Optimal Transmission Frequency for Ultra-Low Power Short-Range Medical Telemetry

D. C. Yates[1]; Dr. A. S. Holmes[1]; Dr. A. J. Burdett[2]

1. Department of Electrical and Electronic Eng., Imperial College, London, SW7 2BT
2. Toumaz Technology Ltd, Abingdon, Oxfordshire, OX14 3DB

Analysis determining the optimal transmission frequency for maximum power transfer across a short-range wireless link is introduced, including a comparison of near-field transmission with far-field transmission. A new near-field power transfer formula has been derived, which allows direct comparison with the well-known far-field Friis transmission formula. Operating charts are presented, which provide the designer with the preferred transmission frequency as a function of distance and antenna dimensions, together with surface plots which show the power transfer for this frequency.

1. Introduction

One important emerging application area for lightweight portable technologies is ubiquitous medical monitoring. The ubiquitous computing paradigm applied to patient health staus monitoring envisages devices being worn, carried by or even implanted in users. The devices concerned are capable of forming ad hoc networks, and exist to gather, process and route data.

Central to this vision is the apparent invisibility of many of these devices to the user, who is aware of, but not inconvenienced by their presence. This places stringent limits on device size, weight and power consumption. To achieve a lifetime measured in years, devices powered from small coin cells must consume no more than a few microwatts.

One of the major barriers in realising hardware for ubiquitous health monitoring is the absence of ultra-low power wireless transceivers that can operate at microwatt power levels. Typical off-the-shelf low-power transceivers, when operated at a sufficiently low duty cycle to achieve this power consumption, achieve data rates of only tens of bits per second [1-3]. The same is true of devices presented in the academic literature [4-7].

In order to achieve ultra-low power operation, power must become the main design criterion, and the relevant trade-offs must be identified and investigated. This paper sheds some light on one such trade-off. To achieve optimal far-field radiation characteristics, antennas generally have to be some proportion of the wavelength. For size-constrained devices this suggests that high frequencies should be used. However, the power dissipation in the RF processing electronics will increase with frequency. As a first step to solving this problem we have determined the optimal frequency for particular antenna dimensions, in terms of maximising the power transfer from the transmitting antenna input to the receiver. This minimises the required power input to the transmitting antenna for successful demodulation at the receiver.

The analysis presented in this paper has been performed for the loop antenna, since it is particularly suited to ubiquitous computing applications. The relatively non-directional nature of loop antennas and monopole antennas makes them ideal for use in ad-hoc mobile wireless networks. The loop antenna has the advantage of being electrically larger in a given volume than a monopole or dipole antenna, resulting in greater radiation efficiency. Furthermore, the loop antenna is used in all systems known to the authors where wireless power delivery is required, such as the powering of biomedical implants [8] and RFID tags [9]. The ability to receive wireless power may well prove essential for true autonomy in many ubiquitous computing systems. The charging of batteries or the providing of initial power for the energy scavenging electronics are two strong reasons for requiring this facility.

2. Modelling Power Transfer

The mathematical relationships governing the power transfer from transmitter to receiver differ substantially depending upon whether the receiver lies in the near-field or the far-field. The aim of the analysis presented here is to determine the optimal frequency in terms of power transfer for a certain transmission distance, given particular constraints on the maximum allowable antenna dimensions.

2.1 Far-Field Transmission

The receivers in most wireless transmission systems will lie in the radiating far-field either because of the large distance involved such as for typical AM radio broadcasting or because of the high frequencies involved such as for Bluetooth. In this case the power transfer from the input to the transmitting antenna to the receiver load is given by the well known Friis formula dealt with in standard antenna texts such as [10, 11]:

$$\frac{P_{RX}}{P_{TX}} = p \cdot \frac{\eta_{TX} D_{TX_{MAX}} \eta_{RX} D_{RX_{MAX}} \lambda^2}{(4\pi r)^2} \tag{1}$$

where D represents the directivity, λ is the wavelength, r, is the distance between the transmitting and receiving antennas. The subscripts TX and RX denote transmitter and receiver parameters respectively. p is a factor taking into account misalignment of the antennas. The radiation efficiency, η, describes the fraction of power input to the antenna that is radiated in the far-field:

$$\eta = \frac{R_{RAD}}{R_{RAD} + R_{LOSS}} \tag{2}$$

2.2. Near-Field Transmission

In order to increase the power transfer, near-field transmission systems (such as those used in RFID devices and for implanted medical devices) use one of the four possible combinations of series or parallel tuned resonant coils in the transmitter and receiver [9, 12]. Analysing these topologies using standard nodal equations is tedious and does not facilitate intuitive insight. Fortunately, the analysis can be simplified for the kinds of applications we are considering, because the mutual inductance will always be small.

A general equivalent circuit for a poorly coupled near-field system is given in figure 1. It should be noted that this equivalent circuit could equally well represent any one of the four tuned resonant coil topologies. Using this equivalent circuit we can derive a formula expressing the power transfer from transmitter to receiver, allowing direct comparison with the far-field Friis transmission formula. Due to space limitations, the detailed derivation of this expression is beyond the scope of this paper and the interested reader should refer to [13]. Under near-field conditions, the power transfer ratio can be expressed as:

$$\frac{P_{RX}}{P_{TX}} = p \cdot \frac{\mu_0^2 \pi^2 N_{TX}^2 N_{RX}^2 a_{TX}^4 a_{RX}^4 \omega^2}{16 R_{TX} R_{RX} r^6} \qquad (3)$$

where $N_{TX(RX)}$ and $a_{TX(RX)}$ represent the number of turns and radius of the transmitter (receiver) antenna coils respectively; $R_{TX(RX)}$ represents the total coil resistance at the transmitter (receiver) (i..e. loss resistance plus radiation resistances); p is an antenna misalignment factor and r is the distance between transmitting and receiving antennas.

3. Optimal Transmission Frequency

Based on equations (1) and (3), this section presents two operating charts (figures 2 and 4), which indicate how the preferred transmission frequency, chosen from a selection of standard frequency bands, varies with the transmission distance and loop radius for a single-turn loop antenna. Copper wire and peer-to-peer communication are again assumed. Surface plots (figures 3 and 5) are also presented, showing the power transfer for the preferred frequency as a function of the same variables. The frequencies compared are the ISM bands of 40MHz, 433MHz, 900MHz, 2.4GHz and also the mobile phone band of 1.8GHz. Two sets of graphs are presented because the power transfer characteristics are also heavily dependent upon wire thickness (since this affects the antenna resistance). In general the wire radius is assumed to be a twentieth of the loop radius. However, a large loop radius may well be acceptable whereas a large conductor radius may not. For instance, large radius loop antennas can be unobtrusively embedded into clothes or paper as long as the conductor is sufficiently thin and flexible. This suggests that for a particular application there will also be a maximum allowable wire thickness. Therefore, two charts have been presented, one with a maximum wire radius of 2mm, the other with a maximum radius of 0.5mm. The frequencies represented in figures 2-5 are:

- 40MHz Near Field
- 433MHz Far Field
- 900MHz Far Field
- 1.8GHz Far Field
- 2.4GHz Far Field

with darker colours representing lower frequencies, i.e. 40MHz = black and 2.4 GHz = pale grey.

3.1 The Near Field

It can be seen from equation (3) that near-field power transfer increases with frequency. 40MHz was chosen as the near-field frequency to be used in this comparison since it is the highest ISM frequency for which suitable transmission distances are still in the near-field. Near-field transmission is shown to be preferable for large loop radii and short distances. The near-field is superior at short distances but far-field power transfer quickly becomes preferable as distance increases, since the energy stored in the near-field decays with r^6 whereas the power transfer available at far-field frequencies decreases with r^2 (equations 1 and 3). The region in which near-field transmission is superior is significantly decreased when the wire radius is limited to 0.5mm, because the advantage of lower series loss resistance (due to operating at a lower frequency) is reduced for thinner wire.

In the region where the far-field frequencies are dominant, the preferred far-field frequency decreases with increasing loop radius. The boundary between preferred frequencies is determined by the 'crossover' point of two frequency dependent factors. The radiation efficiency decreases as the electrical size of the antenna decreases (see figure 9) but the far-field power transfer is inversely proportional to frequency squared. Figures 3 and 5 demonstrate superior power transfer for larger antenna dimensions, which is explained by the same two factors.

3.2. The Far Field

The power transfer has been evaluated for 40 discrete values of antenna radius, scaled logarithmically between 3mm and 7cm, using the Friis formula combined with additional directivity and radiation efficiency analysis [13]. For each of these antenna radii, the power transfer was calculated for 70 logarithmically scaled discrete far-field frequencies between 100MHz and 5GHz, from which the optimal far-field transmission frequency for a particular loop radius has been determined. Figures 6 and 7 show this optimal frequency and the power transfer over a distance of 1m for this optimal frequency. To a first approximation, the optimal frequency is inversely proportional to the coil size, and corresponds to a circumference to wavelength ratio of approximately 0.2, as shown in Figure 8. The oscillations in this graph at larger radius values are due to the finite resolution of the numerical calculations.

The relationship between optimal frequency and coil size can be understood by viewing the radiation efficiency graph (figures 9) in conjunction with the Friis equation (equation 1). From the Friis equation, it can be seen that the power received for a particular transmit power decreases with frequency squared (if all else remains constant). If the loop radius is held constant, increasing frequency will improve the radiation efficiency as shown in figure 9. The optimal frequency occurs at the point where any further increase in the radiation efficiency would not overcome the frequency squared term in the denominator.

It should be noted that the optimal circumference to wavelength ratio is relevant only for a fixed antenna radius. If the constraint is instead fixed frequency then the antenna radius can be increased to give larger radiation efficiency and larger directivity as desired in order to improve the power transfer.

4. Discussion

We have presented a method of determining the optimal transmission frequency in terms of maximum power transfer across a wireless link for different antenna dimensions. This is the first time a comparison between near-field and far-field transmission has been presented. This comparison has been facilitated by the derivation of a near-field power transfer formula equivalent to the far-field Friis equation. The analysis is important for ubiquitous computing applications such as health status monitoring where devices will be size constrained and power is crucial.

The optimal/preferred frequencies have been illustrated for the particular case of peer-to-peer communications, where the transmitter and receiver antennas are assumed to be identical. The analysis presented is, however, not limited to this case and can be used to evaluate the optimal transmission frequency for the case where the transmitter and receiver have a different size limitation. We have shown that the optimal frequency for far-field transmission corresponds to an antenna circumference of about 0.2 wavelengths for peer-to-peer communication (see figure 8). It can also be shown that a single-turn loop has a high Q-factor for this electrical size [13]. We can therefore conclude that the requirements of efficient power transfer and minimum noise can be achieved simultaneously

The choice of transmission frequency will affect the power dissipated in the transceiver RF electronics. The analysis and results presented in this paper do not take this into account. Future work will be carried out by the authors to investigate this issue, enabling an optimal transmission frequency in terms of minimum power consumption for the entire transmission system to be found.

5. References

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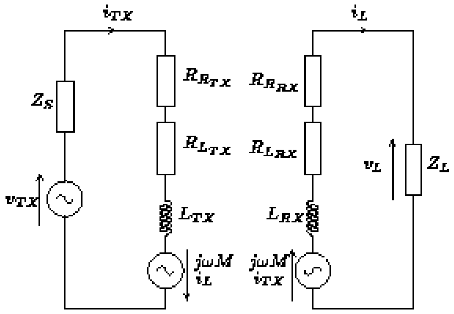
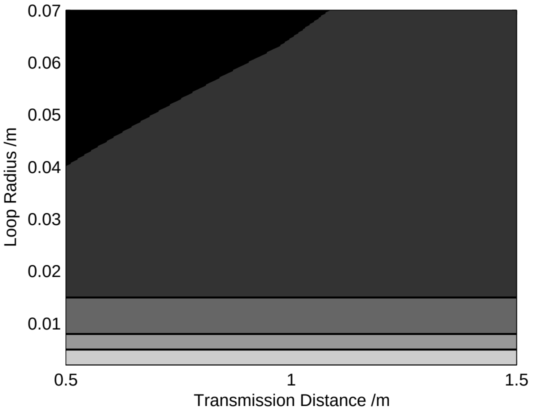
[13] D. Yates, A. Holmes and A. Burdett, '*Optimal Transmission Frequency for Ultra Low Power Short Range Radio Links*', Accepted for Publication in IEEE Trans. Circuits and Systems Part I: Circuit Theory.

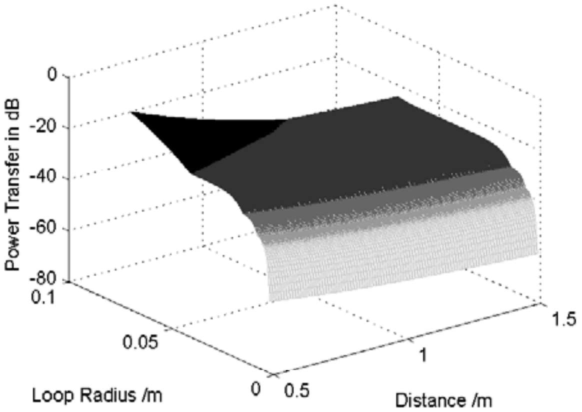
6. Figures



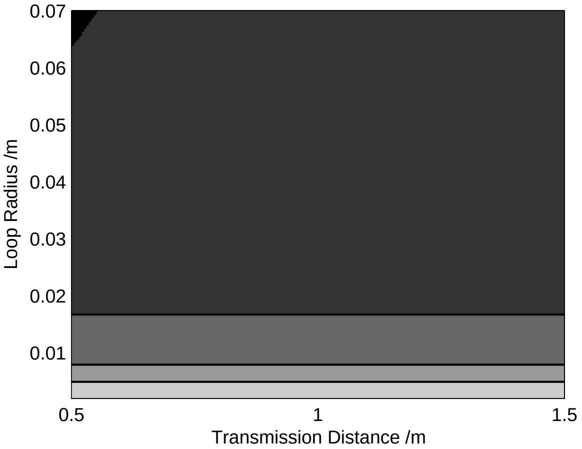
1. Near-field transmission equivalent model assuming poor coupling



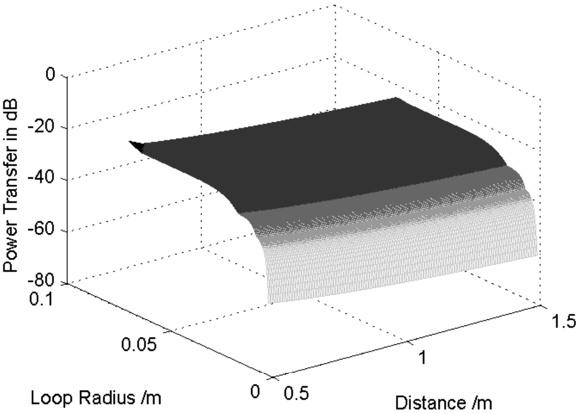
2. Operating chart informing designer of preferred transmission frequency, depending on antenna dimensions and transmission distance, for a maximum wire radius of 2mm



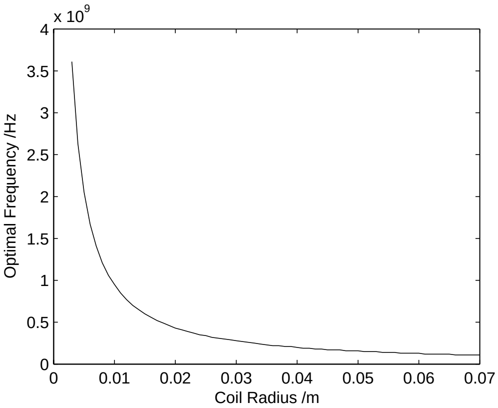
3. Surface plot shows the power transfer for the preferred transmission frequency, depending on antenna dimensions and transmission distance, for a maximum wire radius of 2mm



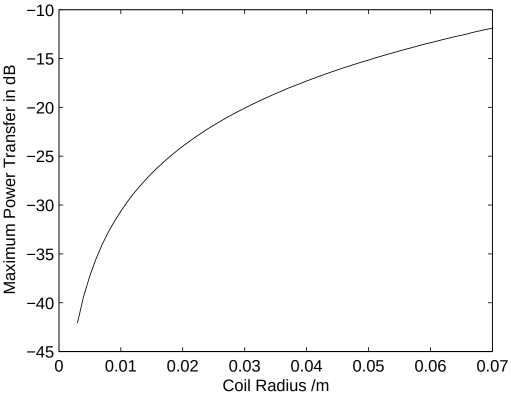
4. Operating chart informing designer of preferred transmission frequency, depending on antenna dimensions and transmission distance, for a maximum wire radius of 0.5mm



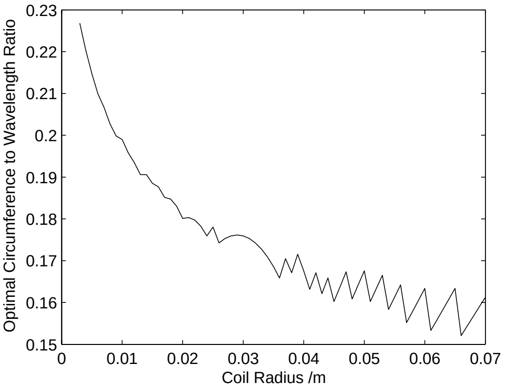
5. Surface plot shows the power transfer for the preferred transmission frequency, depending on antenna dimensions and transmission distance, for a maximum wire radius of 0.5mm



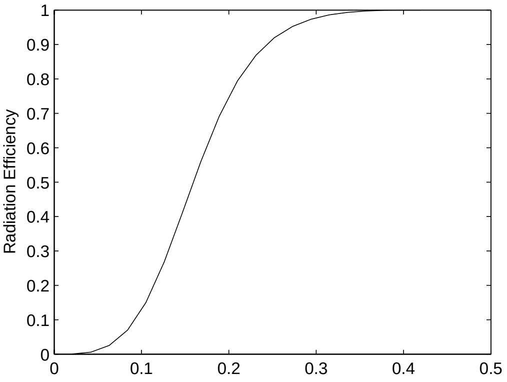
6. Optimum far-field frequency for maximum power transfer versus coil radius



7. Power transfer for optimum far-field frequency over a distance of 1m



7. Optimum circumference to wavelength ratio (in terms of maximum power transfer) versus coil radius



9. Radiation efficiency versus electrical size for a loop antenna of radius 5mm and a conductor radius equal to one twentieth of the loop radius