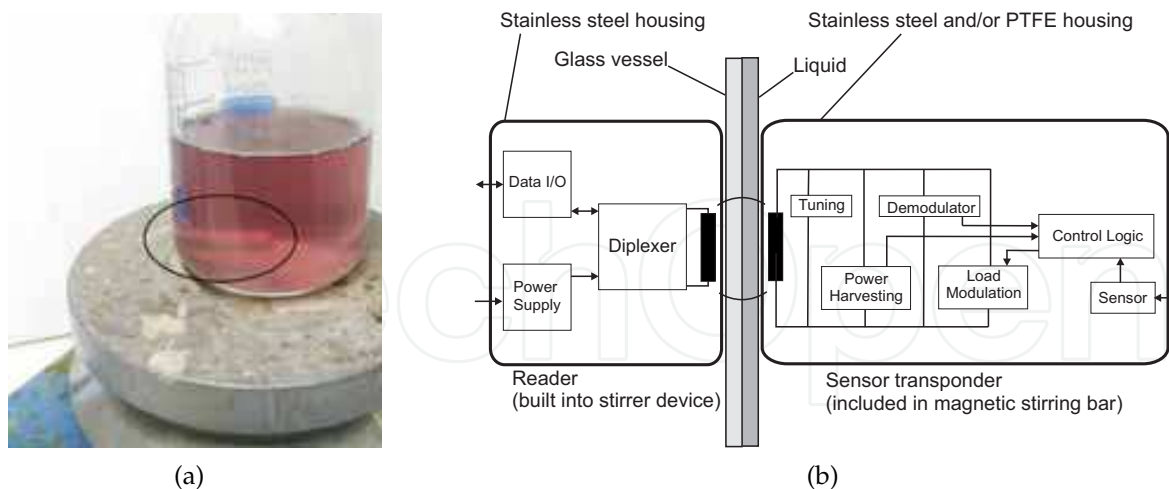


Fig. 3. (a) Photo of an example measurement setup for transmitting measurement data (e.g. temperature or pH data) from a sensor built into the magnetic stirring bar. The stirrer device will be equipped with a suitable readout circuitry and a numeric display. (b) Schematic of a measurement setup for transmitting measurement data.

An interpretation of these levels with respect to inductive wireless devices is provided in Figure 5. For a single turn circular loop with a square area of 1 cm^2 , the voltage ranges from about $1 \mu\text{V}$ to several mV. However, this induced voltage is not sufficient to power an electronic circuit. With current semiconductor technology, the peak voltage should roughly exceed 1 V for a circuit to operate. Several techniques that can be used to increase the voltage are summarized in Table 2. The easiest methods are an increase of the area of the transponder antenna and an increase of the number of turns. Both methods are restricted by size and costs of the transponder. Resonance gain is also commonly exploited. Here, the antenna inductance L and an additional capacitor C form a resonance circuit. With this simple circuit, the antenna current and the voltage across the inductor as well as the capacitor are increased by the quality factor $Q = \frac{2\pi fL}{R}$ of the resonance circuit, which means that the coil resistance R must be low compared to the impedance of the coil inductance at the given frequency f . At lower frequencies, the resonance condition $f = \frac{1}{2\pi\sqrt{LC}}$ requires high L and/or C values, which may be difficult to implement. On the other hand, coils with high numbers of windings may have too low self resonance values due to parasitic capacitances e.g. in the HF range. Another drawback of high quality factors is the associated low bandwidth. A slight change of the inductance L or the capacitance C will change the resonance frequency of the circuit and the gain effect is lost. The resonance is also affected when two or more resonance circuits are in close vicinity. Therefore, in applications where many devices may be present (e.g. in batches of casino tokens) the quality factor is usually kept low. Further increases of the voltage can be achieved with electronic components such as diodes, e.g. in voltage multipliers (e.g. Gosset et al. (2008)) or in active up-conversion. The latter has the drawback that energy is required to get the up-conversion started (cf. section 3.2.1).

Usually, a combination of several of these techniques is necessary to make the low induced voltage useful for powering electronic devices. An example for the HF domain is provided in Figure 7. With several turns, an area of several square centimeters, and a quality factor above 10, the voltage can be sufficient to power the circuitry.

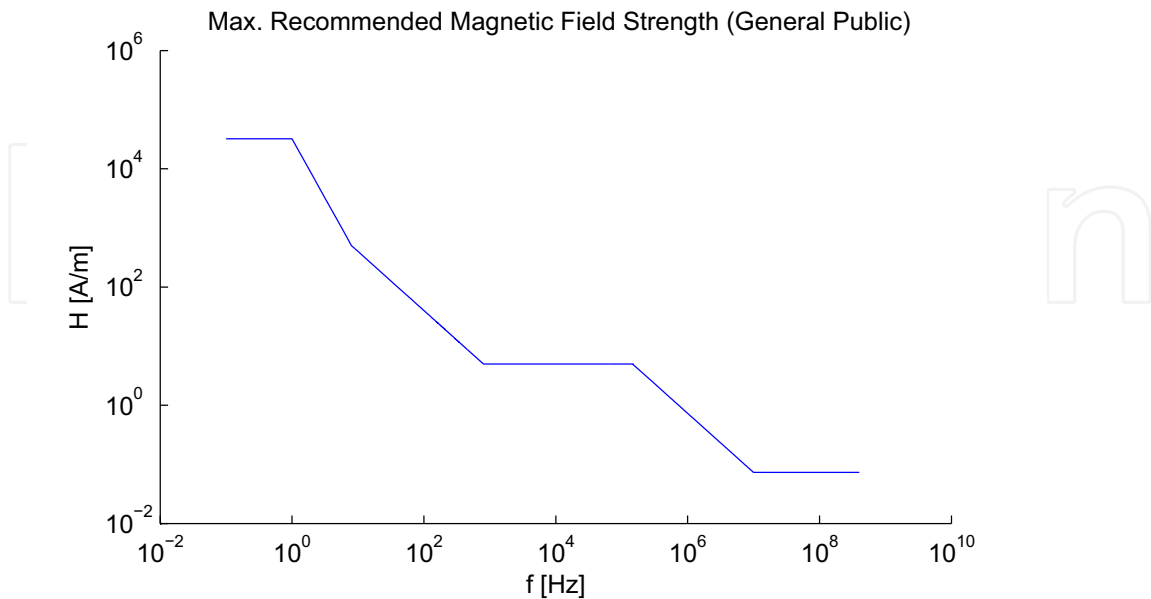


Fig. 4. Reference levels for the magnetic field strength for general public exposure to time varying fields ICNIRP (1998). These levels are obtained based on the impact (particularly on head, neck and trunk) of induced currents on the nervous system (up to 10 MHz) and the temperature increase of tissue due to absorption (above 100 kHz).

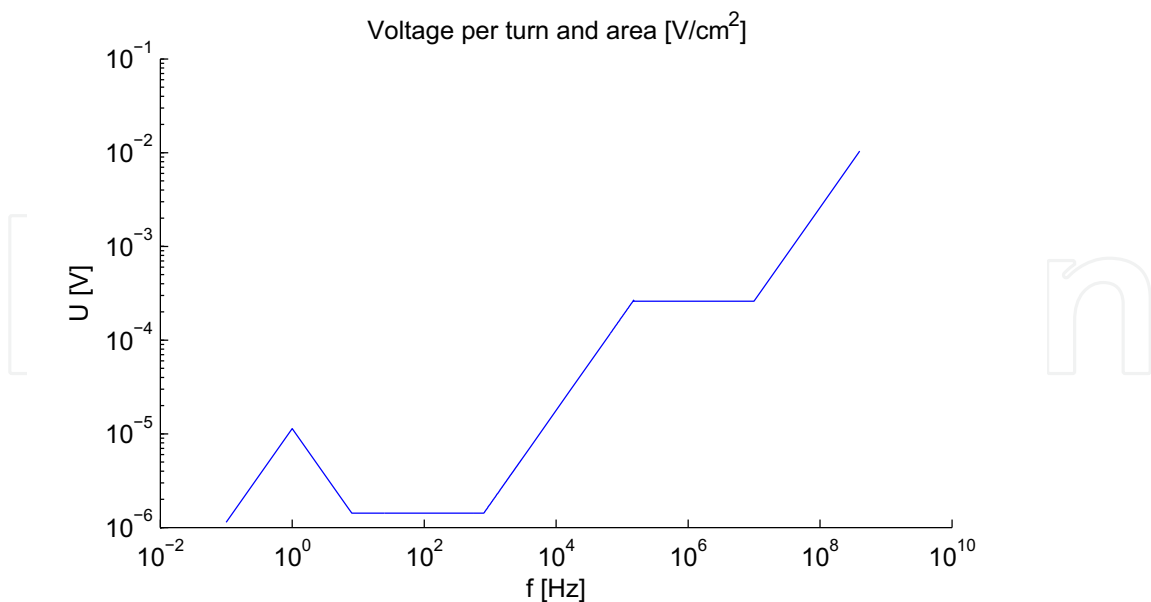


Fig. 5. Induced voltage for a single loop coil with an area of 1 cm² at the reference levels according to ICNIRP (1998).

Method	Disadvantages
Large number of turns	Low self resonance due to parasitic capacitance, costs
Larger area	Size, costs
Exploitation of resonance gain	Detuning, local increase of field strength, high C or high L for low frequencies
Ferromagnetic core (field concentrator)	Local increase of field strength, weight, costs
Voltage multiplier	Requires minimum induced voltage
Active conversion	Requires power up

Table 2. Comparison of methods for voltage enhancement.

With the small induced voltage at the reference levels for human exposure, e.g. in the ELF domain, one may wonder if this ranges can be of practical relevance. As long as it can be ensured that sensitive parts of humans will not reside permanently in the close vicinity of the reader devices, stronger fields can be used. In this case, it can be an advantage that the magnetic field strength decreases with the third power of the distance. However, besides limitation due to human exposure it is also mandatory that electromagnetic disturbances with respect to other devices are kept low. The permitted field strength is usually defined in a distance of 10 meters to the reader device. Therefore, it is possible for a certain antenna geometry to determine the maximum field strength at any distance in free air but also when the field is partially shielded, e.g. due to a metallic object. Limits according to *ERC Recommendation 70-03: Relating to the use of short range devices (SRD)* (2007) are shown in Figure 6. Based on these limits we can now determine the induced voltage at a certain distance.

Low frequencies offer the advantage that they are less affected by conductive material and have larger penetration depths. Consequently, such systems can be used for wireless sensing truly from the inside of, e.g., a steel object.

3.1 Environmental Influences

One of the major concerns for passive wireless communication is the reliability of the wireless link in the vicinity of conductive or strongly dielectric materials. In this section we will show that the use of low frequencies even permits communication through metal walls of e.g. several millimeters of stainless steel Zangl et al. (2008). Thus, a sensor can be placed inside of tanks without the need for cables or batteries.

The influence of a conductive wall on the magnetic field is illustrated in Figure 8 for a the range of 50 Hz to 50 kHz. Whereas the 50 Hz field is hardly affected by the wall, a significant attenuation occurs at higher frequencies. Therefore, lower frequencies are preferable for applications in the vicinity or through metallic objects. Recently, also an IEEE standard using low frequencies (131 kHz) in order to safely operate in the vicinity of conductive objects has been approved (*IEEE Standard 1902.1 for long wavelength wireless network protocol*, 2009). In this standard, also referred to as "RuBee", active communication rather than load modulation is used.

Often, the antenna inductance and a capacitor form a resonance circuit in order to increase the voltage in the transponder or the current in the reader. However, the resonance can be detuned when conductive or dielectric material is brought into the vicinity of the antenna. This has to be considered when a transponder is integrated into, e.g., wood or concrete. Otherwise the

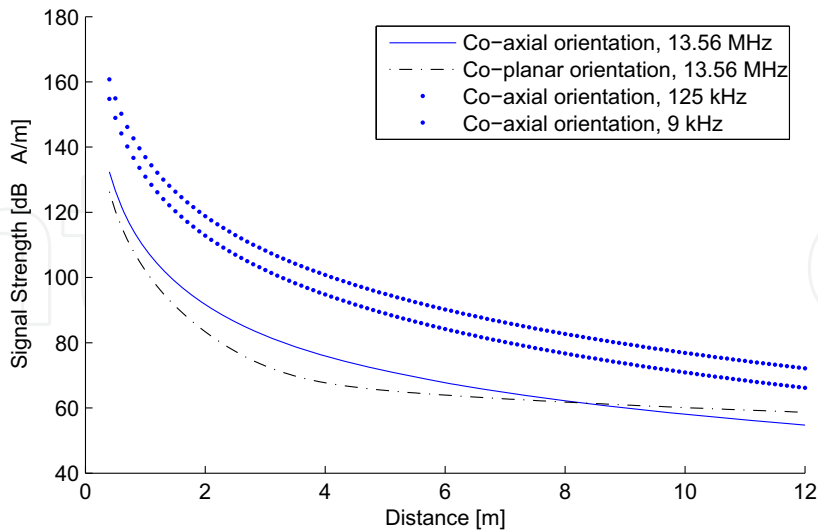


Fig. 6. Comparison of the permitted field strength according to *ERC Recommendation 70-03: Relating to the use of short range devices (SRD) (2007)* (based on a reader antenna of 20 cm times 30 cm). The graph can be used to determine the powering range. E.g., standard HF tags *Standard ISO/IEC 15693 (2006)* are required to operate above $103.5 \text{ dB}\mu\text{A/m}$. Looking at the corresponding graph, this corresponds to a distance of about 1.6 meters. This could be slightly increased, e.g. by using a different antenna, but at this distance the shape has only minor influence. However, if a low power (low voltage) device can operate at about $80 \text{ dB}\mu\text{A/m}$ (such as shown in Zangl and Bretterkieber (2007b)) the powering range extends to about 3 meters. For readers with lower field strength, the corresponding graphs just need to be shifted along the y-axis.

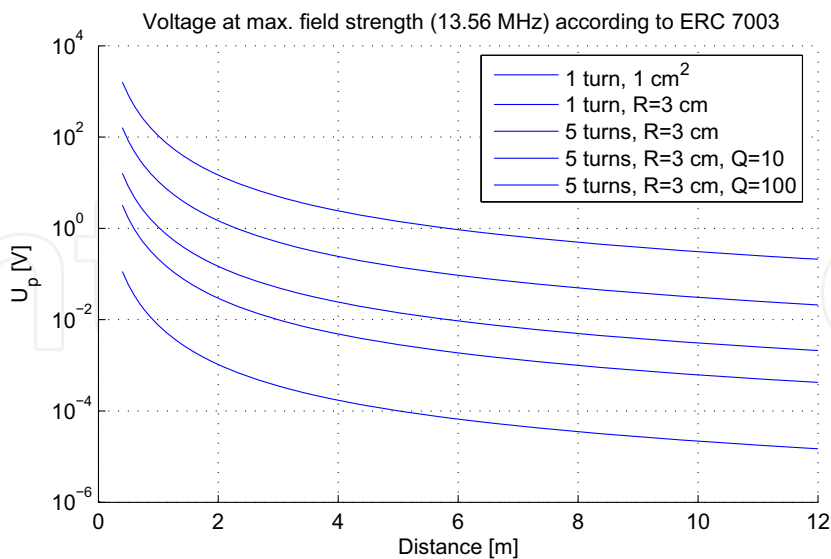


Fig. 7. Generation of the supply voltage: As the induced voltage per loop is very low, several techniques are used to increase the available voltage. Considering that current semiconductor technology starts to operate at about 1 V, a combination of the voltage enhancement techniques can yield sufficient voltage also at long distances to the reader.

performance will degrade. Antennas with low quality factors and non-resonant antennas are less sensitive to environmental conditions.

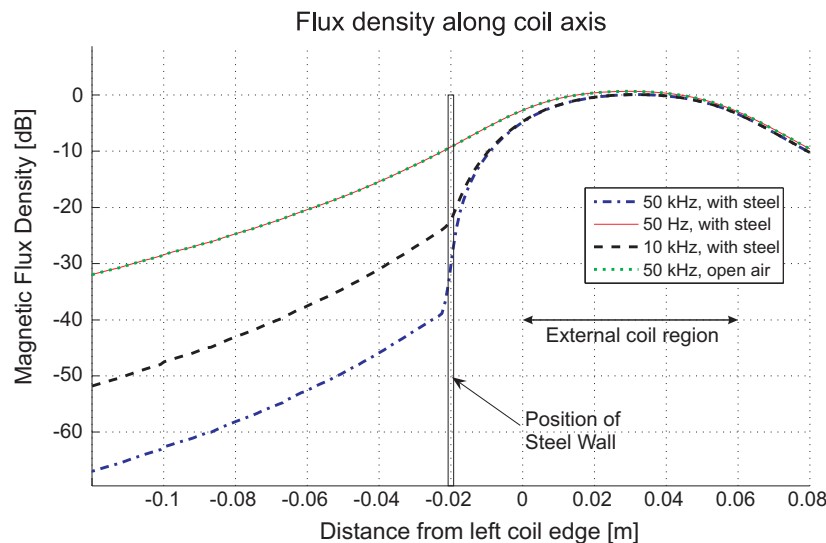


Fig. 8. Variation of the magnetic flux density along the rotational axis of the field coil for different frequencies, obtained by Finite Element Analysis. Regions of external coil and steel wall are marked by arrows. The curves for 50 Hz with steel and 50 kHz without steel (open air) coincide. Magnetic flux densities are referred to the maximum value, while the horizontal axis corresponds to the distance from the right edge of the steel wall. It can be seen that the steel wall hardly effects a 50 Hz signal while significant damping occurs at frequencies of 10 kHz and 50 kHz.

3.2 Data Transmission

With the ever decreasing power and voltage requirements of electronic components it can be expected that the powering range will further increase in the future. Does that mean that the operation range of passive wireless devices will also continue to increase? In situations where the powering range is the limiting factor, yes. However, with decreasing field strength and increasing data rates, another quantity becomes of major interest: The environmental noise. For a successful data transmission, the ratio E_b/N_0 between the bit energy E_b and the spectral noise density N_0 has to be sufficiently high; a reasonable value for good detection rates is a ratio of more than 10 dB Sklar (2001). Load modulation systems modulate the field that is generated by the reader. With increasing distance, the field to modulate becomes weaker and weaker and so does the generated response. Additionally, the distance for the data transmission also increases, which additionally lowers the E_b/N_0 ratio. The bit energy also decreases when we want to transmit at a higher data rate, as the signal to modulate and thus the total signal power remains the same, regardless of the bandwidth we use. Consequently, the modulated signal has to be as high as possible. Unfortunately, the environmental noise levels are very variable and are thus hard to predict; the sources in the considered frequency ranges are usually man-made. Reference levels can be found e.g. in *ERC Report 69: Propagation model and interference range calculation for inductive systems 10 kHz - 30 MHz* (1999).

When the amount of data is low, good E_b/N_0 ratios can also be obtained when energy is accumulated and then used for active transmission. On the other hand, when the coupling is

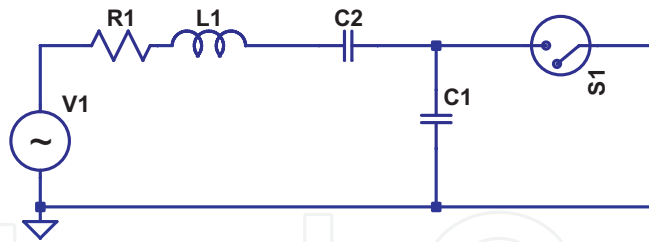


Fig. 9. Circuit for high data rate with high resonance gain. $V1$ represents the induced voltage due to the magnetic field generated by the reader; $L1$ represents the coil inductance and $R1$ the coil resistance. For a better illustration of the effect, the tuning capacitors $C1$ and $C2$ are of the same value. The tap point for the power supply rectifier circuit is between inductor $L1$ and $C2$, the switch $S1$ can, e.g., be an n-channel transistor. When the switch is closed, the resonance frequency is increased by a factor of $\sqrt{\frac{C1+C2}{C1}}$.

good and the modulation is strong, then high data rates (megabits per second) can be achieved Witschnig et al. (2007).

3.2.1 Resonant Modulation

Some of the techniques that we can use to increase the received voltage also increase the signal strength of the load modulated signal. This is true e.g. for larger area and resonance gain. Indeed, a quality factor $Q = 100$ means that the field strength at the position of the passive wireless devices is 100 times higher (with opposite orientation) when the device is present than when it is not. This may seem surprising as the device obtains energy from the field, but can be explained by the higher current compared to a short circuit loop. Furthermore, it could be assumed that a high quality factor would only permit low data rates, as the settling time for transitions between 0 and 1 would be proportional to the reciprocal of the bandwidth Finkenzeller (2003). However, as load modulation is a non-linear process, this is not necessarily always true as shown in Figures 10 and 11 for the circuit given in Figure 9. In this circuit the induced voltage is represented by $V1$. This model is valid when the reader is hardly affected by the transponder, i.e., when the coupling is low. For better coupling, the loading of the reader antenna has to be considered (Jiang et al., 2005).

3.2.2 Non-Resonant Modulation

A modulation circuit for non-resonant modulation, which is particularly useful at low carrier frequencies, is shown in Figure 12. Here, the modulation frequency is chosen higher than the carrier frequency. This has several advantages: Usually, up to HF the environmental noise level decreases with the frequency ERC Report 69: *Propagation model and interference range calculation for inductive systems 10 kHz - 30 MHz* (1999). Furthermore, the induced voltage in the reader coil increases as the slope of the magnetic field is increased. Additionally, this principle acts as a voltage converter, which can boost the voltage to a higher level.

A received signal at a receiver coil for a setup corresponding to Figure 2(b) is provided in Figure 15.

4. Reader Circuitry

A “reader” usually comprises the following components:

- Low noise power amplifier

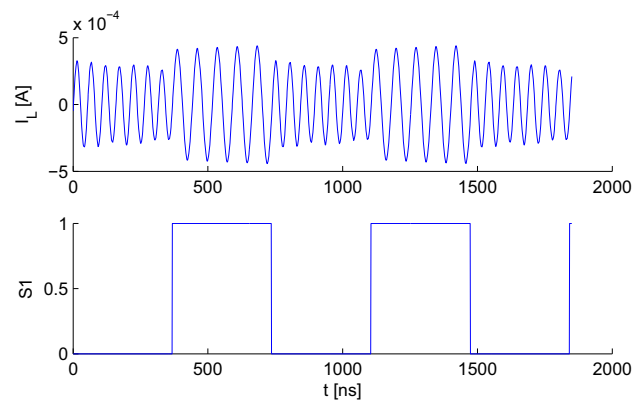


Fig. 10. Time signal for load modulation with resonance gain and high data rate. Ideally, the switching point for S_1 is at the zero crossing of the voltage across C_1 , then no energy is lost. Provided that $C_1 \gg C_2$ the energy loss also remains low even when the optimum switching point is missed. While the switch is closed, the resonance circuit continues oscillation but at an increased frequency. Looking at the carrier frequency in the spectrum, this means that the carrier signal is "turned off" immediately after closing of S_1 , no settling time is required. Once the switch is opened again (ideally at zero crossing of the voltage across C_2) the signal immediately returns to the original frequency.

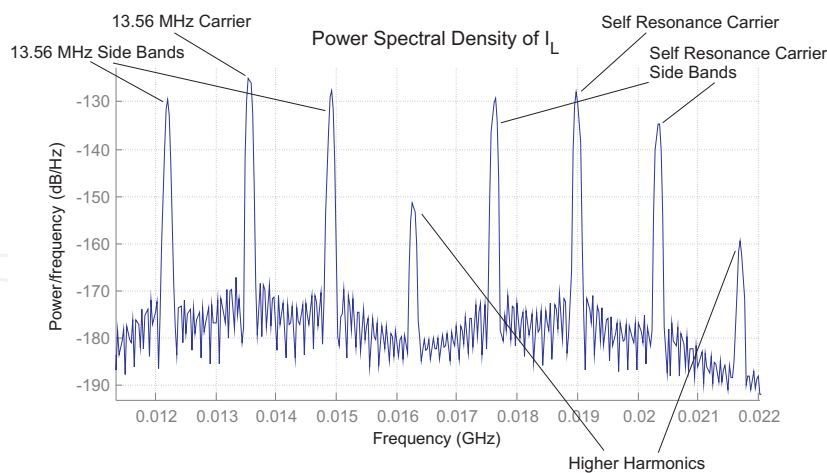


Fig. 11. Spectrum of the time signal of the coil current (proportional to the magnetic field) according to Figure 10. Besides the on-off amplitude modulation of the carrier, an alternating modulation of the switched resonance frequency with almost the same signal strength can be observed. With C_1 being much larger than C_2 , the frequency difference would remain low and the spectra would overlap.

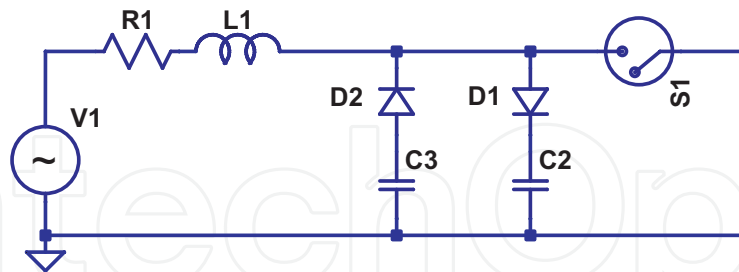


Fig. 12. Circuitry for non-resonant modulation with a low frequency for power transmission. $V1$ represents the induced voltage due to the magnetic field generated by the reader; $L1$ represents the coil inductance and $R1$ the coil resistance, $C2$ and $C3$ are energy storage capacitors.

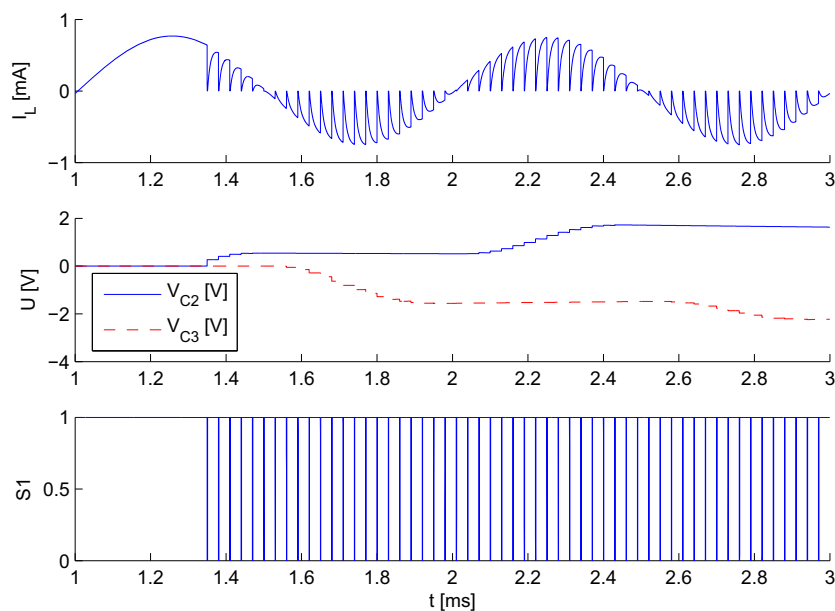


Fig. 13. Coil current and capacitor voltages for non-resonant modulation according to Figure 12. While the switch $S1$ is closed, the current in the coil increases due to the induced voltage $V1_p = 10$ mV, which is proportional to the rate of change of the field generated by the reader. When the switch is opened, the coil energy is rapidly transferred to capacitor $C1$ or $C2$ depending on the phase), such that the coil current returns to zero. Then, the switch $S1$ is closed again. The circuit does not only generate a modulation but also acts as a step up voltage converter.

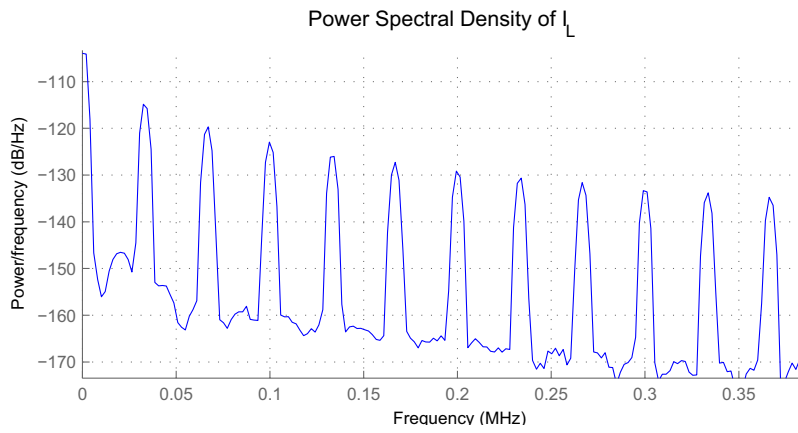


Fig. 14. Spectrum of the coil current according to Figure 13.

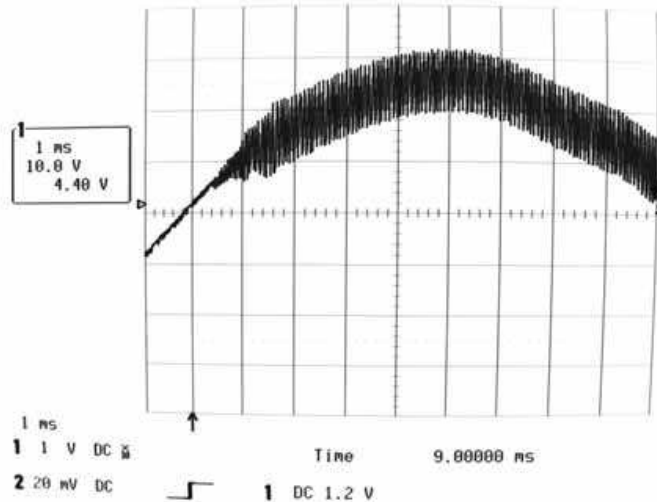


Fig. 15. Received voltage signal for non-resonant modulation, measured with a separate pick-up coil as shown in Figure 2(b). The modulation (higher frequency, here 1.6 kHz) generated by the passive wireless device and the signal from the reader (here 50 Hz) are superimposed but can be easily separated due to the large frequency offset. Even though no resonance is exploited, the received signal achieves a reasonable signal strength.

- Resonance loop antenna
- Carrier suppression
- Demodulation
- Symbol detection

Any of these components may be responsible for a certain limitation. For long range applications, high currents in the reader antennas are required. Often, resonance gain is also exploited for the reader such that the requirements for the power amplifier are eased. Linear and digital amplifiers are used, for the latter the resonance circuit also acts as a filter. In single antenna readers, the resonance loop acts as a filter for the signal received from the passive devices as well as for the noise, thus the E_b/N_0 ratio does not change. For high gain factors, the suppression of the modulated signal will be high such that the input referred noise of the receiver circuitry may dominate the environmental noise. In this case the E_b/N_0 ratio falls below the theoretical value and the performance degrades. In two antenna-readers, i.e. readers with a separate antenna for powering and receiving, this effect is not as important. Additionally, the pick-up antenna may be shaped (e.g. two opposite loops) such that the reader signal is suppressed, which eases demodulation and suppresses noise caused by the power amplifier. Other suppression techniques for the reader signal comprise active and passive filtering and directional couplers. Demodulation and detection of the signals are nowadays often performed in the digital domain. In this case the signal is sampled and processed on a Digital Signal Processor (DSP) or a dedicated hardware such as a Field Programmable Gate Array (FPGA). Such systems require an A/D conversion, which makes it mandatory to suppress the carrier. Demodulation can also be achieved with simple diode rectifiers in the analog domain. In this case, no additional carrier suppression is needed. Diode rectifiers can also be used to obtain inphase and quadrature (I and Q) signals (Zangl and Bretterkieber, 2007a).

5. Conclusion

The chapter presents passive wireless communication in the ELF to HF frequency range. With this technology, passive wireless devices can achieve ranges of up to several meters (at a low data rate), data rates of several megabit (at a low range). The devices can provide a well defined range of operation and they can permit communication in the vicinity or even through conductive or dielectric objects.

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Mobile and wireless communications applications have a clear impact on improving the humanity wellbeing. From cell phones to wireless internet to home and office devices, most of the applications are converted from wired into wireless communication. Smart and advanced wireless communication environments represent the future technology and evolutionary development step in homes, hospitals, industrial, vehicular and transportation systems. A very appealing research area in these environments has been the wireless ad hoc, sensor and mesh networks. These networks rely on ultra low powered processing nodes that sense surrounding environment temperature, pressure, humidity, motion or chemical hazards, etc. Moreover, the radio frequency (RF) transceiver nodes of such networks require the design of transmitter and receiver equipped with high performance building blocks including antennas, power and low noise amplifiers, mixers and voltage controlled oscillators. Nowadays, the researchers are facing several challenges to design such building blocks while complying with ultra low power consumption, small area and high performance constraints. CMOS technology represents an excellent candidate to facilitate the integration of the whole transceiver on a single chip. However, several challenges have to be tackled while designing and using nanoscale CMOS technologies and require innovative idea from researchers and circuits designers. While major researchers and applications have been focusing on RF wireless communication, optical wireless communication based system has started to draw some attention from researchers for a terrestrial system as well as for aerial and satellite terminals. This renewed interested in optical wireless communications is driven by several advantages such as no licensing requirements policy, no RF radiation hazards, and no need to dig up roads besides its large bandwidth and low power consumption. This second part of the book, Mobile and Wireless Communications: Key Technologies and Future Applications, covers the recent development in ad hoc and sensor networks, the implementation of state of the art of wireless transceivers building blocks and recent development on optical wireless communication systems. We hope that this book will be useful for students, researchers and practitioners in their research studies.

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