Wireless Power and Network Synchronisation for Agricultural and Industrial Remote Sensors using Low Voltage CMOS Harvesting and Data Demodulator IC

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Abstract—**This paper presents a wide area medium frequency loosely coupled magnetic energy harvesting system with power delivery and network synchronisation for remote sensors, intended for agricultural and industrial environments. Intended for situations with poor service access, power is supplied from a source via a large area loop. Receiver nodes may use ferrite cored coils for good efficiency with modest volume. Transmission of low bandwidth network synchronisation data permits very low operational duty cycle with the need for real time clocks or wake up receivers and their associated power drain. As a key enabler for the system, a full custom energy harvester and QPSK data demodulator IC has been designed and fabricated in a commercial 180nm CMOS technology. The IC occupies 0.54mm2 and can deliver 10.3µW at 3V to an external battery or capacitor. With standard MOS device thresholds the rectifier can start from cold with only 250mV peak from the antenna loop, and the battery charge output is delivered with 330mV peak input. Results are presented from laboratory evaluation and from preliminary measurements in the field with a 10m x 10m loop driven at 800kHz.**

I. INTRODUCTION

Remote sensor networks are becoming well established with the availability of very low power IC technology. For many applications, a simple battery remains the most sensible choice of power and service lifetimes of several years are common. Where access for maintenance is restricted, energy harvesting or scavenging systems have become popular allowing indefinite operation. Photovoltaic cells are a common and very successful source provided that adequate illumination is available [1]. In some industrial environments, periodic vibration from machinery can be used successfully [2].

For agricultural and industrial applications power can be obtained by a variety of methods depending on the specific circumstances. Where photovoltaic generation is not practical, wireless power becomes attractive. Rather than attempt to recover adequate power from an ill-defined ambient electromagnetic environment at some high frequency, we investigate supplying power in the near field via very weak magnetic coupling from a medium frequency source using a large-area loop. In this frequency range a ferrite-cored loop receiver antenna may be used to increase effective area and ensure acceptably small volume. The use of a lower-frequency source also reduces problems associated with localised signal attenuation due to walls etc., making deployment in less well-defined environments easier. The current in the transmitting loop is not considered a significant issue for the applications envisaged provided that current levels are not impractical and that the power required for the source does not exceed the limits of a single-phase AC mains outlet. A further benefit of supplying the power from a known source is that management and control data may be transmitted without a significant bandwidth penalty. Supplying timing information to a number of deployed sensor nodes provides the opportunity to operate at very low duty cycle ratios without the need for a real-time clock or a wake-up receiver, eliminating the disproportionate power of such functions. To achieve workable operating range in a physically small unit, the receiver power recovery circuits must be able to cold start with the lowest possible voltage and hence the weakest magnetic field in a given operation area. Rather than focus on power transfer efficiency, we instead direct our effort to ensuring that the receiver can start from an unpowered ("cold start") condition with the minimum voltage at the antenna coil. The main effort of this work is hence directed at demonstrating the feasibility of an IC that performs the functions of rectifier, data demodulator and power management.

We first describe the overall architecture for the proposed system, and then the requirements for the receiver IC. We then present some aspects of the circuit design and show measured results from laboratory and field experiments.

II. SYSTEM ARCHITECTURE

A. Wide-Area MF Loosely-Coupled Magnetic Power Transfer

Much research has been directed into harvesting or scavenging power from electromagnetic sources. In the main, these works have looked at extracting energy from the ambient conditions in the UHF and low microwave regions from cellular and wireless LAN transmissions [3]. At these frequencies, a physically small antenna can easily be of the order of a wavelength and thus achieve good efficiency. Whilst potentially attractive from the user's perspective, there are some

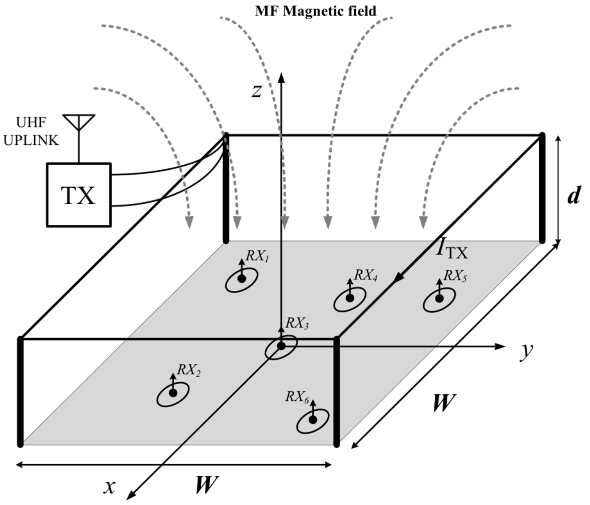

Figure 1. Wide area MF magnetic loosely coupled energy harvesting.

drawbacks. If the source is an RF service intended for another purpose, the field strength at the intended location may vary considerably. Propagation is also restricted to essentially line of sight or with only insubstantial obstructions for the sensor antenna locations.

In this work, we seek to address the needs of applications where sensors may need to be deployed within a defined area but may be sited where direct illumination is not available, or behind or below some barrier substantially opaque at UHF and microwave frequencies. Industrial and agricultural sites may pose such challenges, but the site may well be suited to providing a dedicated RF source. Fig. 1 shows an example of a wide area MF magnetic, loosely-coupled, energy-harvesting system. A dedicated magnetic field is created by a large loop antenna that may be fixed at or near the boundary of the operational site. The power for the MF current source can be from AC mains or other large fixed supply, and is consistent with typical small industrial equipment.

The sensors, represented by several secondary coils, harvest the available energy within the transmitter loop. Air cored receive coils may be used, but the use of ferrite cores can reduce the physical size of a practical receiver to a few cm^3. The requirement for the magnetic system is to provide enough voltage at the receiver coil terminals to activate the harvesting electronics. For this system, 250mV was set as the target antenna voltage for a cold start.

Figure 2 shows a plot of the field created by an example configuration of a 10m x 10m loop (as used in practical measurements). It can be seen that the magnetic field is relatively constant within the loop, and decays rapidly outside its perimeter [4], making interference with other spectrum users unlikely.

Note that while the regulatory framework in many territories does not currently permit such proposed systems, some territories are permitting experimental work, and it is likely that the declining use of MF broadcasting will make narrow band non-radiating systems more likely elsewhere.

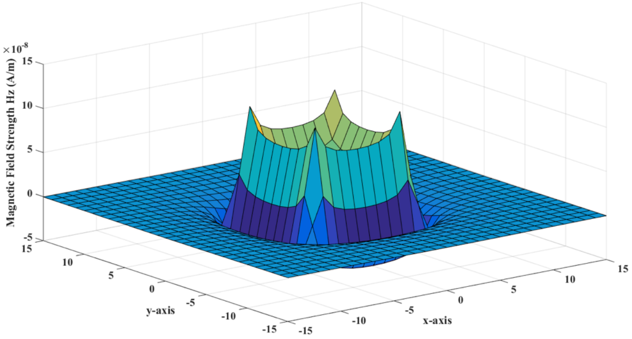

Figure 2. Calculated magnetic field pattern for a 10mx10m square transmit antenna loop.

B. Synchronisation Protocol

Almost all remote sensors are configured to operate with a low active duty cycle, as this enables very significant average power savings when data collection is only needed at a very slow sample rate. The calculation of the average power consumption of the smart sensor can be done by using equation (1). P is the average power consumption; P_n is the power consumption of the module; t_n is the active time of the module per period and t_T is the total time period.

$$P = \frac{P_1 t_1 + P_2 t_2 + P_3 t_3 + \ldots.}{t_T} \qquad (1)$$

For example; a smart sensor collects data once every hour. The sensor module requires a receiver, a sensing transducer and an uplink transmitter (typically UHF) where the power consumption and the active time of the modules are shown in table 1. By using equation (1), the average power consumption of the smart sensor is 0.24μW.

Problems arise when the duty cycle is made very low in terms of guaranteeing that a data burst sent from a node is received reliably by the controller. If the timing is not accurate, the controller itself may be in a sleep mode, or there may be a collision between data bursts from two or more remote nodes. Conventional means to control synchronization employ high accuracy real-time clock circuits, or wake-up receivers that monitor a similar frequency to the uplink. In both cases, some significant power drain is associated with the circuits that are always on, making further demands on the energy harvesting and limiting the available energy for the data acquisition.

In the proposed system, we use the MF power transfer system to carry a low-speed data channel, conveying basic system management and timing information. In this way any receiver

Table 1. Representative relative power consumption of typical components in a remote sensor.

Module	Current supply	Voltage supply	Power consumption	Active time (per hour)	Energy consumption (per hour)
Sensor node	350μA	3V	1.05mW	130.2ms	136.71μJ
Transmitter	10.5mA	3V	31.5mW	4ms	126μJ
Microcontroller	365μA (Active) 11nA (Idle)	3V	1.095mW (Active) 99nW (Idle)	200ms	219μJ (Active) 356.4μJ (Idle)

nodes within the loop can maintain precise synchronisation and avoid data collisions with the small power overhead needed for a low-rate demodulator function.

Figure 3 illustrates the flow chart of a possible synchronisation protocol for the system. Initially, the sensors harvest the magnetic energy from the primary source. When the receiver is ready to operate, an acknowledge command is transmitted to the source and the initialisation of the system is complete. In normal operating mode, the sensors are only active when they receive the *wake-up* command from the transmitter. The receiver can consume less power as it operates with a very low duty cycle without timing problems.

III. RECEIVER ARCHITECTURE

Figure 4 shows the block diagram of the complete harvester/receiver IC, as implemented in CMOS technology. Critical to the operation of the whole IC is the active AC-DC rectifier block, as its performance sets the lower operating voltage limit, and hence the range or size of transmit loop.

As the receiver loop coil is relatively small compared with the size of the transmitter loop, hence a ferrite material is used to increase the permeability of the loop coil [5]. The induced voltage received from the ferrite rod can be magnified by employing a parallel capacitor to form a high Q factor resonant circuit.

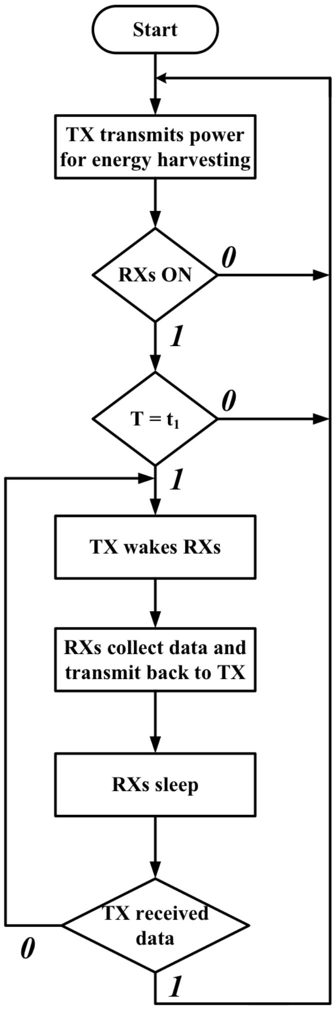

Figure 3. Example of synchronization protocol for network.

A rectifier circuit is used to convert the incoming AC voltage to DC supply. The received voltage in the intended application might be very small since the coupling coefficient is very poor. Thus, a very low start-up voltage of the rectifier is more important than the power conversion efficiency (PCE), and hence impedance matching the antenna to the rectifier in its cold state is not desirable. Implementing a rectifier in standard CMOS presents problems since the transistors will not turn on significantly until the threshold voltage is reached, typically around 0.4V – 0.5V for common processes. This threshold may be avoided by using a costly non-standard IC process with devices such as Schottky diodes [6] or near zero threshold voltage transistors [7]. To avoid the associated cost and difficulty obtaining such a special process, we use internal circuitry to cancel most of the MOS threshold apparent in the rectifier, as shown in figure 5. Using such techniques, simulations show, the circuit can start from cold with an input much less than the MOS threshold, in this case at about 250mV peak.

Once the rectifier starts, its inherent doubling function gives an output VRECT at nearly twice the input. When this reaches around 600mV the power management functions are also able to operate, and a DC-DC charge pump raises the recovered power to a level suitable for slowly charging an external lithium-ion battery or other load. In a complete sensor-node application, this would typically include a low power microcontroller and a VHF/UHF transmitter as well as the sensor transducer itself.

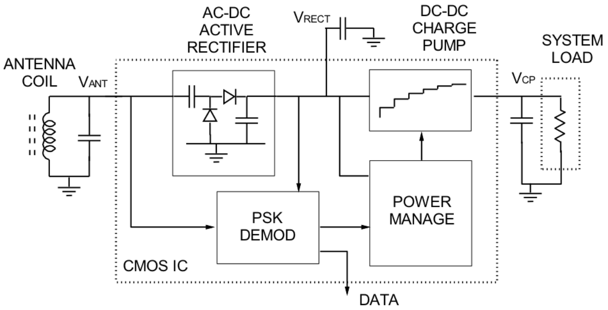

Figure 4. Block diagram of the MF harvester/receiver IC.

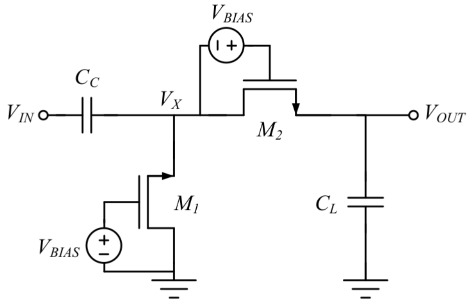

Figure 5. Active rectifier concept to reduce impact of MOS threshold voltage.

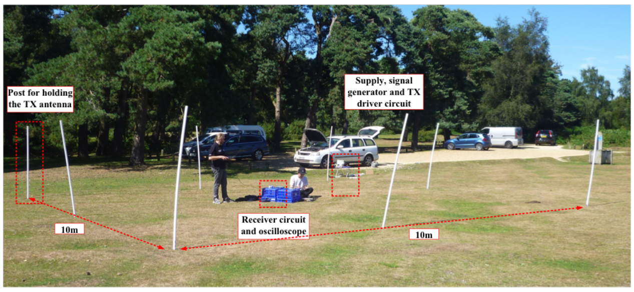

Figure. 6. Measurement setup of the wide area MF magnetic loosely coupled energy harvesting.

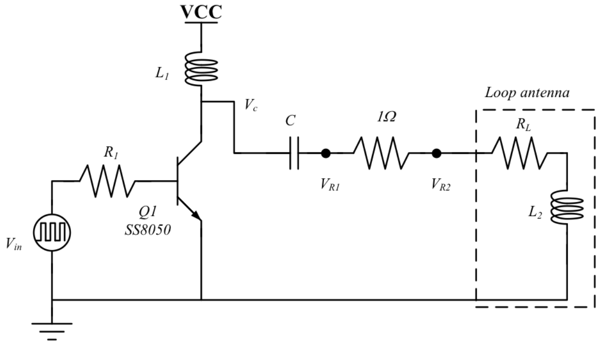

Figure. 7. Transmitter loop driver circuit.

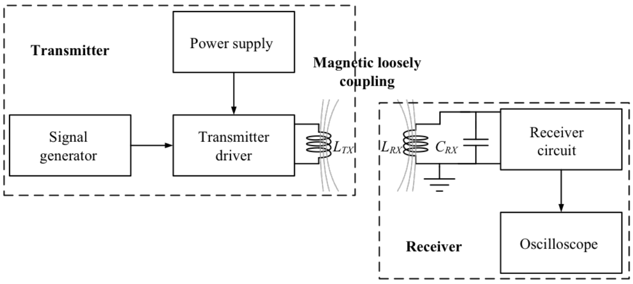

Figure. 8. Testing setup for the magnetic loosely coupled energy harvesting measurement.

TABLE 2 MEASURED HARVESTED SIGNALS IN THE RECEIVER IC

Position (m)		Received voltage (mV_{peak})	V_{RECT} (mV)	V_{CP} (V)	DC output power (uW)
x	*Y*				
4	-4	278	914	2.64	0.697
0	-4	246	860	-	-
0	0	209	805	-	-
2.5	2.5	227	900	-	-
-2.5	4	241	754	-	-
-2.5	-2.5	231	910	-	-
-4	-4	264	915	0.915	0.084
-4.5	-4.5	337	915	3.2	1.024

TABLE 3 MEASURED HARVESTED ENERGY OF THE RECEIVER IC AT CENTRE OF THE TRANSMITTING COIL WITH DIFFERENT TRANSMITTER COIL CURRENTS

Transmitter current (mA_{RMS})	Received voltage (mV_{peak})	V_{RECT} (mV)	V_{CP} (V)	DC output power (uW)
220	209	805	-	-
230	239	0.77	0.343	0.012
570	280	928	2.709	0.734

IV. MEASUREMENT RESULTS

In addition to conventional lab measurements the IC was tested with a large area loop in an electrically quiet external environment. A square loop antenna with 10x10m^2 was constructed to provide a dedicated magnetic field for the energy harvesting system operating at ~800kHz as can be seen in figure 6. The loop was implemented using copper wire with a resistance of 0.57Ω/m is attached to the top of non-magnetic poles 2m above ground level (as might be constructed using fencing structures). The calculated inductance of the transmitting antenna is 90µH while the resonance capacitance is 413pF. Figure 7 illustrates the transmitter driver circuit implemented using the bipolar junction transistor SS8050 for the switching active device. The block diagram of the testing setup is shown in figure 8. The driver circuit is supplied from a bench power supply while the input switching signal is generated from a function generator. The receiver antenna is implemented using a 4cm x 1cm diameter ferrite rod antenna with the resonant capacitor. The loss resistance of the coil is 0.83Ω while the loop coil inductance and resonant capacitance are 53µH and 700pF respectively. The measured in circuit Q-factor of the receiving antenna was 33. The receiver was tested at different positions within the square loop antenna where the vertical distance between the coils is approximately 0m.
Table 2 shows the measured harvested power of the receiver IC in a grid where the origin (x = 0m, y = 0m) is at the centre of the square loop. The measured transmitting current generated from the driver circuit is at 220 mA_{RMS}. The receiver IC achieves 1.024µW maximum output power at 3.2V when the receiving coil is located close to the corner of the square loop antenna. Table 3 shows the measured harvested energy of the receiver IC at the center of the transmitting coil (x = 0m, y = 0m) when the transmitter current is varied. The results indicate that the received energy can be increased to usable levels and all the subsystems made functional by increasing the output current of the driver circuit.

V. CONCLUSION

A wide area magnetic loosely coupled energy harvesting system has been presented, incorporating a dedicated localised wireless power source. An embedded data channel for management and synchronization open the way for operation at very low active duty cycles with attendant average power savings. The key component for the system, the low-power harvester/receiver, has been implemented in a full custom CMOS integrated circuit. The IC has been shown to start from cold with as little as 250mV at the antenna coil terminals and with slightly larger inputs all of the internal functions are active. The measurement of the harvesting energy using the wireless energy harvesting IC shows the maximum output power of 1.024μW at 3.2V. Measurements in an exterior setting confirm that the system can operate with practical transmit and receive power levels.

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