Tiny and autonomous IEEE1451 Sonic Anemometer to deploy in environmental Wireless Sensor Network

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Abstract**—Wind speed and direction are important parameters in the study of applied meteorology, for example, in weather prediction, air pollution, transport safety and structural safety. In this paper, we propose the design and deployment of an interoperable Smart Ultrasonic Anemometer that uses the IEEE 1451 standard and operates in a Wireless Sensor Network (WSN). This standard permits interoperability and introduces self-calibration and self-configuration tasks. We include power management considerations to calculate the energy consumption using a low power sampling protocol BMAC with variable duty cycle. Experimental tests are included to study the current consumption using an energy harvester with solar panel and super capacitors to increase the reliability and lifetime of the sensor node.**

Index Terms**— Environmental monitoring, IEEE1451 standardization, sonic anemometer, Wireless Sensor Network (WSN).**

I. INTRODUCTION

WIND speed and direction are key factors in many situations and activities related to applied meteorology. With the maturity of Wireless Sensor Networks (WSN), today is feasible the measurements of Wind speed (WS) and Wind direction (WD) with high accuracy using small wireless smart sensor nodes in a WSN. Some early research used traditional cup anemometers and vanes. For example, in [1] researchers used a multi-tiered portable wireless system namely FireWxNet for monitoring weather conditions in rugged wildland fire environments. In this case, a fire fighter takes wind measurements using an external belt-weather kit and each hour a data report back to base camp. Other recent deployments take in account the WS and WD to monitor the high-mountain sites [2] on a rock glacier located at 2500 m, on top of the Genepy, a mountain in the Swiss Alps, using a cup anemometer to model the microclimate. At the same time, on an urban scale, CitySense [3] has shown the monitoring of air pollutants and concentrations of biochemical agents in distributed system using sensor nodes that will be directly programmable by the end user. Furthermore, WS and WD sensor nodes can be includes in the road control system networks for transport safety, or monitor railway bridges as shown in [4], and others wind measurements can be included in structural safety of large infrastructures such as bridges or buildings [5] for indirect detection of structural state through the measurement and interpretation of ambient vibrations with strong winds. The above applications may need the support of wind measurements using an external sensor node submodule that depends on the measurement method in each case. In this work, our wind small sensor node can be namely, Wireless Transducer Interface Module (WTIM) to be deployed in urban or remote area. This prototype is oriented to monitor WS and WD and make observations by monitoring the weather conditions of UPC campus located in Castelldefels, Barcelona, near sea altitude. The main requirements of WTIM node in this application are introduced in a bottom-up approach with the respective contributions. In a low level, the platform used was Telosb [6] and the requirements to measure the wind in two axes include a small external front-end submodule with no moving parts using four small ultrasonic transducers (UT). We employ an attached energy harvesting submodule with a small solar panel and super-capacitors to increase the battery life of this sensor system. In a high level, the WTIM node includes the IEEE1451 standard and employs all mandatory Transducer Electronic Datasheets (TEDS) used for self-calibration and node self-configuration. The nature of the expected wind measurements allows a small data traffic to send over air to the sink node or coordinator node, namely in this work, Network Capable Application Processor (NCAP). The quantity of data information involved in each measurement depends of the data fidelity requirement. We have chosen a duty cycle of 1 % and 6 % to monitor WS and WD and sending immediately the information to a sink node in a practical node deployment. Weather monitoring involves just 46 bytes to send to a NCAP using a duty cycle of 1%. In this case some wind measurements are lost because the node is not continuously active but this application doesn't use high data fidelity requirements unlike others applications for example volcano monitoring [7].

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II. ESTIMATING WIND SPEED AND WIND DIRECTION

Table I summarizes the types of anemometers commonly used to measure wind speed and direction in micro-scale and others instruments used in atmospheric research to achieve meso and macro layers of the atmosphere. With sonic anemometers WS and WD are calculated by propagation of sound velocity of moving air mass in the atmosphere. Typically, this method

TABLE I. METHODS COMMONLY USED TO MEASURE WIND SPEED AND DIRECTION

Sensor	Starting Threshold [m/s]	[1]constant (m)	[2]ratio	accuracy	resolution	Range	Temp [ºC]	Output type
010C Cup WD Met One	0.22	1.524	--	±1% or 0.0671m/s	0.1m/s	60m/s	-50 to 65	pulse
020C Vane WS Met One	0.22	0.91	0.6	±3 deg	1 deg	357°	-50 to 65	DC voltage
WindSonic Gill	0.0	--	--	*V*: ±2% θ: ±2 deg	0.01m/s 1 deg	60m/s	-35 to 70	Analog / Digital
Propeller 05103-L Campbell	1.0	2.7	0.3	*V*: 0.3m/s θ: ±3 deg	--	100m/s 355°	-50 to 50	AC voltage
Flat Array Sodar Scintec	< 1	--	--	*V*: 0.03 - 0.1 m/s θ: 2 - 3°	--	50 m/s 360°	-35 to 50	Digital

1. The distance travelled by the air after a sharp edged gust has occurred for the anemometer rate to reach 63% of the new speed.
2. Ratio measure the damping of wind vanes. It represents the ratio between the consecutive damped deflection amplitudes (for example 3rd amplitude to 1st amplitude) in one direction.

uses a pair of UT in one, two or three-axis, avoiding the traditional problems of the mechanical anemometers: friction, acceleration and deceleration of moving parts or delayed response in gusts of wind. In this case UT does not have mobile parts, offering high resolution with low wind speed profiles and mechanically robust construction. In the atmosphere, the speed of sound is affected by the air temperature and humidity [8] but the sonic anemometer only uses the Time-of-Fly (TOF): an ultrasonic pulse travels between transmission and reception transducers. By this way the errors in wind speed estimation are eliminated. Table I show the calibration of our sonic front-end anemometer, WindSonic Gill.

A. *WS and WD Estimation in two-axis*

WS and WD estimations are based on the transit time measurement of ultrasonic pulses between two paths. We employ four UTs oriented in orthogonal position in a plane. The first pair of UT is located in North-South (N-S) position and the second one is located in East-West (E-W) orientation. In this configuration the horizontal wind is measured using a TOF North-South (T_{N-S}) using an ultrasonic pulse originated by the North transducer and received by the South transducer. Table II summarize the parameters to use in WS and WD estimation.

TABLE II PARAMETERS TO ESTIMATE WS AND WD

Parameter [units]	Notation
Time of-fly sound wave [s]	*TOF*
Ultrasonic pulse in North-South direction [s]	T_{N-S}
Sound speed [m/s]	S_S
Wind speed [m/s]	W_S
Distance between the pair of ultrasonic transducers [m]	L
Ultrasonic pulse in South- North direction [s]	T_{S-N}
Flow speed vector [m/s]	**U**
Flow speed component parallel to the path [m/s]	U_p
Reference Flow speed [m/s]	U_r
Flow speed component perpendicular to the path [m/s]	U_n
Scaling factor for flow speed perturbation component	ε
Mach number based on reference flow speed	M_r

Equation (1) is used to measure the TOF in North – South direction. In a second step an inverse TOF South-North (T_{S-N}) is obtained. In this case the flow sound speed is opposite. TOF South-North could be obtained as shown in equation (2). The microprocessor uses the equations (1) and (2) to obtain the equation (3) to estimate the WS in one direction.

$$T_{N-S} = \frac{L}{S_S + W_S} \quad (1) \qquad T_{S-N} = \frac{L}{-S_S + W_S} \quad (2)$$

In equation (3) it is assumed that an ultrasonic pulse follows the path line and the measured times aren't affected by lateral speed components if match number M=Ur << 1 namely subsonic airflow. Equation (3) is valid in the case of a steady uniform flow field, but with non steady flow field is considered the correction term $\Delta U_p/U_p \approx \boldsymbol{\varepsilon}^2 * M_r$ that is introduced in [9]. The same method is used to estimate the WS in the other component W_{s2} using a TOF in (E-W) and (W-E) direction. The WS magnitude is calculated using the equation (4). Equation (5) is used in WD estimation using the ratio between the wind components W_{S1} and W_{S2} respectively.

$$W_{S1} = \frac{L}{2}\left[\frac{1}{T_{N-S}} - \frac{1}{T_{S-N}}\right] \quad (3) \qquad W_S = \sqrt{(W_{S1})^2 + (W_{S2})^2} \quad (4)$$

$$W_D = \tan^{-1}\left(\frac{W_{S1}}{W_{S2}}\right) \quad (5)$$

This method is effective because it doesn't evaluate the sound speed and only use TOF and the physical path between UTs. Other configurations are possible using only three UTs each 120 degrees, estimating the WS and WD in two-axis or in three-axis.

III. SENSOR NODE ARCHITECUTRE

Our sensor node is based on Telosb platform and it uses four submodules. They are sensing unit, computing unit, wireless communication unit and power management unit. Figure 1 shows the WTIM node in operation and Figure 2 shows the block diagram of WTIM node. Sensing unit includes a probe assembly [10] that uses four piezoelectric ceramic UTs disposed each 90 degrees in a plane and use two orthogonal paths to determine the components of wind in two-axis.

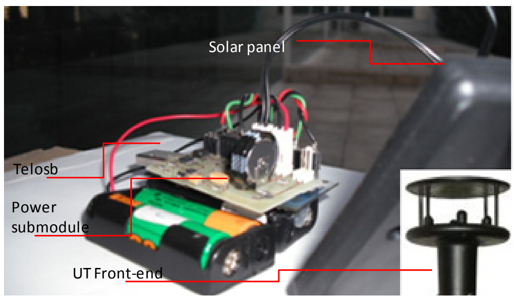

Fig. 1. IEEE1451 Smart Sonic sensor node

WD and WS are calculated and converted into digital values to send via an UART interface to the telosb platform. WTIM node employs a microcontroller (MCU) MSP430F1611 with

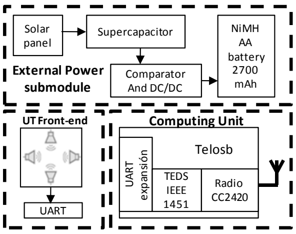

Fig. 2. Block diagram of WTIM node

16-bit RISC CPU that contains digital input/output, 16-bit timers, 12-bits analog to digital converter (ADC), serial interface I2C and UART, Direct Memory Access (DMA), and several I/O pins. WTIM node uses the UART interface to communicate with external UT submodule. Our node is programmed using a real time operative system (RTOS) TinyOS 2.1 [11] and it uses the modules and configurations as shown in Figure 3.

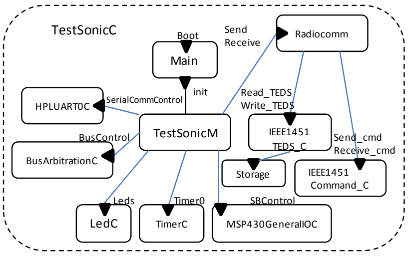

Fig 3. TinyOS component and interfaces used in WTIM node

An transceiver CC2420, compliant IEEE802.15.4 standard working in 2.4 GHz ISM band, is used. It allows interoperability with ZigBee and 6loWPAN standards. This transceiver provides a transmission rate of 250 Kb/s. RF transceiver was configures to transmit 1 mW (0 dBm) in order to achieve a range up 100 m in outdoor location using only a PCB antenna. The power management unit uses a Solar panel MSX-01 [12] to recharge the 1.2 V NiMH Ansmann AA 2700 mAh. The output solar cell current depends on the incident solar irradiance. For a high solar irradiation near of 1 KW/m^2, the solar panel provides 150 mA. The incident sunlight charges two super-capacitors of 22 F connected in series that operates as reservoir to storage the energy and release when it is necessary. WTIM node was configured with a duty cycle of 1 % and 6 % in tests.

IV. IEEE1451 STANDARDIZATION IN WSN

WTIM node uses in a high level the IEEE1451 standard [13] to increase the interoperability with others sensor node vendors and to permit self-calibration and self-configuration tasks. The IEEE1451 is a family of standards organized around a set of common architectures and protocols with the ability to work with wired and wireless smart sensor nodes. IEEE 1451 adopts a common communication protocol independent of any manufacturer. Figure 4 shows our WTIM node that uses the IEEE1451 standard in a WSN [14]. Coordinator node in the WSN is namely Network Capable Application Processor (NCAP) by the IEEE 1451 standard.

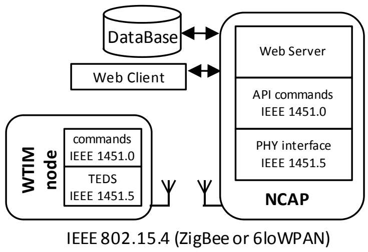

Fig 4. IEEE1451 inclusion in NCAP and WTIM node

Our NCAP node can be passive to receive the data information from WTIM nodes, or active, sending the IEEE 1451common commands IEEE1451. IEEE 1451 WTIM node includes a physical WS and WD channels, all mandatory IEEE 1451 Transducer Electronic Data Sheets (TEDS) that store the node configuration. Mandatory TEDS are: Meta-TEDS with global metadata information about the WTIM node, Transducer Channel-TEDS with information about WS and WD operational parameters, User's Transducer Name-TEDS with self-description information, physical-TEDS with wireless interface communication used and parameters that include in RF transceiver and calibration-TEDS that includes the WS and WD calibration parameters. All metadata information is stored in our WTIM node using a non volatile memory. Metadata information can be used for self-diagnosis, self-calibration and self-configuration WTIM node. In our application, the physical layer was the IEEE802.15.4 but IEEE1451 is compatible in IEEE 802.11 (Wi-Fi), IEEE 802.15.1 (Bluetooth). The NCAP may initiate the discovery and associate WTIM nodes using a bootstrapping process to establish the connection between the NCAP coordinator and WTIM sensor nodes.

V. EXPERIMENTAL RESULTS

Our goal was maintain the sensor node operative continuously using active, idle and sleep operational modes, in order to preserve power and to extend the battery life. For this reason, we include the sampling protocol Berkeley Media Access Control (BMAC) [15] with low power listen to check the radio activity. BMAC is a flexible sampling protocol for wireless communication that uses Carrier Sense Multiple Access with Clear Channel Assessment (CSMA CCA) for collision avoidance detecting the channel activity and packet backoffs for channel arbitration. Our application establishes and maintains a schedule whereby the WTIM node wakes up and expects to receive IEEE1451 standard commands [13] or to send sensing information returning to sleep and to conserve the energy using a variable duty cycle between 1 % and 6 %. Laboratory tests used a current probe Tektronix TCPA300 and oscilloscope DSO6032A Agilent. Figure 5 shows the node current consumption in sleep and active modes using a duty cycle of 1%. We define the total energy consumed in our WTIM node using the experimental current consumption in different operational states.

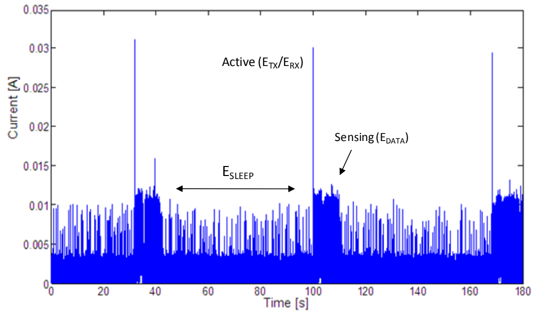

Fig. 5. Measured current consumption using duty cycle of 1%

The energy consumption can be modeled using the next terms: the energy consumed receiving each IEEE1451 command (E_{RX}), the energy consumed in transmission (E_{TX}), the energy consumed listening the radio channel (E_{LISTEN}) , the energy spending sensing the wind speed and direction channels (E_{DATA}) and the energy used in sleep state (E_{SLEEP}). The equation (6) is introduced to calculate the consumed energy in our node. $E_T=E_{RX} + E_{TX} + E_{LISTEN} + E_{DATA} + E_{SLEEP}$ (6)

The low power consumption of our WTIM allows the use of a solar panel with two super-capacitors and boost DC/DC converter storing the energy and recharging the NiMH batteries with the sun. When the batteries are subjected to the highest current levels, the super-capacitors maintain a constant voltage for several seconds extending the battery life. We wired two super-capacitors in series of 22 F and 2,5 V, to decrease the leakages of current. In winter the hours of solar radiation are few and at noon, the maximum voltage is near to 3.3 V but at night, the minimum voltage is near to 0,5 V. The total energy stored in two super-capacitors of 22 F and 2.5 V is: $E_{capacitor} = 0.5*C_1*V_{max}^2 + 0.5*C_2*V_{max}^2 = 38.2mWh$ (7)

and the energy stored in a battery is:

$E_{battery} = \#batt*C*V = 4*2700*1.2V = 12960mWh$ (8)

$A_{utonomy\_no\_sun} = E_{battery}/E_{daily}$ (9)

Using equations (6), (7) ,(8) and (9) we can calculate the autonomy of our WTIM node with no sunlight. The lifetime is shows in Table III.

TABLE III NODE AUTONOMY WITH NO SUNLIGHT

Duty cycle	1%	6%
$E_{nergy\_by\_day}$(mWh)	2592	4490
$A_{utonomy\_days}$ (days)	5	2.88

Finally, our WTIM node offers features beyond those required using traditional sensors. These improvements are a set of standardized transducer electronic data sheets. This information is used in self-diagnosis, calibration, control and operational management. All implemented TEDS, and their size are shows in table IV.

TABLE IV IEEE 1451 TEDS IN WTIM NODE

TEDS	Memory used	Function
Meta-TEDS (IEEE1451.0)	40 bytes	Physical channel number
Transd Ch –TEDS IEEE1451.0	99 bytes	Physical Config channel
User's Transd Name-TEDS IEEE1451.0	25 bytes	Information name in ASCII
PHY TEDS (IEEE1451.5)	98 bytes	Physical interface config
Calibration TEDS (IEEE1451.0)	60 bytes	Calibration parameters

All data is stored in a non volatile memory. In practice, each metadata can be retained in MCU flash memory or use in an external memory to enable the proper operation of each WS and WD channel.

VI. CONCLUSIONS

We have design and implemented a small sonic anemometer in a WTIM node that operates in a WSN that uses IEEE 1451 standard in order to permit interoperability, self-calibration and self-configuration tasks. We have evaluated the energy consumption using a low duty cycle of 1 % and 6 %. Our node uses a small power management submodule that has a solar panel cell and super-capacitors to energy storage, to increase the operational lifetime.

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