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Soil Scouts: Description and performance of single hop wireless underground sensor nodes

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ABSTRACT

Soil Scouts are palm-size wireless underground sensor nodes for monitoring of agriculture soil parameters. The system design is guided by two main criterions: (i) the data packets from underground sensor nodes must be received from up to 1 km away and (ii) the maintenance free underground sensor nodes must be capable of operating for a decade. System solutions are discussed compared to technical restraints and topology issues. Underground sensor nodes communicating with each other would require an excessive density of devices to overcome the range requirement and multi-hop routing would make the energy conservation requirement hard to achieve. This is why the single-hop approach is chosen. 11 Soil Scout prototypes are installed in a heavy clay soil, where up to 236 m distances and -110 dB calculated path losses are overcome with a directive 60° receiving antenna. A reference Soil Scout is installed in a sandy soil, where the 300 m distance is managed uninterruptedly with an omnidirectional receiving antenna. Battery voltage decline for the nodes as well as for previous Soil Scout designs are presented and observed to decline for 18 months and then obtain a sustaining annual temperature dependent fluctuation.

1. Introduction

Soil Scouts [1] are buried wireless underground sensor nodes for real time monitoring of agriculture soil parameters to serve agronomic information gathering and production decision making. Compared to conventional wired sensors with data loggers or to numerous wireless on-soil node designs, wireless devices are easy to install, they do not hinder agricultural soil operations and they produce representative data because the surrounding soil remains undisturbed for several years. The aim of the work was to enable a single hop kilometre-scale data transfer link for data collected by an underground node, which is capable of service-free operation for a decade.

A model for calculating the attenuation of a radio link from underground (UG) to above ground (AG) was developed and validated by case measurements [1,2]. The attenuating phenomena of angular defocusing caused by refraction in the soil–air interface was introduced and verified. The first prototypes of Soil Scouts v1 were installed in 2006 and their data transfer performance reported [3]. A wide-band underground printed circuit monopole antenna was developed to provide Soil Scouts an underground single-ended monopole antenna (USEMA). It is capable of staying tuned despite the soil water content will alter a radio wave length in soil through changing the complex dielectricity of the media [4]. Some of these v1 devices were serviced and reprogrammed in 2009 and are still operating in January 2012 with minimal battery voltage loss so far.

This paper describes the technological choices that were made while designing the second generation of prototypes – the Soil Scout v2 – in order to increase transmission range and further reduce battery consumption. In 2010 two devices were installed in a sandy loam soil, while the main group of 11 devices was installed in a heavy clay

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soil, where MTT Agrifood Research Finland is conducting a nutrient runoff trial.

2. Soil Scout instrumentation and topology compared to related work

The challenges for a Wireless Underground Sensor Network (WUSN) have been discussed [5]. The main challenges concern power management and connectivity, as commonly in wireless sensor networks (WSNs), but the solutions in the complicated underground radio environment differ from terrestrial wireless sensor networks [8]. Intensive work has been devoted to evaluate communication in the cases of underground-to-aboveground link UG–AG, UG–UG and AG–UG. Both stationary and mobile network elements have been considered. Since Soil Scouts only communicate with an AG base station, no actual network is comprised and the devices are referred to as wireless underground sensor nodes (WUS) instead of the proposed abbreviation WUSN.

The UG–UG channel was eliminated for reasons related to both hardware restrictions and network topology, which are discussed in detail in the next subsections. Soil Scout development has been focused towards a system, which can monitor a whole agriculture field without any on-soil in-field instruments. In order to achieve adequate sensor coverage this means that data from a sensor node must travel several hundreds of meters to reach the field boundary.

Soil Scouts (Fig. 1) employ the European license free 869.4 MHz ISM-band at +26 dBm (decibel of mW) transmitting power. The antenna is an advanced omnidirectional USEMA, which is diminished in size and improved in mechanical durability compared to the previously reported design [4]. The system is built around a single-chip transceiver micro controller [6]. The measurement and transmission duty cycle is 55 min and the device is powered by a 2500 mAh 3 V lithium battery [7]. During the 400 ms sensing and processing phase the current varies between 0.05 and 32 mA and adds up to 26 nAh per cycle. The time on air for the 11-byte GFSK modulated packet is 2.6 ms, during which 0.5 A current is drawn resulting in

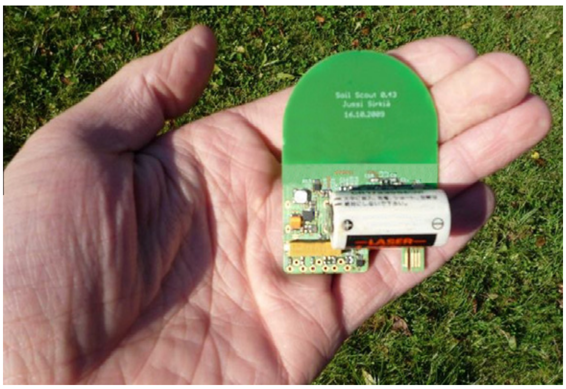

Fig. 1. Soil Scout v2 prototype with size $48 \times 68 \times 20$ mm without moisture sensors. Foto: J. Tiusanen.

4 μAh per transmission. In sleep state the node draws 2.5 μA for 55 min, resulting in 2.3 μAh per cycle.

The mean current 6.9 μA and battery capacity 2500 mAh results in a theoretical life time of 42 years, but in practice the span is limited by battery internal discharge characteristics. However, the battery is guaranteed a 10-year life span at 30 μA discharge current, which is four times higher compared to the Soil Scout consumption.

The sensing subsystem consists of a 12-bit ADC, three commercially available EC-5 sensors [9] and a digital temperature sensor [10]. The sensors and the radio amplifier are powered by a fixed 3.3 V independently from battery voltage.

A few observations concerning the old version Soil Scout v1 must be clarified. In the Soil Scout v1 the radio amplifier was powered directly from the lithium battery once every 10 min. The current peak achieved 32 mA while the battery's nominal discharge current was only 1 mA. This current pulse was excessive enough to damage the battery's internal characteristics, which led the battery voltage not to recover up to 3 V before a new transmission cycle. This caused a premature battery failure in only 2 years. A few Soil Scouts v1 were reprogrammed and assigned a 1 h duty cycle, which resolved the battery damage issue but the high pulse current still caused low battery discharge efficiency. This is why the high 400 mA pulse current for the Soil Scout v2 power amplifier was arranged in a more sophisticated manner and the direct battery current limited below the maximum allowed continuous discharge current. Table 1 presents the technical performance differences of the two designs for comparison. The performance of the v1 design has been reported [3].

2.1. Underground–Underground link evaluation

The radio wave interaction with soil medium is a complicated phenomenon and guides the radio topology options in many ways, of which the choice of radio frequency has most considerable consequences. In general, both the real and the imaginary part of soil permittivity decrease with increasing frequency at least up till 10 GHz [12]. However, because frequency is a factor of soil attenuation coefficient, lower frequencies will suffer from less attenuation caused by the soil medium. In addition, availability and performance of radio transceiver components in the license free ISM-bands must be observed, since Soil Scouts are not a theoretical scheme but actual devices manufactured for agriculture field property monitoring.

All this adds up to the difficult choice between the licence free 433 MHz and 869/915 MHz (Region 1, including Europe/Region 2, including US) bands. In the case of Soil Scouts, the size of the developed underground single-ended monopole antenna (USEMA) [4] lead to the choice of the higher band. A device for 433 MHz would have become larger than 150 mm, which was unacceptable since installation of Soil Scouts in the ploughing layer will be allowed and thus the devices must withstand soil tillage.

Soil Scout development was given the goal of allowing a 1 km data transfer range. The communication range of an UG–UG radio wave device pair at 10 dBm radio power in the 900 MHz frequency range is in general limited to less