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Evaluation of the ZigBee based wireless soil moisture sensor network SoilNet

H.R. Bogena[1], J.A. Huisman, U. Rosenbaum, A. Weuthen & H. Vereecken

Introduction

A remaining challenge in hydrology is to explain the observed patterns of hydrological behaviour over multiple space-time scales as a result of interacting environmental factors. The large spatial and temporal variability of soil water content is determined by factors like atmospheric forcing, topography, soil properties and vegetation, which interact in a complex nonlinear way (e.g. Western et al., 2004).

A promising new technology for environmental monitoring is the wireless sensor network (Cardell-Oliver et al., 2005). The wireless sensor network technology allows the real-time soil water content monitoring at high spatial and temporal resolution for observing hydrological processes in small water-sheds (0.1-80 km²). Although wireless sensor networks can still be considered as an emerging research field, the supporting communication technology for low cost, low power wireless networks has matured greatly in the past decade (Robinson et al., 2008). Wireless environmental sensor networks will play an important role in the emerging terrestrial environmental observatories (Bogena et al., 2006), since they are able to bridge the gap between local (e.g. lysimeter) and regional scale measurements (e.g. remote sensing).

This paper presents a first application of the novel wireless soil water content network SoilNet, which was developed at the Forschungszentrum Jülich using the new low-cost ZigBee radio network.

The SoilNet technology

SoilNet is a wireless soil water content sensor network that was developed at the Forschungszentrum Jülich using the new low-cost ZigBee radio network. ZigBee is a suite of high level communication protocols that uses small, low-power digital radios based on the IEEE 802.15.4 standard for wireless personal area networks. The data communication rate is reduced compared to a WLAN (250 Kbit/s instead of 54 Mbit/s), and is thus especially suited for intermittent data transfer like wireless network applications. The kernel of the communication hardware is the ZigBee compliant high power wireless module JN5139 by Jennic Ltd, South Yorkshire, UK (Jennic Ltd., 2007).

Within SoilNet (or any other wireless network based on the ZigBee protocol), there are three device types. The ZigBee coordinator is the top of the network tree. It stores information about the network and it can provide a link to other networks. Each network only has a single coordinator. An important task of the coordinator is to initiate the wireless links within the network. The second type of device is the ZigBee Router, which acts as an intermediate station that passes data from other devices. The third type of device is the ZigBee end device, which should have just enough functionality to communicate with its parent node (either the coordinator or a router). This allows the node to be asleep a significant amount of the time in order to save energy.

SoilNet belongs to the group of Wireless Underground Sensor Networks (WUSN). A comprehensive review of this network type can be found in Akyildiz and Stunte-

[1]Agrosphere Institute, ICG-4, Forschungszentrum Jülich GmbH
52425 Jülich, Germany.
E-mail: h.bogena@fz-juelich.de

beck (2006). They suggest two possible topologies for WUSNs: the underground topology and the hybrid topology. In the underground topology, all sensor devices are deployed underground, expect for the ZigBee coordinator. In SoilNet, a hybrid topology was selected to achieve larger trans-mission ranges. The hybrid topology is composed of a mixture of underground end devices each wired to several soil sensors and aboveground router devices as shown in Figure 1.

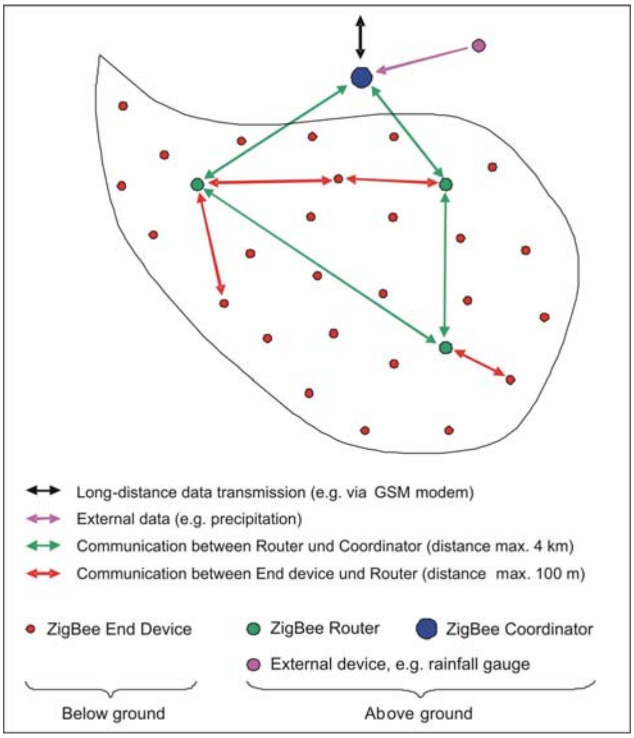

Figure 1. The reactive hybrid WUSN ZigBee topology of SoilNet exemplified for a virtual catchment area.

This configuration allows data to be routed out of the underground in a few steps, thus reducing the amount of power intensive underground steps to save power. Principally, an underground end device can communicate with all router devices within the hybrid topology, but effectively it will only use the nearest routers because these will have the highest signal strength.

Soil water content sensors

A wireless sensor network may consist of hundreds of sensors. There are several factors that have to be considered when selecting a sensor for network applications. In order to maximise the lifetime of a sensor network, the sensors have to be very economic concerning energy demand and should be reasonably robust. Because of the multitude of measurements within the sensor network, the interpretation of the sensor signal has to be straightforward and unambiguous. Last but not least, in order to maximise the number of sensor nodes, the sensors have to be as inexpensive as possible. Since capacitance sensors are relatively inexpensive and easy to operate, they seem to be a promising choice for soil water content measurements with sensor networks.

The capacitance method is a widely used electromagnetic (EM) technique for soil water content estimation (Blonquist et al., 2005). Bogena et al. (2007) evaluated the low-cost capacitance sensor ECH2O EC-5 (Decagon Devices Inc) and came to the conclusion that this sensor is appropriate for sensor network applications. The cognitional ECH2O-TE sensor (Decagon Devices Inc) allows in addition to soil water content also the monitoring of solute concentration and temperature. The ECH2O-TE sensor was recently evaluated by Kizito et al. (2008).

Field experiment

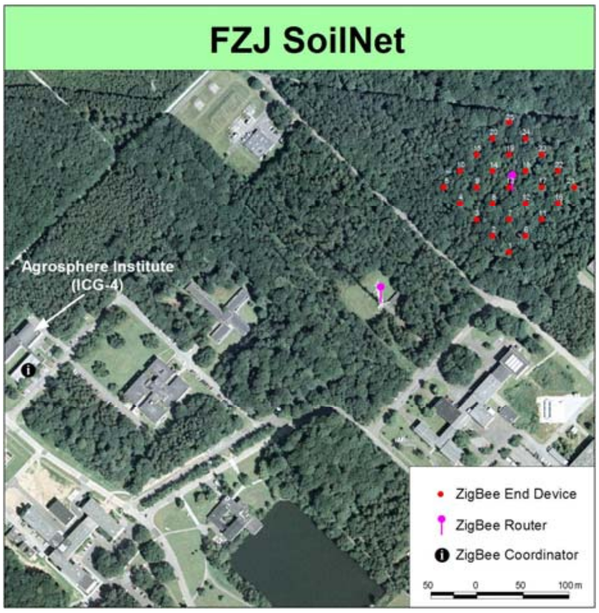

Figure 2. The SoilNet test network at the Forschungszentrum Jülich.

We tested the SoilNet wireless network technology on a 100 by 100 meter forest plot site located on the premises of the

Forschungszentrum Jülich equipped with 25 end devices each consisting of 6 vertically arranged soil water content sensors (4 EC-5 and 2 TE ECH2O probes).

Figure 3 shows the SoilNet end device as well as the installation depths of the EC-5 and TE soil water content sensors (5, 20 and 60 cm).

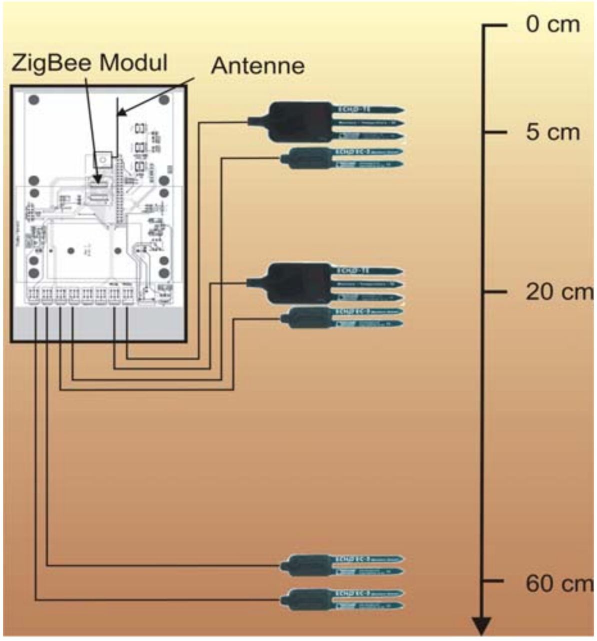

Figure 3. The SoilNet end device and the configuration of EC-5 and TE sensors.

For each depth, two sensors were installed to enable the examination of inconsistencies (e.g. imperfect contact of sensors to the soil matrix).

The reference soil of the test site is classified as a Stagnic Luvisol. The soil texture of the investigated topsoil is loamy silt. Depth dependent porosities and saturated hydraulic conductivities of the reference soil are presented in Table 1.

Tab. 1: Soil properties of the reference soil of the test field.

Depth of soil horizon [m]	Porosity [-]	Hydraulic conductivity [cm d^{-1}]
0 – 0.1	0.63	124.93
0.1 – 0.5	0.45	67.04
0.5 – 1	0.43	3.16
1 – 2	0.33	22.6

Figure 4 presents soil water content time series measured every quarter of an hour with the EC-5 sensors installed in 5, 20 and 60 cm depth as well as precipitation during the period from 28th of February to 13th of May 2008. Soil water content was obtained according to Bogena et al., 2007.

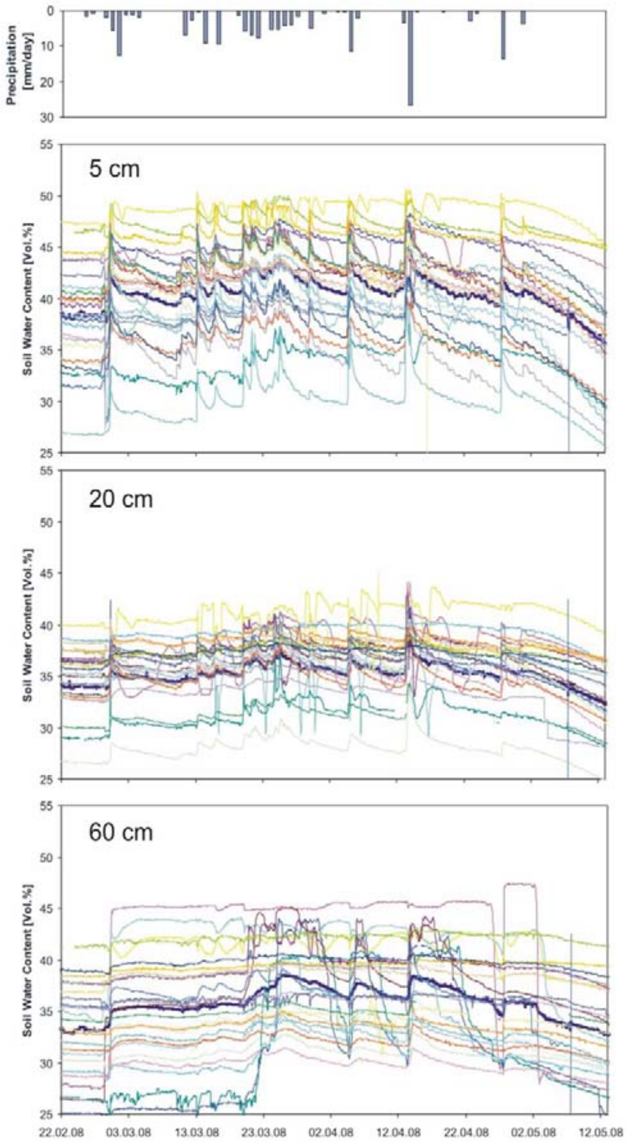

Figure 4. Rainfall intensity and volumetric soil water content obtained from 100 EC-5 and 50 TE sensors installed in 5, 20 and 60 cm depth of the SoilNet test network as well the mean value.

Figure 4 shows that the spatial variability (mean standard deviation (std) of all mean values: 4.4 Vol.%) of measured soil water content in 5 cm depth is higher than the temporal variability (mean std: 2.9 Vol.%), which is mainly caused by the spatial heterogeneity of the test site. The spatial heterogeneity originates from the significant variability of the soil properties of the test site. For example, the porosity of the top soil ranges between 45 and

70 % (n = 50). Furthermore, the influence of the highly heterogeneous litter layer has to be considered. Since a forest canopy was not developed during most time of the measurement period, spatial variation of interception plays a minor role.

Several EC-5 sensors in 60 cm are showing sharp an increase in soil water content due to groundwater rise. The depth to groundwater increases from south to north which is reflected by the different responses of the EC-5 and TE sensors due to groundwater rise.

It has to be noted that contact problems between the sensor rods and the soil matrix may present in the case of higher contents of coarse fragments. Due to the low measurement volume of the EC-5 and TE sensors this may have resulted in an underestimation of soil water content measurements in some cases.

Conclusions

The field evaluation of the SoilNet wireless sensor network has led us to the following conclusions:

- The hybrid underground topology is well suited for wireless soil moisture network applications;
- A field evaluation showed the robustness of the ZigBee radio network;
- The large variability in the soil moisture measurements is mainly attributed to the large heterogeneity of the test site.
- The low measurement volume of the EC-5 and TE sensors may lead to underestimations of the soil water content since higher contents of coarse fragments may produce contact problems between sensor rods and soil matrix.

This paper has shown the principle applicability of the SoilNet wireless sensor network. Future work will focus on the problem of upscaling of point measurements to larger scales (e.g. using SoilNet data for the validation of remote sensing based soil water content estimations or distributed hydrologic model results).

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