Towards Precision Agriculture: Building a Soil Wetness Multi-Hop WSN from First Principles

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***Abstract*—This work presents the design and implementation of a wireless sensor network (WSN) *from first principles*, i.e. without the use of commercial WSN platforms. Specifically, a modular multi-hop WSN was built for humidity, temperature and soil wetness measurements, towards precision agriculture applications. We describe the modules developed for radio communication, low-cost sensing, relaying and storing, and compare the developed hardware with state-of-the-art WSN transceivers and sensors. Furthermore, we briefly describe an outdoor demonstration of the developed, multi-hop, soil wetness WSN. This work provides a concrete demonstration example towards precision agriculture and could potentially assist students, researchers and practitioners to develop their own customized platforms, without dependence on commercial WSN platforms.**

***Index Terms*—Low-cost wireless sensor network.**

I. Introduction

Wireless sensor networks (WSN) technology can in principle enable *precision agriculture* applications [1]; for example, WSNs could efficiently monitor the microclimate of each plant in agricultural fields and schedule irrigation only when needed, potentially offering significant water supply savings. Thus, WSN technology in precision agriculture could unquestionably offer remarkable socio-economic potential.

WSNs relevant to precision agriculture have recently appeared in the literature using commercial WSN platforms (e.g. [2]–[5]) or custom platforms that share software modules with commercial WSN products (e.g. operating system in [6]). One exception is work in [7], where a custom platform was developed for single-hop sensors talking to a base station.

In sharp contrast, this work describes the methodology to design and implement a *multi*-hop WSN, for environmental humidity, soil wetness and temperature monitoring, *from first principles*, i.e. without exploitation of existing, commercial WSN technology. Specifically, this work describes an approach to design and build wireless sensor transceiver nodes and incorporate low-cost humidity sensors; presents technical comparisons with existing WSN platforms and discusses implementation of an outdoor temperature and soil-wetness, multi-hop WSN.

Given that the diverse nature of precision agriculture has only recently started to be explored by the WSN community, it remains to be seen whether existing commercial WSNs are sufficient to accommodate a multitude of relevant applications. From that perspective, the *holistic* and low-cost design and implementation methodology of this work could potentially benefit prospective practitioners as well as researchers in precision agriculture. This work could also offer WSN researchers and/or students a concrete methodology to build and operate custom, non-commercial WSN platform alternatives.

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Fig. 1. The iCube node developed during this project for research and education activities.

Sections II describes the design of iCubes transceiver nodes and compares with commercial or academic transceivers. Section III describes the incorporation of low-cost humidity sensors and compares with commercial products. Section IV describes the outdoor custom WSN demonstration, and finally work is concluded in Section V.

II. Building the Sensor Nodes

The iCube node consists of a Chipcon/TI CC2500 radio transceiver module, interfaced to a Silabs C8051F321 microcontroller unit (MCU).

Each iCube's MCU incorporates several internal peripherals, useful for sensing applications (e.g. Analog-to-Digital and Digital-to-Analog Converters), as well as communication modules (UART, I2C, SPI and USB). The specific MCU family was preferred due to its simple 8051 architecture and well-written documentation. Thus, it was appropriate for both research and teaching/training activities.

The CC2500 transceiver operates at the 2.4 GHz band with maximum transmit power of +1 dBm, programmable rates up to 0.5 Mbps and various modulations schemes (including minimum shift keying). It was selected due to its relatively fast frequency hopping capability and low cost. The radio provides a plethora of control registers that adjust crucial digital communication parameters, such as frequency channel, transmission power, modulation type and other characteristics reported at Table I. Comparison with other radio modules, typically used in WSNs, is also provided.

Each node includes a AA-battery holder, two LEDs (for demonstration purposes) and a 25-pin connector, interfaced to the MCU pins. This connector is used to attach sensor/actuator boards or program the device. The overall cost of all required components is €42 per sensor board (for quantities of 10 nodes), including printed circuit board (PCB) fabrication and excluding soldering costs. For larger quantities, the overall cost per iCube board will be reduced.

A. Hardware Evaluation of iCubes

According to Table I, the iCube node competes with other typical WSN nodes (commercial or academic). CC2500 has the fastest, tunable rate (up to 0.5 Mbps) and supports more types of modulation, including the spectrally efficient MSK. Therefore, iCubes offers new possibilities for wireless communication and networking research. The C8051F321 and the ATmega128L MCUs are the easiest to utilize, due to their simple 8-bit architecture. Additionally, the C8051F321 incorporates up to 14 ADC channels and thus, it is ideal for data acquisition in multi-sensory prototypes.

Furthermore, each iCube node can be wirelessly programmed with a custom firmware updater/bootloader that was developed throughout the project. With such firmware, any kind of standalone application (from simple assembly to RTOS code) can be programmed wirelessly into the device. In sharp contrast, all other devices support *over-the-air-programming* (OTAP) only through complex tinyOS and nesC libraries.

In terms of energy consumption, the iCube node outperforms the ATmega128 module and is close to the iSense module; the latter packages the MCU and the radio in a single chip (System On Chip - SoC).

Finally the iCubes WSN node is relatively cheap, since it was designed, fabricated and assembled in-house.

III. Building Low-Cost/Low-Power and Precise Humidity Sensors

State-of-the-art, commercial humidity sensors for WSNs output measurement data, either in terms of varying voltage (sampled by the MCU ADC and converted to *relative humidity* (%RH)), or incorporate digital logic and output data over a digital bus (e.g. I2C). Although simple in project incorporation, these sensors are often relatively expensive and power-demanding, even though WSNs operate in low voltages and typically require minuscule power consumption. Furthermore, large-scale WSNs, as in precision agriculture, cannot afford expensive sensors.

All the above reasons motivated the development of humidity sensor modules which should be precise, relatively low power and cost less than their commercial counterparts.

The capacitor HCH-1000 by Honeywell was chosen, with a working range of 0-100%RH. Its capacitance varies linearly with the %RH. Following its application note,[1] the sensor is interfaced to a 555 timer circuit; the latter outputs voltage pulses of frequency inversely proportional to the sensor's

[1]http://sensing.honeywell.com/index.cfm?ci_id=154296

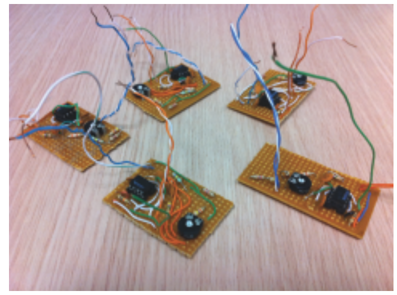


Fig. 2. Prototypes of capacitive humidity sensors developed.

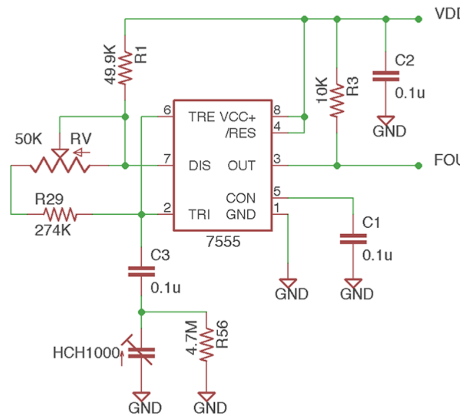
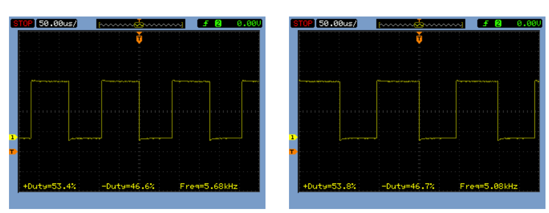


Fig. 3. Capacitive humidity sensor schematic.

capacitance and thus, inversely proportional to %RH (Fig. 4). These voltage pulses trigger an external interrupt on a MCU's general input pin, and by measuring the number of interrupts in a certain period of time, frequency data and thus, relative humidity can be calculated. The above process requires no use of the ADC, or any MCU digital peripheral (such as the SPI or I2C buses).

Unfortunately, most 555 timer circuits (e.g. the NE555N family) require a minimum operating voltage of 5 V and minimum current of 6 mA. Such figures are not suitable for low-power, battery-operated WSNs (usually operating at 3 Volts). Therefore, an ultra-low power 7555 IC built by Intersil was utilized. This timer consumes only 60 μA and has a *minimum* supply voltage of 2 V; thus, such timer device is perfectly appropriate in this context.

The iCube custom humidity sensor circuit has an overall cost of about €6, compared to commercial humidity sensors



(a) Dry environment, freq. @ 5.68 kHz. (b) Humid environment, freq. @ 5.08 kHz.

Fig. 4. Humidity sensor circuitry output, measured at the oscilloscope. Humidity is inversely proportional to frequency.

TABLE I
HARDWARE COMPARISON OF WSN NODES

Sensor Node	**iCube**	**Isense**	**Micaz**	**BTnode**
Developer	TUC Telecom Lab	Coalesenses	Crossbow	ETH
		MCU		
IC	Silabs C8051F321	Jennic JN5148	ATmega128L	ATmega128L
Speed (MHz)	1.5 - 24	4 - 32	up to 8	up to 8
Architecture	8-bit 8051	32-bit RISC	8-bit RISC	8-bit RISC
Flash/ROM (KB)	16	128	128 + 4(EEPROM)	128 + 4(EEPROM)
RAM (KB)	2.304	128	4	4
Consumption Active (mA)	0.41/MHz	0.28/MHz + 1.6	5 @ 4MHz	5 @ 4MHz
		Radio		
IC	CC2500	Jennic JN5148	CC2420	CC1000
Interface	SPI	(Single IC)	SPI	SPI
Max Data-rate (Kb/s)	500	250	250	76.8
Modulation	OOK, FSK, MSK	O-QPSK (802.15.4)	O-QPSK, MSK	FSK
Frequency Band (GHz)	2.4	2.4	2.4	0.868
RSSI/LQI	yes	yes	yes	yes
Consumption TX (mA)	10 @-22dBm, 21.2 @0dBm	15 @0.5dBm	8.5 @-25dBm, 17 @0dBm	8.6 @-20dBm, 16 @0dBm
Consumption RX (mA)	13.3@250Kb/s	17.5@250Kb/s	18.8@250Kb/s	11.8@76.8Kb/s
Consumption Idle (mA)	1.5	-	0.42	0.096
Max Transmit Power (dBm)	+1	+2.5	+0	+10
Max Sensitivity (dBm)	-104@2.4Kb/s	-95@250Kb/s	-95@250Kb/s	-110@0.6Kb/s
Sensitivity@250Kb/s (dBm)	-89	-95	-95	-96@76.8Kb/s (max rate)
		Node Capabilities		
ADC	14 channels	4 channels	8 channels	8 channels
Recommnended RTOS	Keil RTXtiny	custom	TinyOs	TinyOs
OTAP	yes (custom bootloader)	yes	yes	yes
RTOS-independent OTAP	yes (custom bootloader)	no	no	no
Batteries	2xAA	2xAA	2xAA	2xAA
		MCU+Radio Current		
CPU Sleep/Radio Off (μA)	0.1	0.1	15	15
CPU Idle/Radio Off (mA)	0.285	0.0012	4	4
Cpu@8MHz/Radio Off (mA)	3.28	3.84	10	10
Cpu@8MHz/Radio TX@250kbps (mA)	24.5 @0dBm	18.84 @0.5dBm	27 @0dBm	26 @0dBm
Cpu@8MHz/Radio RX@250kbps (mA)	16.58	21.34	28.8	21.8

TABLE II
HUMIDITY SENSORS COMPARISON

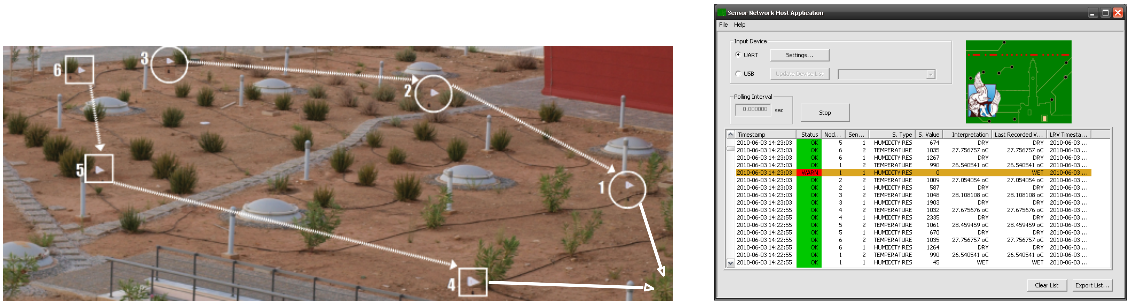
Manufacturer	iCubes	Honeywell	Honeywell	Sensirion	Sensirion	Sensirion
Model	Custom-with HCH1000	HIH3610	HIH4000	SHT1x	SHT7x	SHT21
Range ($\%RH$)	0-100	0-100	20-95	0-100	0-100	0-100
Supply Voltage (V)	2-18	4-5.8	4-5.8	5	5	2.1-3.6
Current Consumption (μA)	300	200	500	550	550	270
Accuracy ($\%RH$)	±3	±0.2	±3.5	±2 - 3	±1.8 - 3	±2
Response Time (sec)	15	15	15	4	4	8
Output Type	Voltage Pulses (var. freq.)	Voltage	Voltage	Data (2-wire)	Data (2-wire)	Data (2-wire)
Cost (€)	6	30	24	19 - 22	22 - 25.5	15

in Table II. It can be seen that the achieved cost is 2 to 4 times smaller. Additionally, the measured current consumption of overall sensor circuitry is 260 to 300μA, which outperforms most of the compared sensors; furthermore, the minimum supply voltage of 2 V is suitable for battery operation. Considering also that they are easy-to-build, the iCube custom humidity sensors are an appropriate solution for experimental or research-oriented WSNs in agriculture.

IV. DEMONSTRATION OF A MULTI-HOP WSN WITH ICUBES

A real-world WSN was developed outdoors to measure soil wetness and environmental temperature, using iCubes. Each iCube MCU incorporates an internal thermistor that readily provided temperature measurements (via the MCU's ADC).

The network was divided in disjoint subtrees (chains), where each chain utilized a unique carrier frequency. In that way, potential interference was reduced, and traded with connectivity [8]. The first chain consisted of nodes $1-3$ and the



(a) Demo Setup. (b) GUI running at the Gateway.

Fig. 5. Demonstration of the multi-hop WSN developed outdoors. Temperature and soil-wetness measurements were relayed to a Gateway personal computer (not depicted) and displayed in a custom Graphical User Interface (GUI).

second chain consisted of nodes $4-6$. Node 7 operated as the gateway (not depicted in Fig. 5-a) and was directly connected to a laptop. Each node relayed information to the next node in the chain, towards the gateway. The closest node to the gateway, switched to a common (across all chains) frequency channel and transmitted towards the gateway utilizing time-division multiple access (TDMA).

In order to address energy consumption challenges, each radio entered "idle" mode after packet transmission, while the MCU was running in *no fetching instruction* mode. The MCU exited "idle" mode when a carefully-initiated timer created an appropriate interrupt. In such multi-hop scenario, it was critical to ensure that each radio was awaken *on time*, i.e. before the previous in the chain node transmitted (otherwise, packets could be lost and chain connectivity would be compromised). Synchronized operation was ensured by carefully selecting each node's duration in "idle" mode, depending on each node's location in the chain. In other words, the implemented relaying scheme fully exploited awareness of the fixed application topology.

Wetness was measured in terms of voltage at a cheap resistive sensor, which was developed in-house for ADC testing purposes. Plastic straws, choke and metal rack hangers (for picture wall hanging) were used for the low-cost construction of these sensors. Similar inspiring sensor designs can be found in gardening pages.[2] The interconnection between each sensor and the MCU's ADC was accomplished via a voltage divider with another resistor of 2.7MOhms, fed with a reference voltage. In dry state, the sensors provided a resistance on the order of a few MOhms, while that resistance dropped one to two orders of magnitude in wet state, resulting in high and very low measured voltage respectively.

Finally, a graphical user interface (GUI) was developed to present and store acquired information from the nodes. Special attention was given to user-friendliness. The GUI software ran on a host PC, connected to the gateway iCube.

V. Conclusion

A detailed design methodology was presented that offers implementation of a multi-hop WSN, towards precision agriculture applications. Additional info can be found at http://www.telecom.tuc.gr/~aggelos/tel404_spring2010/

The network was built *from first principles*, i.e. without exploitation of existing WSN platforms. Perhaps this work could assist students, WSN researchers and precision agriculture practitioners to facilitate custom relevant applications, without relying on commercial WSN products.

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[2] e.g. see work in http://www.cheapvegetablegardener.com/2009/03/how-to-make-cheap-soil-moisture-sensor.html