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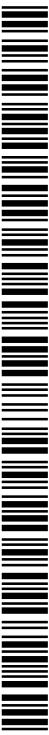
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- (71) **Applicant (for all designated States except US):** QUALCOMM INCORPORATED [US/US]; 5775 Morehouse Drive, San Diego, CA 92121-1714 (US).
- (74) **Agents:** MOBARHAN, Ramin et al.; QUALCOMM INCORPORATED, 5775 Morehouse Drive, San Diego, CA 92121-1714 (US).
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(54) **Title:** WIRELESS POWER RANGE INCREASE USING PARASITIC ANTENNAS

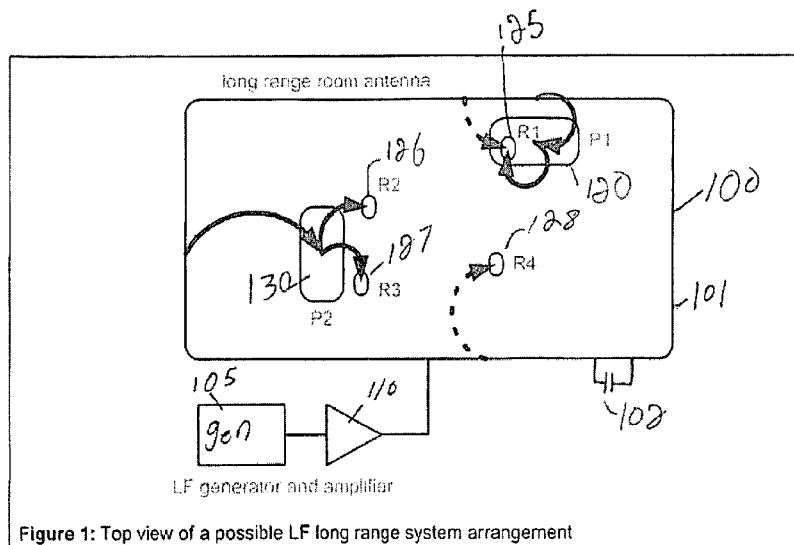


Figure 1: Top view of a possible LF long range system arrangement

(57) **Abstract:** Wireless power transfer is created using a first antenna that is part of a magnetic resonator, to create a magnetic field in an area of the first antenna. One or more parasitic antennas repeats that power to create local areas where the power is more efficiently received.

Wireless Power Range Increase Using Parasitic Antennas

Background

[0001] This application claims priority from provisional application number 60/990,908, filed November 28, 2007, the entire contents of which disclosure is herewith incorporated by reference.

[0002] Our previous applications have described magneto mechanical systems. Previous applications by Nigel Power LLC have described a wireless powering and/or charging system using a transmitter that sends a magnetic signal with a substantially unmodulated carrier. A receiver extracts energy from the radiated field of the transmitter. The energy that is extracted can be rectified and used to power a load or charge a battery.

[0003] Our previous applications describe non-radiative transfer of electrical energy using coupled magnetic resonance. Non-radiative may mean that both the receive and transmit antennas are “small” compared to the wavelength, and therefore have a low radiation efficiency with respect to Hertzian waves. High efficiency can be obtained between the transmit resonator and a receive resonator.

Summary

[0004] The present application describes extending a range over which this power transmission can occur using parasitic antennas.

[0005] Another aspect describes tuning the parasitic antennas.

Brief Description of the Drawings

[0006] In the Drawings:

[0007] Figure 1 shows a block diagram of wireless power transmission using both main and a parasitic transmission antennas;

[0008] Figure 2 shows an antenna around edges of a room;

[0009] Figure 3 shows the antenna at different levels in the room to go around doors and windows;

[0010] Figure 4 shows matching circuitry for the parasitic antenna;

[0011] Figure 5 shows a field strength distribution;

[0012] Figure 6 shows a parasitic antenna;

[0013] Figure 7 shows a schematic of switching capacitors;

[0014] Figure 8 shows the field strength;

[0015] Figure 9 shows a variable area antenna;

[0016] Figure 10 shows a coupling loop and antenna;

[0017] Figure 11 shows detuning vs coupling factor;

[0018] Figures 12A and 12 B show transfer efficiency. ...

Detailed Description

[0019] The classical principle of non-radiative energy transfer is based on Faraday's induction law. A transmitter forms a primary and a receiver forms a secondary separated by a transmission distance. The primary represents the transmit antenna generating an alternating magnetic field. The secondary represents the receive antenna that extracts electrical power from the alternating magnetic field using Faraday's induction law.

$$-\mu_0 \frac{\partial \mathbf{H}(t)}{\partial t} = \nabla \times \mathbf{E}(t)$$

[0020]

where $\nabla \times \mathbf{E}(t)$ denotes curl of the electrical field generated by the alternating magnetic field

[0021] The inventors recognize, however, that the weak coupling that exists between the primary and secondary may be considered as a stray inductance.

This stray inductance, in turn, increases the reactance, which itself may hamper the energy transfer between primary and secondary.

[0022] The transfer efficiency of this kind of weakly coupled system can be improved by using capacitors that are tuned to the precise opposite of the reactance of the operating frequency. When a system is tuned in this way, it becomes a compensated transformer which is resonant at its operating frequency. The power transfer efficiency is then only limited by losses in the

primary and secondary. These losses are themselves defined by their quality or Q factors.

[0023] Compensation of stray inductance may also be considered as part of the source and load impedance matching in order to maximize the power transfer. Impedance matching in this way can hence increase the amount of power transfer.

[0024] According to a current embodiment, a technique is described for powering a wirelessly powered device which can be located anywhere within an room. An embodiment powers the entire room and provides power for a receiver anywhere within the room, independent of the exact position of that receiver.

[0025] The techniques as disclosed herein operate at a frequency of 135 kHz, the so-called ISM band. However, other techniques may operate at other frequencies. For example, other embodiments may operate at a frequency of 13.56 MHz.

[0026] An embodiment uses passive repeaters, referred to herein as parasitic antennas, to extend the range of the wireless power. Power is transferred from a wireless transmitter to all of the parasitic antennas in range. These parasitic antennas form tuned resonators that create areas of maximum power transmission. A wireless power receiver is in the range of the parasitic antenna.

[0027] Figure 1 illustrates a block diagram. A “long-range” room antenna 100 may be fed with magnetic power by a magnetic frequency generator 105, and amplifier 110. The magnetic generator 105 may produce an output having a frequency which is resonant with the antenna 100. Antenna 100 is formed of an inductive loop 101 as shown, and a separate capacitor 102. In another embodiment, the self capacitance of the loop 101 may serve as the capacitor. The LC constant of the loop and capacitor is substantially resonant with the frequency created by the generator and amplifier.

[0028] This creates magnetic field areas near antenna 100. In an embodiment, the antenna 100 may traverse a perimeter of the room. However, since the antenna 100 produces as much signal inside the loop antenna as it does outside the loop, it may be more efficient to place the antenna more toward the center of a room. Therefore, one embodiment may place the antenna, for example, in the floor, or along edges of a table. Any receiver such as 125 can receive power directly from the room antenna 100 and can also receive re- radiated power from the antenna 120.

[0029] The parasitic antenna 120 receives the magnetic field power from the antenna 100 and reradiates to an area close to 120. The receiver 125 may be a receiver of magnetic power.

[0030] The other receivers shown as 126, 127 can also receive power in the same way, receiving part or all of their power from the main antenna 100, and

part of the power that is re-radiated by another parasitic antenna 130.

Alternately, and in this embodiment, it is shown that the receivers 126 and 127 receive power only from the parasitic antenna 130. Yet another receiver 128 is not near a parasitic antenna, and receives magnetically transmitted power, accordingly, only from the main antenna 100.

[0031] The loop antennas may all have the same orientation with respect to the magnetic field, or may each have different orientations with respect to the magnetic field.

[0032] The capability of a receiver antenna to relay power may be mainly dependent on the coupling between the receiver antenna and the room antenna. This coupling, in turn, is dependent on many factors including the area ratio between the receiver antenna and the room antenna. The receiver antenna, however, may be limited in size by the size of the portable device that incorporates it. Parasitic antennas can have a large enough area to allow them to receive and re transmit the power as necessary.

[0033] Another important feature is the quality factor of the antennas. The parasitic antenna can have higher Q factors, since it can be hidden and of any size.

[0034] An embodiment using low-frequency may in general may use more turns of an inductor than those used at high frequencies. One embodiment may use multiple turns on the antenna material as part of the antenna 100 and also

the parasitic antenna. One embodiment may use stranded wire, such as "Litz wire" to compensate for the increased ohmic losses caused by the increased number of turns. The ohmic losses can be reduced using low resistance wire.

[0035] Litz wire is a special kind of stranded wire, where each single-strand is electrically isolated from the other strand. Litz wire increases the effective cross-sectional area of the wire, and thereby partially compensates for the skin and proximity effect.

[0036] More generally, an embodiment may use any material that increases the effective cross sectional area of a wire used for the antenna without increasing an actual cross sectional area of the wire

[0037] The following illustrates differences between conventional wire and Litz wire.

DC resistance of a conventional wire:
$$R_{DC} = \frac{N}{\sigma \cdot b^2 \cdot \pi} \cdot 2\pi \cdot r_A$$

AC resistance of a conventional wire:
$$R_{AC} = \frac{N}{2 \cdot b} \cdot \sqrt{\frac{f \cdot \mu_0}{\sigma \cdot \pi}} \cdot 2\pi \cdot r_A \cdot (\alpha + 1)$$

AC resistance of litz wire:
$$R_{Litz} = \frac{N}{\sigma \cdot b^2 \cdot \pi \cdot \xi} \cdot 2\pi \cdot r_A$$

N = Number of turns [1]

σ = Electrical conductivity [S/m]

b = Wire radius (without isolation) [m]

r_A = Antenna circular loop radius [m]

f = Frequency [Hz]

μ_0 = Permeability constant [H/m]

α = Proximity effect coefficient [1]

ξ = Litz wire packaging factor (in the range of 0.4 – 0.6) [1]

[0038] Based on calculations and simulations, the applicants have found that the AC resistance of Litz wire is about 50-80% lower than the AC resistance of a comparable conventional wire that has the same

[0039] Inductance of the eventual antenna may be an extremely important factor in the antenna's efficiency of operation. The inductance can be expressed as

$$L_A = \mu_0 \cdot N^2 \cdot \frac{A_A}{K_A}$$

A_A = Area of the antenna
 K_A = Antenna shape factor

The factor K_A is dependent of the shape of the antenna. For a rectangular antenna K_A is given by

$$K_{A-rect} = \frac{A_A \cdot \pi}{-2(w+h) + 2 \cdot gsw h - h \cdot \ln\left(\frac{h+gsw h}{w}\right) - w \cdot \ln\left(\frac{w+gsw h}{h}\right) + h \cdot \ln\left(\frac{2 \cdot w}{b}\right) + w \cdot \ln\left(\frac{2 \cdot h}{b}\right)}$$

w = Width of the antenna [m]
 h = Height of the antenna [m]
 $gsw h = \sqrt{w^2 + h^2}$ [m]

For a circular antenna, K_A is given by

$$K_{A-circ} = \frac{r_A \cdot \pi}{\ln\left(\frac{8 \cdot r_A}{b} - 2\right)}$$

The radiation resistance of a loop antenna is given by

$$R_{rad} = 320 \cdot \pi^4 \cdot \left(\frac{A_A}{\lambda^2}\right)^2 \cdot N^2$$

λ = Wavelength of operating frequency [m] (2206.8 m for 135 kHz)

[0040] Characteristics of the active antenna can also be calculated using these formulas. The total resistance of this antenna is formed by the ohmic loss

R_{AC} , the radiation resistance R_{rad} and the medium loss resistances R_{med} . The medium loss resistances models the losses from the room in which the antenna is installed. Metallic parts within the room act like a medium. This medium can be defined according to its complex permeability

$$\mu_{med} = \mu_r' + j \cdot \mu_r''$$

μ_r' = Real part of relative permeability

μ_r'' = Imaginary part of relative permeability

Based on this, the medium loss resistance is defined as

$$R_{med} = 2\pi \cdot f \cdot \mu_r'' \cdot L_d$$

[0041] where μ_r' can be measured, as the relative permeability of the medium, for example as

$$\mu_{med} = 1 + j \cdot 0.018$$

[0042] This value may change for different rooms, where each room will define its own media.

[0043] Figure 2 illustrates the room antenna, also called the long-range antenna. This antenna may be long-range by virtue of its size. Larger antennas of this type usually have a better capability of coupling magnetic power to a recipient. The embodiment uses a special test room which had an approximate size of 12 m x 5.5 m. The antenna can be mounted at the height of the table on which the items will be located, but can also be located on the floor, where it can be more easily hidden.

[0044] One embodiment built the test antennas from RG 213 U coaxial cable. Only the outer conductor of this coaxial cable was used. In this embodiment, since the antenna is large, a self capacitance system can be used.

[0045] The embodiment of figure 2 uses four turns on the ground surrounding the complete perimeter of the room. The measured values were

L [μ H]	R [Ω]	C [nF]	Q [1]
700	26	2.0	23

[0046]

[0047] Other embodiments may have different values. In this embodiment, Q was lower than expected because of properties of the room.

[0048] It was found by experimentation that a single turn antenna in fact in this medium provided the same performance as a multiple turn antenna. For example, different parameters for different heights produced similar values.

L [μ H]	R [Ω]	C [nF]	Q [1]
456	7.5	3.1	52

4 turns at 0.4 m

L [μ H]	R [Ω]	C [nF]	Q [1]
43	0.8	32.3	46

1 turn at 1.3 m

[0049]

[0050] The antenna can also be removed from the walls by about 1 m, and placed on different heights off the ground. The following shows results for antennas spaced from the wall by 1m.

L [μ H]	R [Ω]	C [nF]	Q [1]
30.9	0.42	45.0	62

1 turn at 0.8 m

L [μ H]	R [Ω]	C [nF]	Q [1]
31.1	0.4	44.7	66

1 turn at 2.0 m

[0051]

[0052] Another embodiment, shown in figure 3 includes the antenna lifted off the ground by some amount, and also lifted at the areas 305, 310 to go around doors and windows. Measured values for this antenna are as follows:

L [μ H]	R [Ω]	C [nF]	Q [1]
42.34	1.06	33.26	33.7

1 turn at 1.3 m (lifted 1.8 m at the windows and 2.1 m above the doors)

[0053] The long range antenna 100 may carry a high power. A circuit for the antenna which provides LC values and 50 ohm matching is shown in Figure 4.

According to an embodiment, a special capacitor bank and coupling transformer is used to the antenna. The values of this device may be:

- C1 – C6: 22 nF / 900 VAC capacitor
Type PHE450 from Revox Rifa
- P1 / P2: Female UHF-connector,
designed for RG 213 U cable
- P3: Female N-connector
- T1: 2 x transformer 1:7, each with 2
ferrite cores of the type B64290-L659-
X830, made of N30 material,
secondary winding made of 3 mm HF
litz wire (120 x 0.1 mm \varnothing).

[0054] In an embodiment, the antenna may carry a power rating of approximately 150 W. However, at power levels that are close to this power rating, the capacitor bank carries a current of 12 amps, total voltage of 400 V. This corresponds to a reactive voltage of 4.8 kVA.

[0055] Accordingly, in an embodiment, the capacitor bank is provided on the secondary side of the transformer. Placing the capacitor bank on the primary side of the transformer requires the reactive power to pass through the transformer and to thereby oscillate between the inductance and capacitance. This would increase the transformer size.

[0056] Many rooms include many metal objects, and hence are inherently lossy. The antenna is also intended to have a reasonably large size. Accordingly, the characteristics of this system make it inherently immune from the approaching and moving of people. In essence, this is because the area covered by any person is typically small, e.g., less than 10% of, the area of the antenna. No tuning of this antenna will typically be necessary because of these inherent features.

[0057] In operation of an embodiment, the fixed installation of the long-range antenna creates a magnetic field throughout the entire test room creating a transmit power of about 60 W. Actual results as measured are shown in figure 5. This three-dimensional graph shows peaks along the wall due to cable loops around doors and at the peak points. The field strength also increases towards

the back wall because this wall has less metallic part in the test room compared to other walls. The field strength is reduced at the window side due to the metallic frames of double glazed windows.

[0058] One embodiment may exploit this effect by placing loops of antennas along certain walls, e.g., in areas of the room that either need more signal, or just in general.

[0059] Appropriate design of the antenna loop might minimize these hotspots or provide supplemental antennas to these hotspots. In the central part of the room the field strength is often nearly constant.

[0060] The power scales according to the square root of the transmit power. Therefore, doubling the transmit power may increase the power density in the room by $\sqrt{2}$.

[0061] The magnetic field in the room was also measured, and stays within safety limits at all points at 60 watts of transmitted power.

[0062] Figure 6 illustrates a parasitic antenna used according to an embodiment. A first embodiment uses a 14 turn loop 600, formed of 120 x 0.1 mm diameter high frequency Litz wire. The inductance of the loop is influenced by a number of factors including turn-by-turn spacing, where smaller spacing between the turns results in a higher inductance and therefore a higher quality factor.

[0063] In the embodiment, the turns are filled with hot glue to secure exact position. A guide may also be used. The lower limit for the turn to turn spacing is the necessary withstanding voltage of the antenna. For example, at 20 W, there may be a 1K reactive voltage, leading to a turn-to-turn voltage of 75 V. The antenna shown in figure 6 includes a 14 turn loop 600 forming the inductance and a single turn “coupling loop” 606 unconnected to the main loop 600. Figure 6 shows the antenna built into a picture frame.

[0064] The capacitance of the parasitic antenna is formed by a bulk capacitance 600 and a variable capacitance. The variable capacitance in this embodiment is formed by a step switch 604 which controls switching of a capacitor bank 603.

[0065] Figure 7 illustrates a capacitor bank that can be used to tune the parasitic antenna. The bulk capacitance 602 may be in parallel with the tunable capacitance 603 connected via a multiple contacts switch 700. The switch position 1 is no extra capacitance, and provides only the bulk capacitance. According to an embodiment, this provides a resonant frequency of 137 kHz. More capacitance can be added in parallel with the capacitor bank by changing to different switch positions. Position 2 provides 90 pf capacitance, for example, and position 3 provides 160 pF. 135 kHz resonant frequency is realized at position three. Position 6 (330 pf) may tune the frequency to 132 khz.

[0066] The antenna may be detuned by nearby metallic objects and the frequency shift can be corrected by adding more capacitance. The additional capacitance may lower the quality factor as the LC ratio of the resonant circuit is lowered.

[0067] Each metallic object inside the generated magnetic field of an antenna compensates a portion of the antenna's total inductance thus results in raising the resonant frequency of the antenna. The antenna does not have a substantial electric field. Accordingly, the presence of dielectric materials has very little impact on the antenna. Therefore, low-frequency antennas of the type in an embodiment have resonant frequencies which shift upward due to detuning effects. A tuning compensation system according to the present system may accordingly always pull down the resonance to provide a non-symmetrical tuning range.

[0068] The parasitic antenna of an embodiment has the following characteristics:

Nominal frequency [kHz]	135
Tuning range (coarse tuning) [kHz]	132 - 137 (in 5 steps)
Tuning range (fine tuning) [kHz]	+/- 0.25
Quality factor	250
Inductivity [μ H]	260
Bulk capacitance [nF]	5.13
Maximum power capability	20 W (approx.)
Number of turns	14
Wire	Litz wire 120 x 0.1 mm \varnothing
Size	0.7 x 0.5 m (average turn size)

[0069] Another embodiment may use multiple small capacitors that add together to increase the overall capacitance.

[0070] Yet another embodiment may use semiconductor switches or relays to change the capacitance.

[0071] Another compensation system is shown in figure 8. This provides a short circuited loop part 800 within the field of the parasitic antenna 600. This causes a portion of the H field to be compensated, thereby lowering the inductance of the parasitic antenna. A lower inductance leads to a higher resonant frequency with a constant capacitance. Accordingly, this technique can also be used to tune the resonant frequency of the antenna. The amount of compensation of the resonant frequency is dependent on the ratio between the areas of the main transmit antenna 600 and the area of the compensation antenna 800. The area of the short-circuited loop defines the amount of influence – where a smaller loop has less influence than a larger one.

[0072] A conceivable disadvantage of this technique is that the short-circuited loop lower the overall Q factor of the parasitic antenna.

[0073] Another embodiment may implement a short-circuited loop which is mechanically changeable in area. Figure 9 illustrates an embodiment where a loop has a variable area by virtue of the ability to move its characteristics. The loop in figure 9 is a triangular loop with copper plated bars. First bar 902 and

second bar 904 are connected together via center rotatable couplings such as 903. The bars 902, 904 are also connected together via movable parts 906, 907. The parts 906, 907 can be varied with reference to one another, and pivoted on the portions 910, 911, 912. A spring 915 may assist in folding and unfolding the antenna. In the embodiment, the the main bars 902, 904 are of length X ., and the folding bars 906, 907 are of length $X/2$. The triangle is deformed by pulling the upper corner of the triangle. However, when the pulling force gets less, the spring 915 closes the triangle and makes a smaller area.

[0074] Different shapes including rectangles and trapezoids could also be used for this purpose.

[0075] A receiver antenna is illustrated in figure 10. According to this embodiment, the receiver antenna can be formed of a 70 turn loop of high frequency litz wire. The receiver antenna 1000 can have turns wound in five layers with 14 turns on each layer. This can form a rectangular profile where in essence a stack 1002 of wires defines a perimeter that can be integrated around the edge of a mobile device. The antenna parameters are shown as:

Nominal Frequency [kHz]	135
Tuning range [kHz]	133 - 135
Quality factor	175
Inductivity [μ H]	625
Bulk capacitance [nF]	2.2
Maximum power capability	2 W (approx.)
Number of turns	70
Wire	Litz wire 75 x 0.05 mm \varnothing
Size	90 x 40 mm (average turn size)

[0076] This system can also use a coupling loop which is wholly separate from the receiving antenna. The coupling loop can be a three turn loop 1005, for example.

[0077] Antenna detuning may occur when coupling between antennas increases and the antennas begin influencing the inductance of one another and thus influence the resonant frequencies. This causes a strong detuning of the antennas. Hence, when a wireless receiver gets too close to the parasitic loop, decoupling can occur. Simulation and measurement produces the graph of figure 11 which shows the impact of coupling factor to the power transfer between two antennas.

[0078] An adjustable coupling between antennas may be used to avoid this detuning. Multiple taps can be added to the antenna turns and used as coupling loops. The strength of the coupling can be changed by switching between the taps.

[0079] System efficiency defines how the system transfers power to the receiver. System efficiency is defined by transfer efficiency between the long-range antenna and parasitic loop; transfer efficiency between the long-range antenna and the receiver and transfer efficiency between the long-range antenna to parasitic loop to receiver.

[0080] Exemplary results are shown in figures 12A and 12B for the specific test setup described herein. Figure 12A shows the single hop transfer efficiency, while Figure 12 B shows the double hop transfer efficiency.

[0081] The measurements given above confirm that use of parasitic antennas can compensate for losses which would otherwise occur due to room boundaries. The parasitic antennas allow better use of the existing materials. Moreover, these can stay within IEEE and NATO defined exposure limit of 125.4 amps per meter at 130 kHz, which can be met at any point in the room at a transmit power of 60 W using a parasitic antenna.

[0082] Although only a few embodiments have been disclosed in detail above, other embodiments are possible and the inventors intend these to be encompassed within this specification. The specification describes specific examples to accomplish ~ more general goal that may be accomplished in another way. This disclosure is intended to be exemplary, and the claims are intended to cover any modification or alternative which might be predictable to a person having ordinary skill in the art. For example, other sizes, materials and connections can be used. Other structures can be used to receive the magnetic field. In general, an electric field can be used in place of the magnetic field, as the primary coupling mechanism. Other kinds of magnets and other shapes of arrays can be used.

[0083] Also, the inventors intend that only those claims which use the-words "means for" are intended to be interpreted under 35 USC 112, sixth paragraph. Moreover, no limitations from the specification are intended to be read into any claims, unless those limitations are expressly included in the claims.

[0084] Where a specific numerical value is mentioned herein, it should be considered that the value may be increased or decreased by 20%, while still staying within the teachings of the present application, unless some different range is specifically mentioned. Where a specified logical sense is used, the opposite logical sense is also intended to be encompassed.

What is claimed is:

1. A system, comprising:

a first system including a transmitting antenna of a first size, transmitting wireless power in a magnetic field; and

a parasitic antenna, of a second size smaller than said first size, repeating said wireless power in an area.

2. A system as in claim 1, wherein said parasitic antenna is a formed of an inductive loop and a capacitance.

3. A system as in claim 2, wherein said inductive loop is formed of stranded wire with strands that are electrically isolated from one another.

4. A system as in claim 2, wherein said inductive loop is formed of a material that increases the effective cross sectional area of a wire used for the antenna without increasing an actual cross sectional area of the wire.

5. A system as in claim 1, wherein said transmitting antenna surrounds a perimeter of a room.

6. A system as in claim 5, wherein said transmitting antenna is at different levels in the room.
7. A system as in claim 1, wherein said first system includes a frequency generator, and a matching system, said matching system including a coupling transformer, and a capacitor on a primary side of said transformer.
8. A system as in claim 2, wherein said parasitic antenna includes a tuning part that is adjustable to change a resonant frequency of said parasitic antenna.
9. A system as in claim 8, wherein said tuning part includes a variable capacitance.
10. A system as in claim 8, wherein said part only adjusts said resonant frequency in a downward direction.
11. A system as in claim 8, wherein said tuning part includes a portion that short circuits a portion of said inductive loop.
12. A system as in claim 11, wherein said part has a variable size to change an area of the inductive loop that it short circuits.

13. A system as in claim 12, wherein said part is triangular.

14. A system as in claim 9, wherein said variable capacitance is a switched capacitance.

15. A system, comprising:
 - a parasitic antenna , tuned to receive and repeat magnetically-generated wireless power in an area of said parasitic antenna.

16. A system as in claim 15, wherein said parasitic antenna is a formed of an inductive loop and a capacitance.

17. A system as in claim 16, wherein said inductive loop is formed of a material that increases the effective cross sectional area of a wire used for the parasitic antenna without increasing an actual cross sectional area of the wire.

18. A system as in claim 17, wherein said inductive loop is formed of stranded wire with strands that are electrically isolated from one another.

19. A system as in claim 15, further comprising a transmitting antenna that transmits magnetic energy.
20. A system as in claim 16, wherein said parasitic antenna includes a tuning part that is adjustable to change a resonant frequency of said parasitic antenna.
21. A system as in claim 20, wherein said tuning part includes a variable capacitance.
22. A system as in claim 20, wherein said tuning part only adjusts said resonant frequency in a downward direction.
23. A system as in claim 20, wherein said tuning part includes a portion that short circuits a portion of said inductive loop.
24. A system as in claim 23, wherein said tuning part has a variable size to change an area of the inductive loop that it short circuits.
25. A system as in claim 24, wherein said part is triangular in its outer shape.
26. A system as in claim 22, wherein said variable capacitance is a switched

capacitance.

27. A system, comprising:

a parasitic antenna , formed of an inductive loop in series with a capacitance, said inductive loop is formed of a material that increases an effective cross sectional area of a wire used for the parasitic antenna without increasing an actual cross sectional area of the wire, an LC value of the inductive loop and capacitance defining a resonant frequency at a specified frequency, to receive and repeat said specified frequency of magnetically-generated wireless power in an area of said parasitic antenna.

28. A system as in claim 27, wherein said inductive loop is formed of stranded wire with multiple strands of wire that are electrically isolated from one another.

29. A system as in claim 28, wherein said stranded wire is Litz wire.

30. A system as in claim 27, further comprising a transmitting antenna that transmits magnetic energy at said specified frequency.

31. A system as in claim 27, wherein said parasitic antenna includes a tuning part that is adjustable to change a resonant frequency of said parasitic antenna.

32. A system as in claim 31, wherein said tuning part includes a variable capacitance.
33. A system as in claim 31, wherein said tuning part only adjusts said resonant frequency in a downward direction.
34. A system as in claim 31, wherein said tuning part includes a portion that short circuits a portion of said inductive loop.
35. A system as in claim 34, wherein said tuning part has a variable size to change an area of the inductive loop that it short circuits.
36. A system as in claim 32, wherein said variable capacitance is a switched capacitance.
37. A system, comprising:
- a parasitic antenna, formed of an inductive loop in series with a capacitance, an LC value of the inductive loop and capacitance tuned to a resonant frequency at a specified frequency, to receive and repeat said specified frequency of magnetically-generated wireless power in an area of said parasitic

antenna, said parasitic antenna including a tuning part that is adjustable to change a resonant frequency of said parasitic antenna by short circuiting across a portion of said inductive loop.

38. A system as in claim 37, wherein said inductive loop is formed of a material that increases the effective cross sectional area of a wire used for the antenna without increasing an actual cross sectional area of the wire.

39. A system as in claim 37, further comprising a transmitting antenna which transmits magnetic power at said specified frequency.

40. A system as in claim 37, wherein said part has a variable size to change an area of the inductive loop that it short circuits.

41. A system as in claim 40, wherein said part is triangular.

42. A system, comprising:

a wireless power transmitter, including a magnetic field generator, that generates a magnetic field at a specified frequency, and a transmitting antenna that transmits wireless power by producing a magnetic field that has said specified frequency, said transmitting antenna having an inductance, and having

a capacitance, forming an LC value that is substantially resonant with said specified frequency, said inductance formed by an antenna loop that extends around a loop, and the area forming the loop has at least two different planar sections, with a first of the planar sections being above the second planar section.

43. A system as in claim 42, further comprising a parasitic antenna, smaller than said loop of said transmitting antenna, and repeating said wireless power in an area.

44. A system as in claim 42, wherein said antenna has a first area in a first plane, and a second area in a second plane that is horizontally above said first plane.

45. A system as in claim 44, further comprising a third portion which extends between said first and second planes.

46. A method, comprising:

producing wireless power from a first antenna that forms a first part of a magnetic resonator and which produces wireless power as a magnetic field;

using a parasitic antenna, within a range of said first antenna, to repeat

said wireless power; and

receiving said magnetic power that has been repeated by said parasitic antenna wirelessly into a portable device and using said power to power said device .

47. A method as in claim 46, wherein said first antenna has a larger outer size than said second antenna.

48. A method as in claim 46, further comprising using a material that increases an effective cross sectional area of a wire used for the antenna without increasing an actual cross sectional area of the wire.

49. A method as in claim 46, wherein said producing uses a transmitting antenna that surrounds a perimeter of a room.

50. A method as in claim 49, wherein said transmitting antenna is at different height levels in the room.

51. A method as in claim 46, further comprising tuning a resonant frequency of said parasitic antenna.

52. A method as in claim 51, wherein said tuning comprises changing a value of a variable capacitance.

53. A method as in claim 51, wherein said tuning comprises short circuiting a portion of said inductive loop.

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2 System overview

In order to achieve a long range wireless powering and charging system in a lossy environment preventing from achieving high antenna Q-factors, a two step approach is considered: The power cannot be transferred directly from a large transmitter (several m²) to a small receiver (several cm²), but has to be transferred to a parasitic antenna first, which then acts like a relay or repeater to the small receiver.

The term "long range" is somehow inexact due to this two step approach where the energy hops from one resonator to the next. "Wide area" wireless powering and charging system describes it more accurately. Figure 1 illustrates the architecture of this system approach using loop antennas of different sizes.

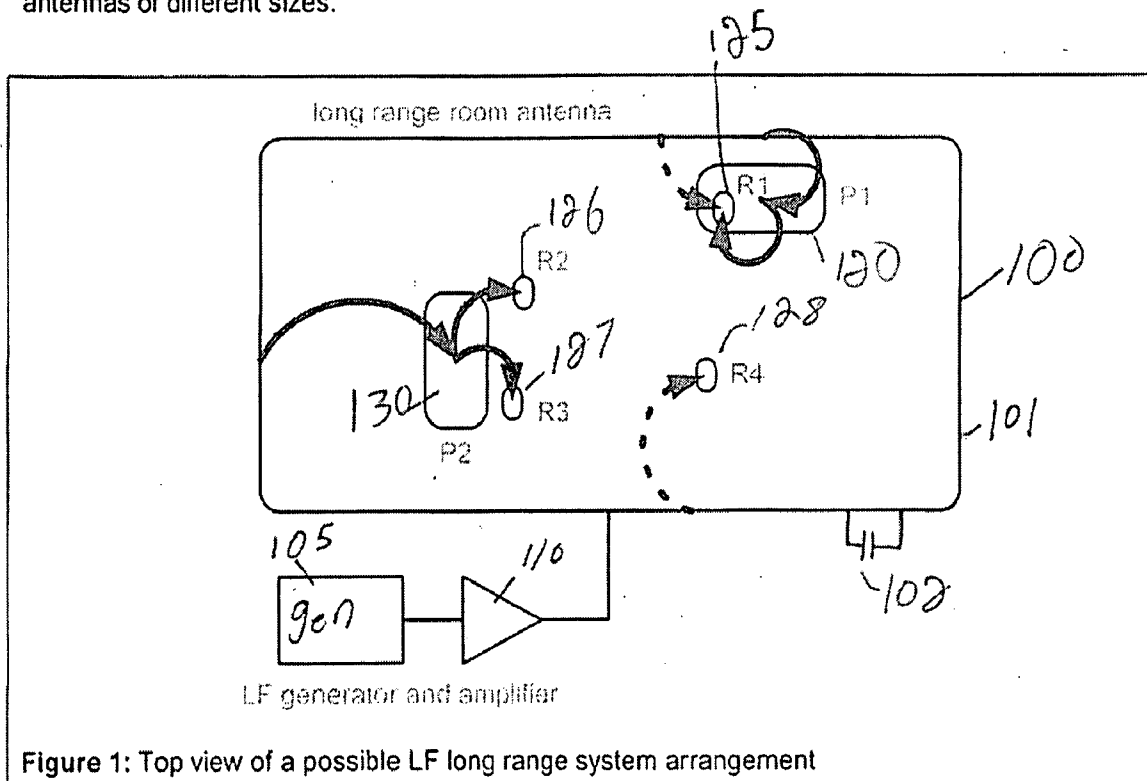


Figure 1: Top view of a possible LF long range system arrangement

The parasitic antenna P1 receives power from the long range room antenna and reradiates a magnetic field, so that the receiver R1 also receives power. If close enough to the room antenna wire, R1 might get useful power directly from the large room antenna.

R2 and R3 both get power through the parasitic antenna P2. There is no considerable direct link to the room antenna.

R4 does not get useful power due to the missing proximity to a parasitic loop or a direct link to the room antenna.

Figure 1 assumes that all loop antennas the same orientation with respect to the magnetic field. This is however not the general case.

The capability of a receiver antenna to relay power is mainly dependent on its coupling to the room antenna, which is again dependent on the area ratio between the receiver antenna and the room antenna. So the parasitic antennas and the receiver antennas only differ in size. The parasitic antennas have a relatively larger area to be able to receive and reemit enough power.

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4 Room Antenna

The long range room antenna is the main antenna used for the long range wireless energy system. The development of this antenna was done with a step-by-step approach. Initial measurements were needed in order to design the antenna. The following subchapters describe this process and the resulting performance.

4.1 Initial measurements

The first tests for a long range transmitter were done in the test room of Ascom AG, which has an approximate size of 12 m x 5.5 m. Due to the goal of powering the entire room, the long range antenna embraces the room. Ideally, it is installed at the height of a table (around 0.7 m above the floor) to have zero distance to a receiver antenna placed on a table.

The first test antennas were built from a coaxial cable type RG 213 U, using only the outer conductor, which has a diameter of 8.1 mm. The inner conductor (normally the signal path) was not used.

All measurements were done with a calibrated vector network analyser (VNA) to determine the real and imaginary part of the impedance of the loop. The real part gives the total loss resistance R, and the imaginary part is ωL (self-capacitance neglected). This is why in the following tables (Figure 2 - Figure 5), the values L and R are measured, the values C and Q are computed. The capacitance C is calculated for a target resonance frequency of 135 kHz, but the loop itself was non-resonant by the time of the measurement.

Initially, four turns were laid out directly on the ground (Figure 2 and Figure 3). In air, this loop should provide a quality factor of 750, but it turned out that due to metallic parts, the eddy current losses are enormous. The resulting Q was 23 only.

The room can be considered as a medium (like ferrite is a medium) which influences the magnetic field and thus the antenna itself.

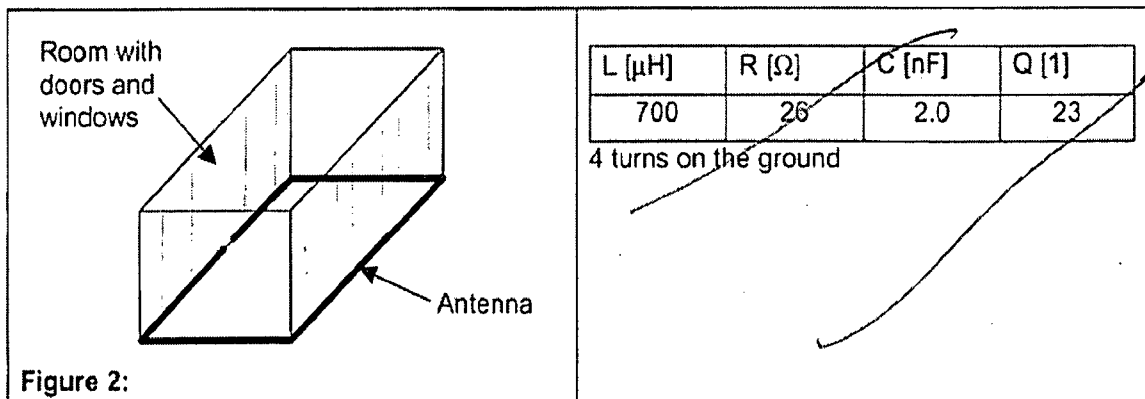


Figure 2:

To further determine the influence of the room, the four turn loop was lifted by 0.4 m above the floor and measured again (Figure 4). As a result, the Q increased by more than 100% to 52.

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4.2 Construction and performance

After preliminary loss measurements, a fixed installation of a long range antenna was realized. The antenna has one turn only and is made of RG 213 U cable already used for the initial measurements. The antenna is resonant at a frequency of 135 kHz, using a combination of 6 capacitors with a total capacitance of about 33.3 nF.

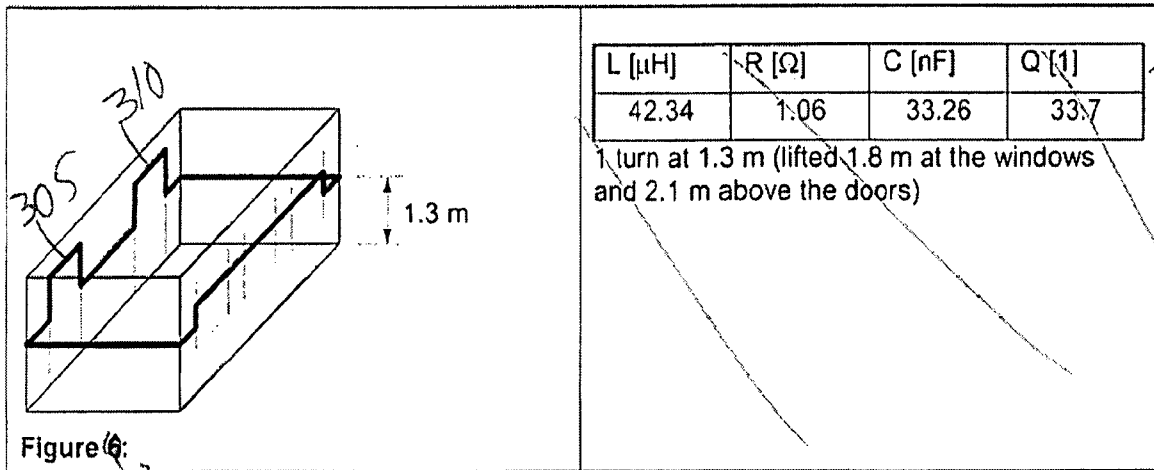
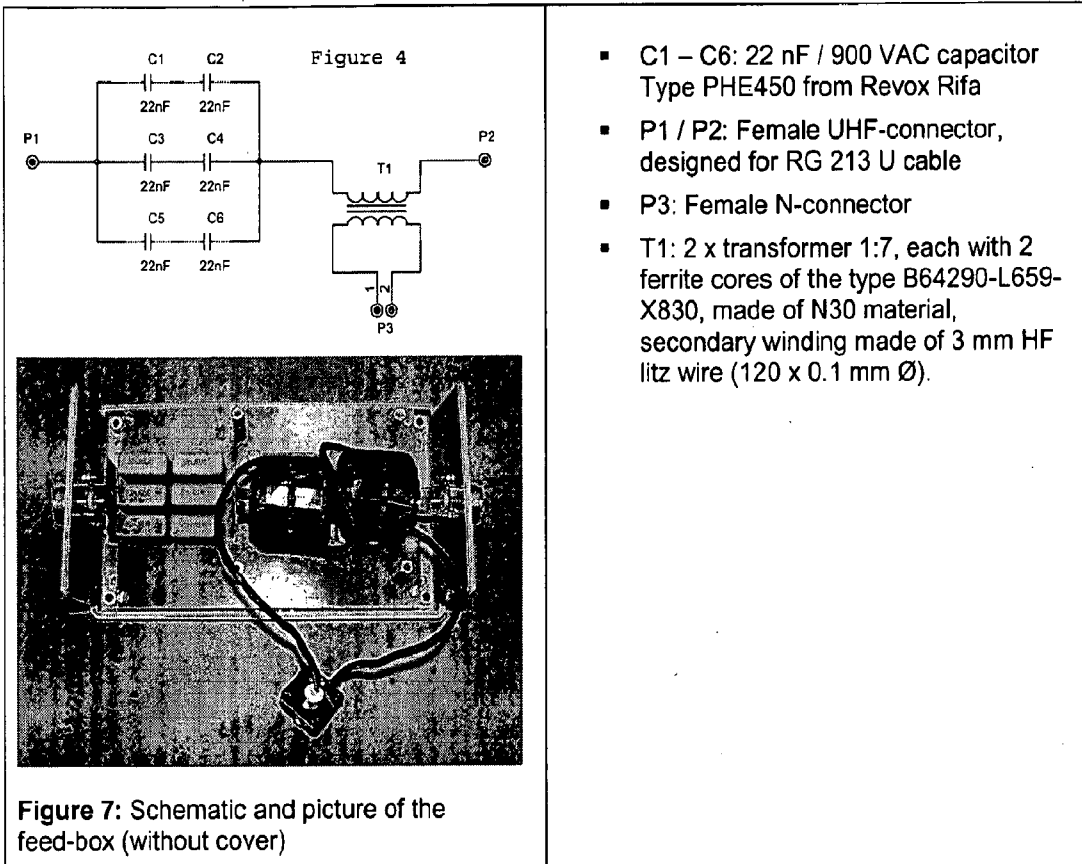


Figure 6:

To be able to use the antenna as a transmitter, an appropriate coupling to the 50 Ω generator-amplifier-system is needed, and the 33 nF capacitor has to be realised. For this purpose, an antenna feed-box was designed which contains a capacitor bank and a specially designed coupling transformer (Figure 7).

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The long range antenna system is designed for a power rating of 150 W. At power levels close to this rating, the capacitor bank has to carry a current of 12 A and a voltage of 400 V, which corresponds to a reactive power of 4.8 kVA. This was the reason to include the capacitor bank on the secondary side of the transformer. If the capacitor bank is included on the primary side of the transformer, the reactive power needs to pass the transformer in order to oscillate back and forth between the inductance (antenna loop) and the capacitance because the transformer is in-between the resonant elements. In order to transfer 4.8 kVA of power, the transformer size would increase dramatically.

Figure 8 shows the S_{11} antenna characteristics, including the feed-box. The transformer and the capacitor do not degrade the antennas quality factor.

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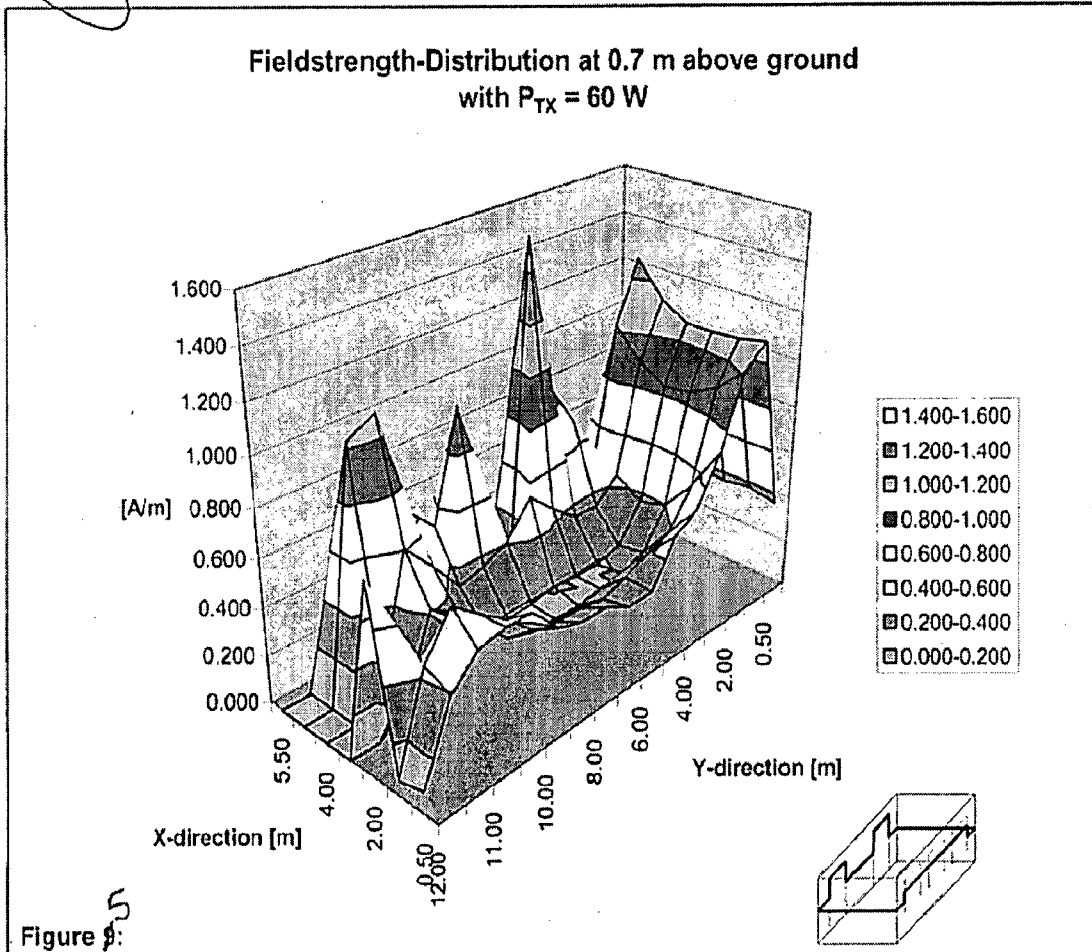


4.2.1 H-Field strength distribution in the room

With the fixed installation of the long range room antenna, it is possible to generate a significant magnetic field throughout the entire test room using a transmit power of 60 W. To compare the achieved field strength with the computed field strength, the magnetic field was measured with a small pick-up loop antenna connected to an Oscilloscope.

The field strength was measured at 0.7 m above ground which is considered as the typical operating height for portable and desktop operated receivers. At this height the H-field is predominantly vertically polarised, thus favouring receiver designs sensitive for vertical H-field polarisation. Due to this fact, only the vertical component of the H-field was measured.

Both the long range room antenna and all envisaged receiver designs are vertically polarized, so the measurements were limited to the vertical component of the field. The other two field components cannot be exploited by a vertically oriented receiver. Figure 9 shows the measurement results.



The 3d-graph is displayed with the same aspect angle like the drawing in Figure 6. The peaks along the wall with the doors are due to cable loops around doors and at feed point (between the two doors). Towards the back wall ($Y = 0\text{ m}$), the field strength increases, because this wall does contain less metallic parts compared to the front wall or the side wall with the windows. At the window side, the field strength is reduced, mainly due to the metallic frames of the double-glazed windows, acting like short cut loops that generate a counteracting H-field.

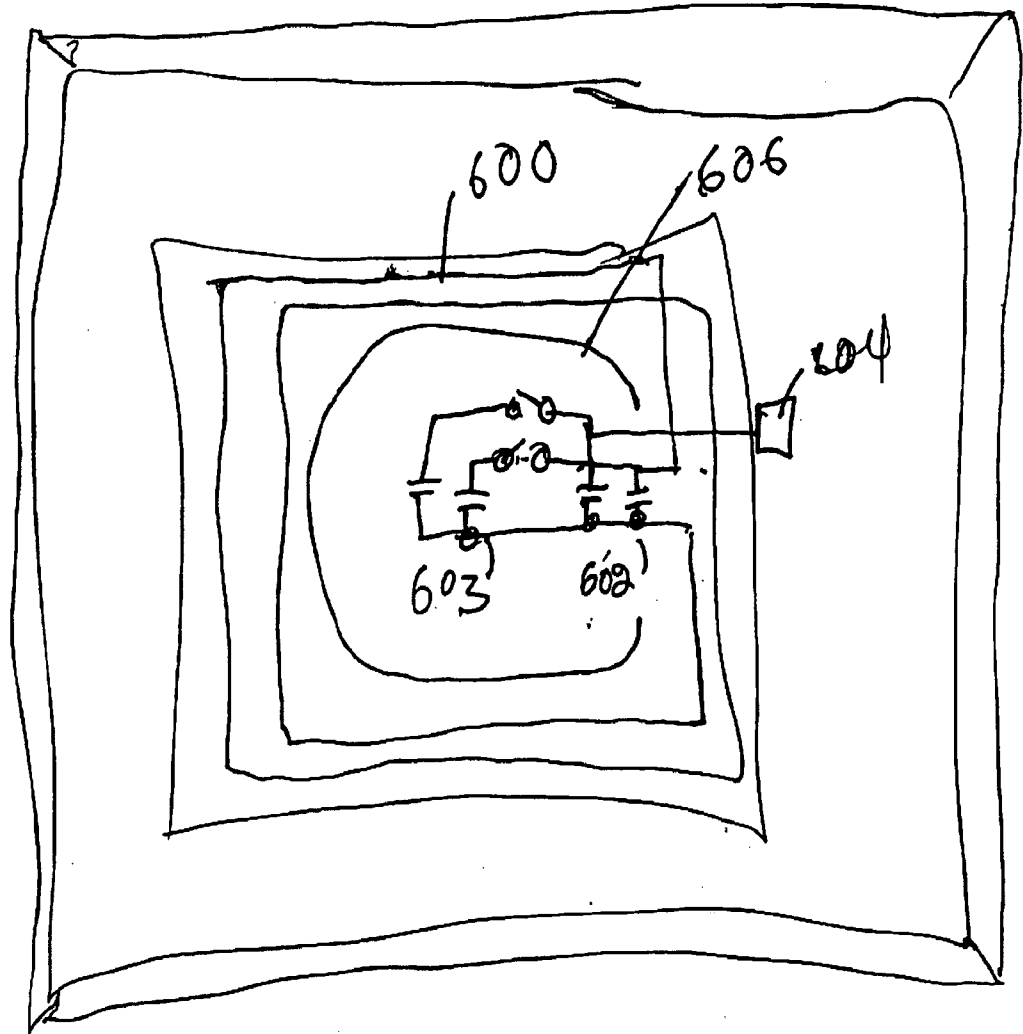


FIG. 6

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ascom

The following table summarizes the antenna parameters:

Nominal frequency [kHz]	135
Tuning range (coarse tuning) [kHz]	132 - 137 (in 5 steps)
Tuning range (fine tuning) [kHz]	+/- 0.25
Quality factor	250
Inductivity [μ H]	260
Bulk capacitance [nF]	5.13
Maximum power capability	20 W (approx.)
Number of turns	14
Wire	Litz wire 120 x 0.1 mm \varnothing
Size	0.7 x 0.5 m (average turn size)

P
✓ 19

5.1 Applied tuning methods

Each metallic object inside the generated H-field of an antenna compensates a part of the antennas inductance. This results in an upward-shift of the resonance frequency of the antenna. Due to the lack of a strong E-field, dielectric materials have nearly no impact on the antennas. The conclusion has to be drawn that the detuning of low frequency antennas is always upwards in frequency. So a detuning compensation has to pull the resonance down again. This results in a non-symmetrical tuning range.

5.1.1 Capacitor bank

To tune the parasitic antenna to the correct resonance frequency of 135 kHz, a capacitor bank (see Figure 11, C2 – C6) was implemented in addition to the bulk capacitance (C1). With the bulk capacitance only (switch position 1), the resonance frequency is 137 kHz. By adding more capacitance with the capacitor bank, the resonance is lowered to a minimum value of 132 kHz (switch position 6). 135 kHz is reached in position 3. If the antenna is detuned due to nearby metallic objects, the resulting upwards frequency-shift can be corrected by adding more capacitance. The additional capacitance lowers the quality factor because the L/C-ratio of the resonant circuit is lowered. There are negligible additional losses due to the capacitors.

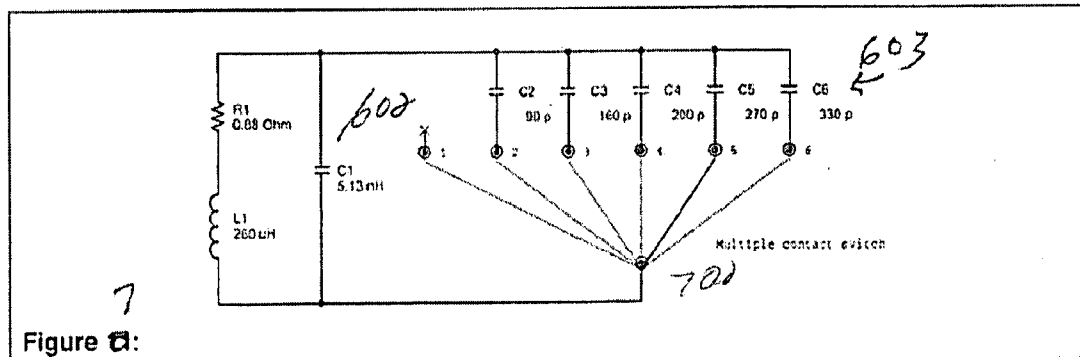


Figure 11:

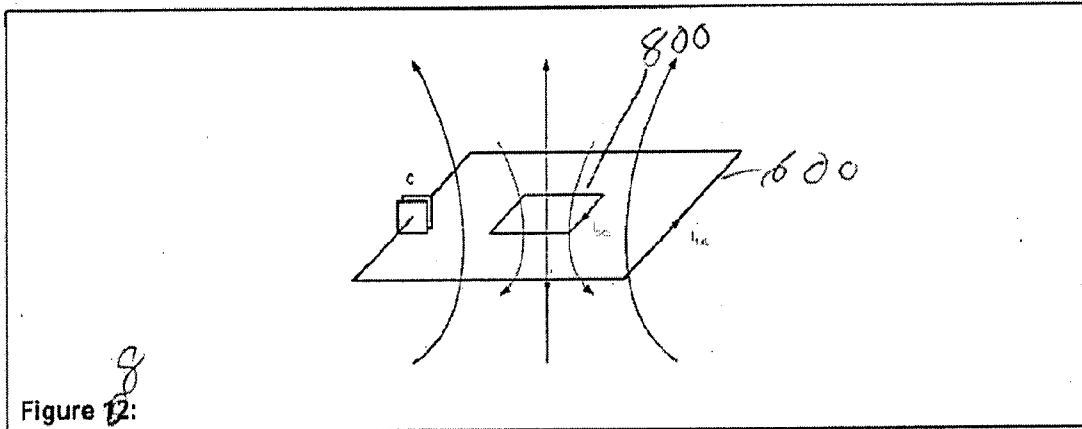
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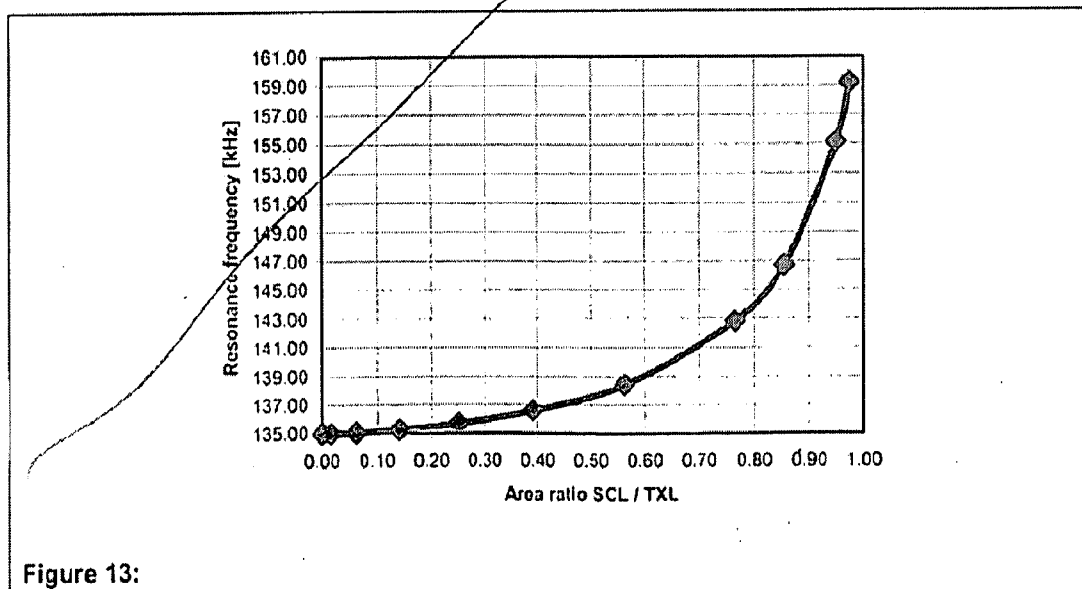
In the current implementation of the capacitor bank, the capacitors are not used very efficiently. It would be better to combine several small capacitors (e.g. 5 x 60 pF) additive, not selective. But to do this, the switching gets more complicated and cannot be realised with a simple mechanical COTS-switch anymore. For this purpose, semiconductor switches or relays could be used, together with a small control logic to enable or disable the correct capacitor values. Suitable semiconductor switches or relays have to be evaluated in further research work.

5.1.2 Short circuit loop

By inserting a short circuited single turn loop (SCL) into the field of the parasitic antenna (TXL), a part of the H-field is compensated, which leads to a lowering of the parasitic antennas inductance. A lower inductance results in a higher resonance frequency (if the capacitance C is kept constant). So this effect can be used to tune the resonance frequency of the parasitic antenna.



How much H-field is compensated is dependent on the area ratio between the TXL and the SCL. Obviously, a small short circuited loop has less influence compared to a large one. Figure 13 shows the results found by simulation for a single turn TXL and a single turn SCL. The influence of N, the number of turns of the TXL, has to be investigated.

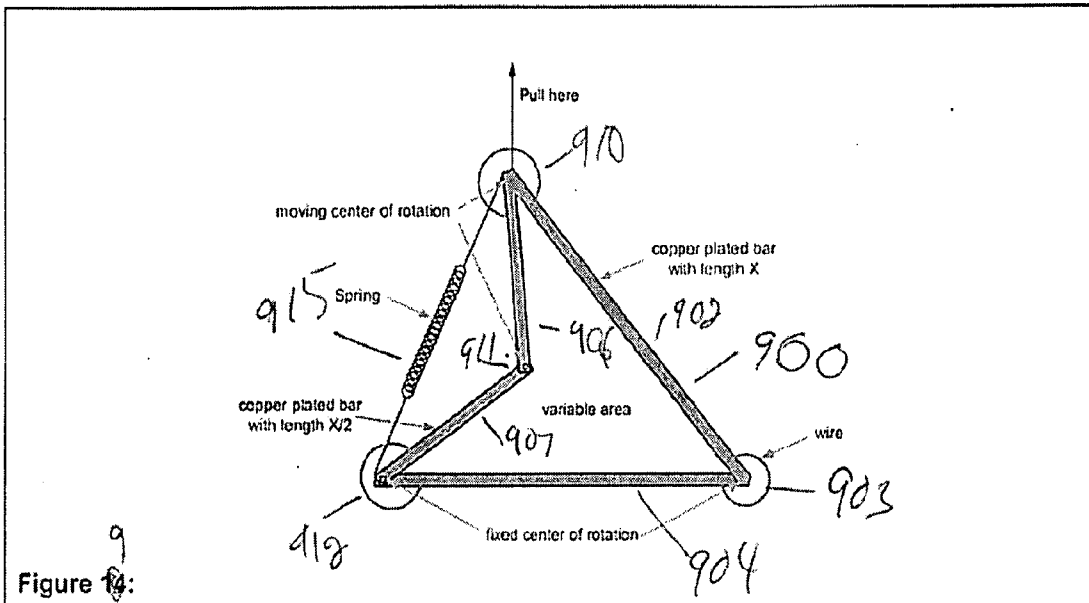


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The disadvantage of this method is that the losses of the SCL are transformed into the parasitic antenna and thus, lower the quality factor. The SCL has to be as loss free as possible. Of course, the quality factor gets degraded anyway due to the lowering of the inductance which leads to a lower L/C-ratio of the resonant circuit.

The challenge is to implement a short circuited loop, which is mechanically changeable in its area. The approach used for the parasitic antenna is shown in Figure 14.



By pulling at the upper corner of the triangle, the triangle is deformed (opened). The spring closes the triangle when the pulling force gets less. The variable area and the resonance frequency do not increase linearly with the pulling distance of the upper edge. By choosing an appropriate shape (e.g. a rectangle instead of a triangle), the pulling distance and the related change in frequency could be linearized.

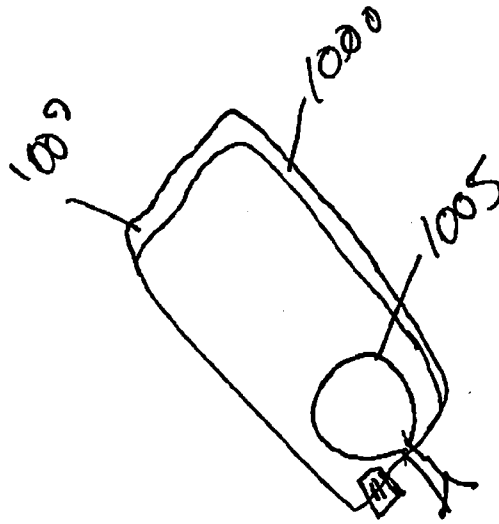


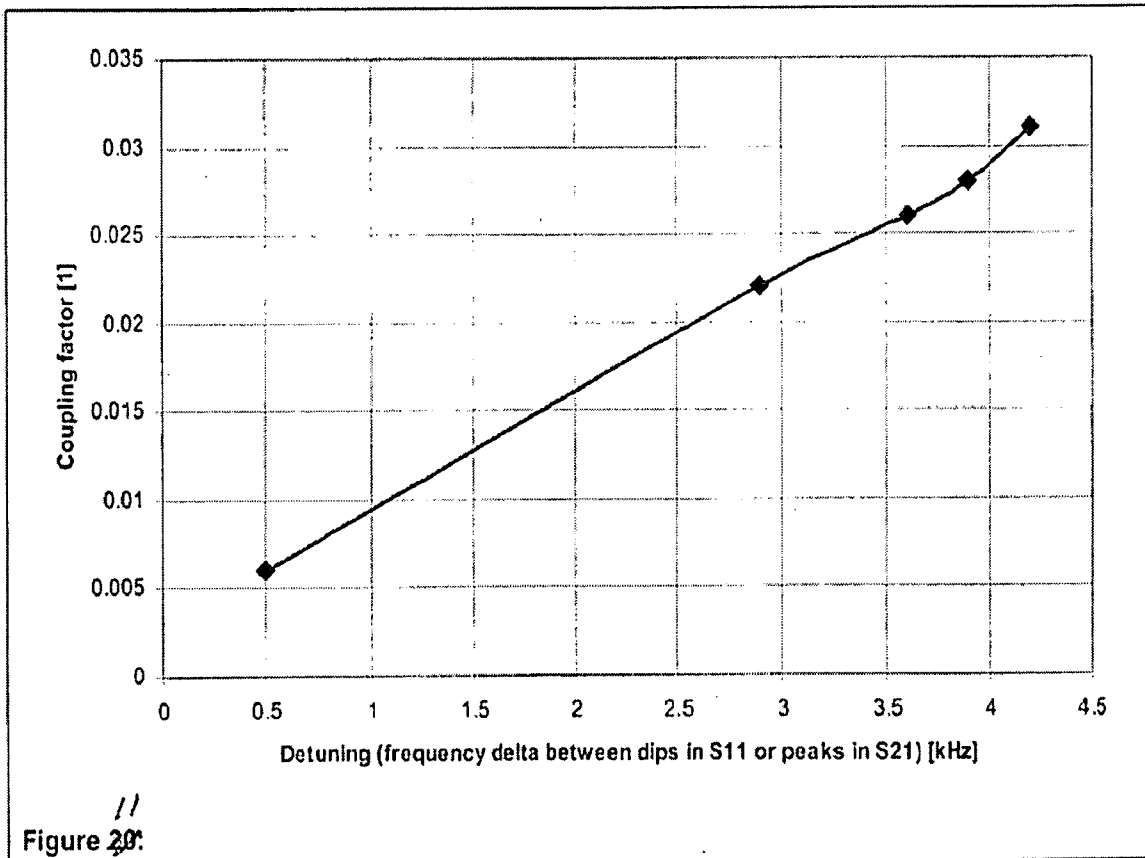
FIG 10

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Beside S_{11} and S_{22} , S_{21} is the most important simulation result. Figure 19 shows the impact of the coupling factor to the power transfer between the two antennas (S_{21}). With increased coupling factor, a dip develops at 135 kHz. Because the system is still working at 135 kHz, this highly influences the power transfer. With a coupling factor of 0.05, S_{21} is -15 dB at 135 kHz (see the dark green graph in Figure 19). So 15 dB are lost due to the detuning, this corresponds to a factor of 32.

The detuning effect can be used to determine the coupling factor of two antennas, because the amount of detuning and the coupling factor have a direct linear relation. So by measuring the frequency delta between the two peaks (like in the graph in Figure 19) the amount of detuning can be measured. Figure 20 shows the relation between the detuning and the coupling factor for some measured detuning values.



To mitigate this detuning effect, the coupling to each antenna, the transmitter and the receiver, has to be increased. There is no use to try to retune the resonance frequencies of each antenna.

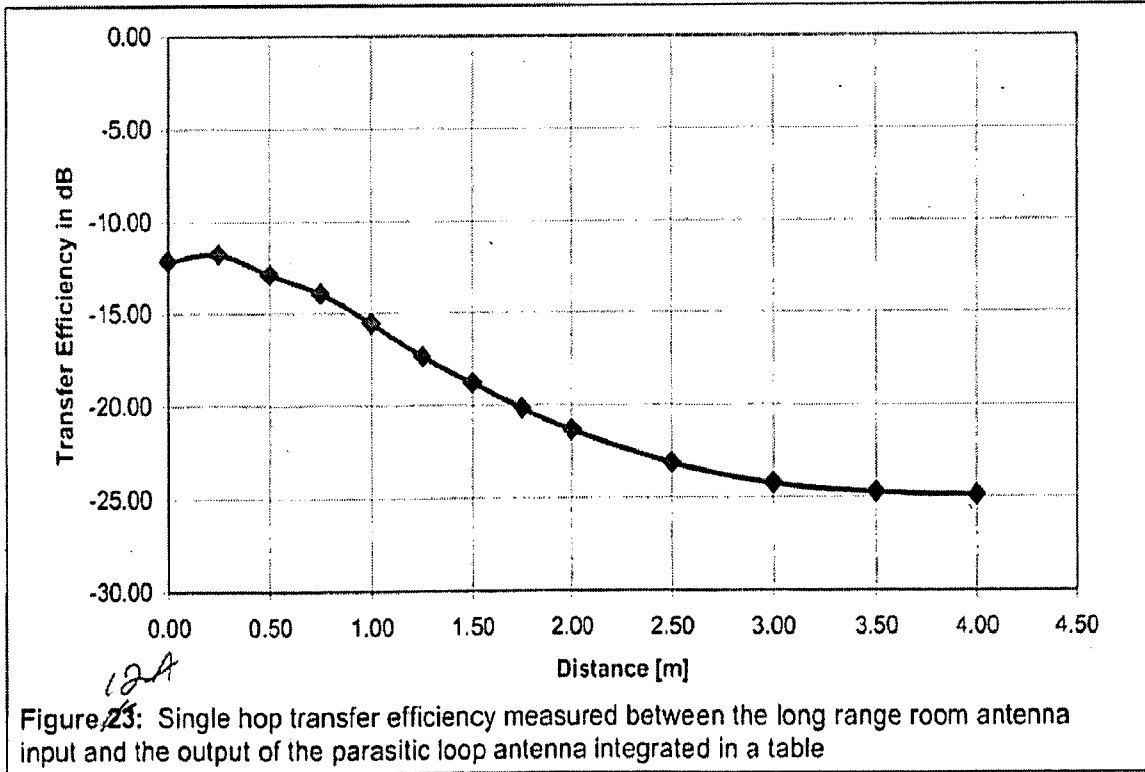
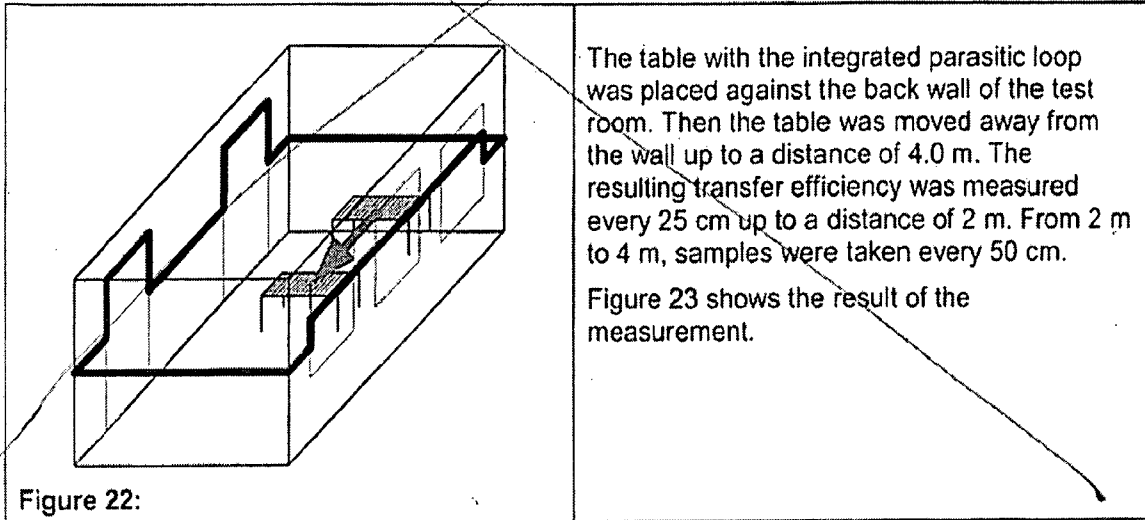
In the simulation that means to increase the K of the Mutual2 component ($K2$) and the K of the Mutual3 component ($K3$). Figure 21 shows S_{21} if $K2 = 0.9$ and $K3 = 0.6$. The inter-antenna coupling was adjusted to 0.04. The loss is reduced to -1.04 dB, compared to more than 10 dB in Figure 19. This example shows that it is possible to optimize the antenna system for a nearly loss less power transfer, if the antennas are closely coupled.

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8.1 Room antenna to moving parasitic antenna

The transfer efficiency between the long range room antenna and the parasitic antenna integrated in a table was measured. Figure 22 shows the setup.



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8.2 Room antenna to fixed receiver on moving parasitic antenna

The transfer efficiency between the long range room antenna and the receiver antenna placed on the table (with integrated parasitic antenna) was measured. The receiver remained in the centre of the table, while the table was moved. Figure 25 shows the setup.

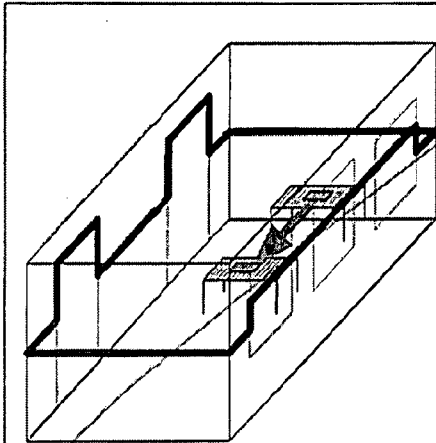


Figure 24:

The receiver antenna was placed in the center of the table and the table with the integrated parasitic antenna was placed against the back wall of the test room. Then the table was moved away from the wall up to a distance of 4.0 m. The resulting transfer efficiency between the room antenna and the receiver antenna was measured every 25 cm up to a distance of 2 m. From 2 m to 4 m, samples were taken every 50 cm. During this measurement the parasitic antenna was unloaded at its output port.

Figure 25 shows the result of the measurement.

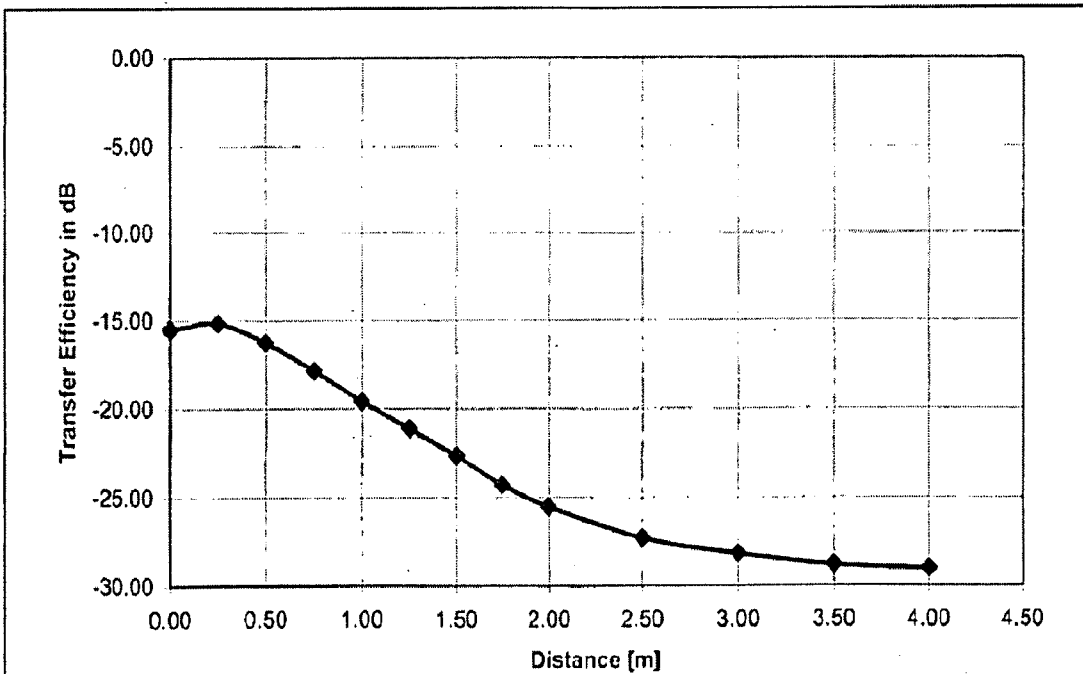


Figure 25: Double hop transfer efficiency measured between the long range room antenna input and the output of the small receiver antenna placed on the table integrating a parasitic loop

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2008/084767**A. CLASSIFICATION OF SUBJECT MATTER***H01Q 3/26(2006.01)i, H01Q 3/28(2006.01)i, H01Q 3/34(2006.01)i, H01Q 3/24(2006.01)i*

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 8 H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean Utility models and applications for utility models since 1975
Japanese Utility models and applications for utility models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal)

"Keywords: antenna, magnetic field, loop, parasitic, non-feed, Litz wire, matching, variable capacitor"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A		5, 6, 11~13, 23~25, 34, 35, 40, 41, 49, 50, 53
Y A	JP 05183318 A (CASIO COMPUT CO LTD) 23 JULY 1993 See the abstract; figures 1, 2; paragraphs 11~15; and claim 1	2~4, 7~10, 14, 16~18, 20~22, 26~33, 36~39, 42~45, 48, 51, 52
A		1, 5, 6, 11~13, 15, 19, 23~25, 34, 35, 40, 41, 46, 47, 49, 50, 53
Y A	US 20060038730 A1 (PARSCHE, FRANCIS EUGENE) 23 FEBRUARY 2006 See the abstract; figures 3~5; paragraphs 18~34; and claims 1~5	3, 4, 17, 18, 27~33, 36, 38, 48
A		1, 2, 5~16, 19~26, 34, 35, 37, 39~47, 49~53

 Further documents are listed in the continuation of Box C. See patent family annex.

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Date of the actual completion of the international search

31 JULY 2009 (31.07.2009)

Date of mailing of the international search report

03 AUGUST 2009 (03.08.2009)

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Telephone No. 82-42-481-8357



INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2008/084767

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

International application No.

PCT/US2008/084767

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