A real-time Wireless Sensor Network for temperature monitoring

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***Abstract* — In the past, several approaches have been proposed to employ Wireless Sensor Networks in distributed control environment. The aim is to exploit advantages as mobility and scalability, but their diffusion is limited by reliability and predictability requirements. In particular, event-driven protocols usually adopted in standard solutions (as IEEE802.11 or IEEE802.15.4) are not well suited for industrial applications. In this paper, authors propose an hybrid approach that ensures time deadlines respect by means of a TDMA allocation schema and utilizes CSMA/CA for network management purposes. Experimental prototypes, based on COTS hardware, have been realized to verify the feasibility of this solution. A star network with up to 16 nodes and a cycle time of 128 ms has been implemented in order to monitor the fluid temperature in plastic machineries.**

I. INTRODUCTION

During the last few years wireless technologies have experienced a great growth within the office automation. Nowadays we are observing an increased interest about wireless communication also in industrial environment.

Benefits of wireless technologies are fairly obvious; Wireless Sensor Networks (WSNs) facilitate installation and maintenance, they eliminate expensive cables and save the costs, besides the plant can be easily reconfigured. One potential dominant technology, which seems to be really effective for the industrial application, is the IEEE802.11 standard [1,2]. Thanks to its high signal strength and high transfer rate, IEEE802.11 can be a solution for the wire replacement. On the contrary, its main drawback still remains the cost, especially if simple wireless sensors are considered. On the other hand, cheaper technologies as IEE802.15.4 and Bluetooth (IEEE802.15.1) are already important actors in the markets. As a disadvantage, they seem not suitable to be adopted in control applications as they are limited in terms of timing requirements and Quality of Service (QoS).

At the same time, the ZigBee Alliance is rapidly growing. Building on the work of the IEEE 802.15.4 group, ZigBee was created to address the market need for cost effective, standards-based wireless networking solutions that support low data rates, low power consumption, security and reliability [3]. Another notable proposal has been presented by IEEE P1451.5 task group for wireless smart sensors in industrial sensing application.

As regards power consumption, battery powered solutions could have some problems with respect to environment (e.g. wide temperature range); nevertheless it must be noticed how the main power supply is easily accessible within an industrial environment. For all these reasons, wireless solutions have been already adopted with success when the "information rate" (that we define as the number of active nodes divided by the refresh cycle time) is relatively low. In addition, another advantage adopting a wireless link is the elimination of the expensive compensating cables used to connect the thermocouple with the electronic circuit.

Basic circuit of thermocouple interface comprises signal conditioning stage, reference junction compensation and linearization so that a microcontroller is typically present on board. Adding a RF transceiver to establish the wireless link leads only in a minimal cost increase. Some commercial devices can be found on the market. The most powerful is probably the TCLink from Microstrain [5] that allows a sample rate in the order of 5Sa/s. A well-built solution is offered by Accutech [6], which allows a sample rate of 1Sa/s. However, both manufacturers does not specify network characteristics, e.g. the maximum sample rate as a function of the number of active nodes.

The aim of this paper is to propose a solution able to work with higher information rate (short cycle time), despite its low cost. Simple RF (Radio Frequency) transceivers with only the physical layer together with 8-bit microcontrollers have been used.

The selected protocol has to be very simple, it is fully processed by the microcontroller and it must deal with synchronization problem of the reference clock. The basic idea is to synchronize nodes in order to oversample quantities of interest; in this way it is possible to reconstruct the signal even when the radio frequency (RF) link vanishes due to the bursty nature of the radio link noise. Traditional strategies ensure QoS retransmitting lost packets; this approach could lead to a dramatically increase of the minimum cycle time and rise up the overall power consumption. More complex solutions can be designed to take advantages from antenna or path diversity, at the expense of a greater cost and computational effort [7].

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Our solution is to avoid interferences from other RF sources by exploiting channel diversity: a known backup frequency channel is used when the selected one is busy, eliminating continuous transmissions or reconnections [8]. A similar feature is suggested in Bluetooth systems too. Also this standard operates in the 2.4GHz region and exploits a 1MHz RF-channel spread by means of Frequency Hopping (FH) modulation technique over the whole ISM band. Starting from the BT1.2 specifications [9], released at the end of 2003, the concept of AFH (Adaptive Frequency Hopping) has been introduced. Rather than over all 79 available channels, FH can occur over a subset specified in a channel map, according to a {good,bad,unknown} classification. However, specifications do not tell how this classification is to be performed.

The paper is structured as follows; in the subsequent section a brief description of the protocol stack is given, after that the fabricated prototypes are detailed, then some experimental results showing the feasibility of the proposed solution are remarked.

II. THE PROPOSED NETWORK

Extruders, as well as other machineries for plastic and thermoplastics, are essentially made up of a screw that turns in a barrel and pushes the plastic forward. Temperature along the barrel should remain near the melting point: for this reason, the barrel is divided into several zones continuously measured. The final product quality greatly depends on the temperature profile, that must be carefully chosen according to the material. We have considered applications with a maximum of N=16 thermal probes (nodes) scanned with a cycle time of Tcycle=128ms. The adopted transducer is a J type thermocouple; transmitted temperature is expressed with a resolution of 0.1°C over a typical range [0,400]°C.

A proprietary protocol stack has been developed to minimize the overhead, reduce the transmitted bytes (fewer the bytes, shorter the transmission time and longer the battery life) and to achieve high efficiency decreasing computational effort.

As previously mentioned, we have chosen a IEEE802.15.4 compliant PHYsical layer (PHY), implemented by a single chip transceiver. Concerning the Medium Access Control layer (MAC), every kind of communication can be grouped in two different sets: Time-Driven and Event-Driven. In the former one, it is the time that determines when messages must be sent. Every node has its own time slot where communication occurs, so that medium is shared in a fair way. Obviously, some form of clock synchronization is needed in order to avoid superposition between adjacent time slots. On the contrary, in event-driven approach data exchange occurs whenever new information is available. Some techniques to avoid collisions must be adopted, but typically they are tolerated if not frequent. In our solution we adopt an hybrid approach. We use Time Division Multiple Access (TDMA) to guarantee the cycle time deadline of sensory data transmission and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for network management purposes. In fact, as occurs in most of monitoring applications, messages length is very short and therefore data efficiency is of main concern. The use of TDMA allows for small overhead since parameters as node ID, message length, etc… can be encoded in the scheduling schema. On the other hand, affiliation procedure or diagnostic/ancillary data exchange are intrinsically aperiodic (i.e. they occur at inconstant datarate) and can be easily managed by means of CSMA/CA. There are many different solutions in literature that exploit advantages of both MAC schema, as resumed in [10].

As regards the NetWorK (NWK) topology, a star architecture has been adopted. In fact, nodes along the barrel are relatively close one from each other and no complex routing strategies are needed. Thus a small firmware footprint can be obtained. Each sensor node can talk only with a special node, called network coordinator. Several subnets can coexist exploiting frequency diversity.

With regard to the APPlication layer, it simply encapsulates sensor data within the protocol datagram. No particular attention has been devoted to security, since this is not a real problem in monitoring applications.

The network coordinator is mains powered and is always in the on-state. It periodically sends a BEACON packet that delimits the beginning of a new cycle. The first part of the cycle is devoted to network constitution (Join Period in Fig. 1); it lasts 32ms.

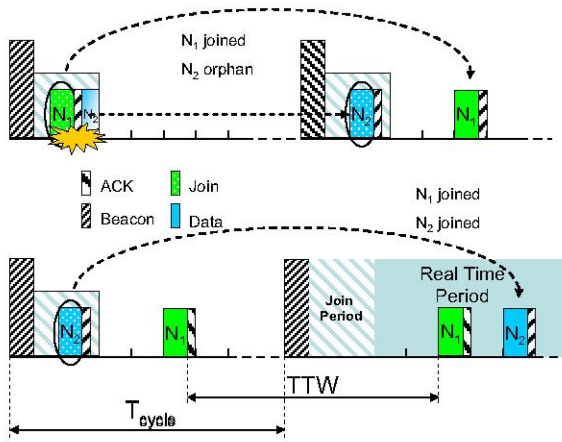

Fig. 1. CSMA/CA and TDMA hybrid approach.

A node that wants to join the network waits for the BEACON and sends a JOIN packet with a CSMA/CA approach. If the coordinator accepts, it sends an ACK packet specifying the Network IDentifier (NID) and the node time slot, that corresponds to the Devide IDentifier (DID). Datagrams are shown in Fig.2. The PHY level header and the FCS: Frame Check Sequence fields are imposed by the IEEE802.15.4-PHY. The PROT field is used to distinguish the proposed protocol with respect to IEEE802.15.4 and specifies protocol version; SQN is a sequence number to allow for cycle traceability; SN is the node univocal identifier (factory set); the TTW (Time To Wake-up) indicates the amount of time that must elapse before next wake up and allows for time synchronization, as better explained in the following; BC is the Backup Channel as detailed in the following; RVD is a reserved field.

The remaining part of the cycle (Real Time Period in Fig. 1) is devoted to real time data communication that occurs by means of TDMA; it lasts 96ms. Once a node is linked with the coordinator, it sleeps for most of the time in power saving mode and periodically (every Tcycle) wakes up and sends its data - DATA packet - to the coordinator that answers with the ACK packet.

Application payload is made up of seven bytes; two bytes are reserved for the temperature information (TCJ), two bytes constitute a progressive sequence number (SQN), two bytes are for diagnostic and identification purposes (DIAG: node status, battery level, cold junction status…); finally, one checksum byte is computed to check data integrity (CHK) and ensure that frame belongs to this kind of network.

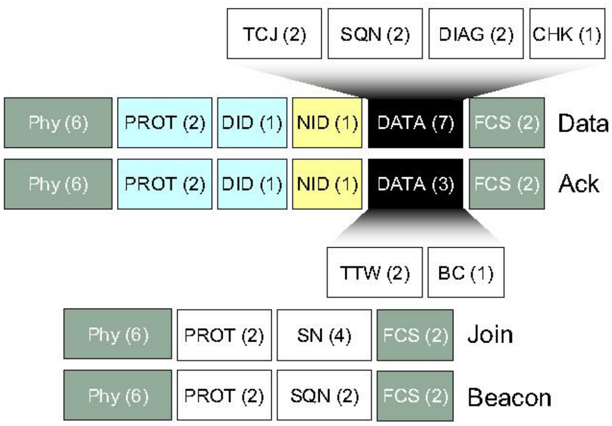

Fig. 2. DATA and ACK datagrams; field lengths are in octets.

The sensor nodes (N=16) could not be all present in the same instant and their time allocation occurs according to their "appearance" within the network in order to maximize slots distance. The coordinator has stored a time table with an entry for each node and the corresponding time slot allocation.

In a distributed time-triggered system, a synchronized timebase is a crucial requirement to enable a reliable system behavior [11]. First requirement is not to overlap two successive 6ms-wide slots. This condition may be complicated by very low performance clock that microcontrollers use in power save mode. The so called "rate synchronization" has been chosen, i.e. all nodes measure the same time interval lengths. In fact, in this application we do not need to share a global reference time, as permitted by the IEEE1588 [12], that implements also the "offset synchronization". The coordinator detects the time of arrival of each packet sent by nodes and computes the next Time To Wakeup [ms] TTW based on its internal clock. The TTW and Tcycle values should coincide, but relative drift between coordinator and node clocks makes them different. A simple P(roportional)I(ntegral) controller has been implemented to correct the "error" between them. In this way, it is possible to neglect uncertainties in radio messages delivery and it is very easy obtain a synchronization error less than 1% of Tcycle even considering environmental variations (e.g. temperature…). It should be noticed that the proposed solution minimize the time the sensor must be on if compared with an IEEE802.15.4 beacon-based approach.

As asserted before, nodes wait for an ACK packet; if this packet gets lost, i.e. a timeout condition is reached, a single retransmission occurs, signaled in DIAG field. No ACK is sent to stay within the time slot duration thus avoiding collisions.

In order to increase link reliability, frequency agility has been applied. The coordinator is able to scan all the 16 available channels and measure RF activity by means of the RSSI feature offered by the transceiver itself. All channels are divided into two groups according to their floor noise. The best one of the first group is chosen as the Communication Channel (CC), while the best of the second group becomes a sort of Backup Channel (BC). Coordinator specifies in the BC field of ACK packet if next single sensor data retransmission must occur in the same CC channel or in the BC one. Obviously, only one channel at a time (CC or BC) can be used. For that reason, authors suggest to include in the coordinator two transceivers (with only a slight increase in the overall cost), one set on the CC and the other on the BC channel.

Each sensor is active only in its own time slot (TS=6ms); a fraction of TS (T_{SETT}=1ms) has been reserved for the analog signal chain settling time, measurement and computation. Another portion T_{TX}=1ms is occupied by each transmission. A retransmission can occur after a timeout T_O=2ms during T_G=2ms, that is the guard time (refer to Fig.3).

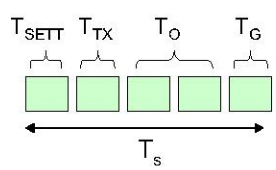

Fig. 3. Single node time slot.

In the developed application, the coordinator acts also as a MODBUS RTU [13] slave, allowing a maximum transfer rate of 19.2kbps. If a higher throughput is required other solutions (e.g. Ethernet) can be adopted; in this case dual processor architecture could be preferable.

III. THE WIRELESS THERMOCOUPLE

A wireless thermocouple for industrial application must be cost competitive with wired solutions. A special attention has been taken at the power supply strategies; all circuits are switched on only during the measurement and transmission operations and kept in a low power mode for most of their time (≈92%). In order to ensure the fastest transient response during the off/on transition, coupling capacitors have been carefully placed and analog filtering has been realized only by means of passive circuit. A DC/DC converter (TPS61016 from TI), has been used to provide the required supply voltage (Vcc=3.3V) utilizing two AA-size batteries. The supply voltage can also be derived from the main power if available.

The analog section (the "Amp" block in Fig.4) is based on a low noise, low offset amplifier designed around the OPA336 from TI that adjust the low level thermocouple signal to the input range of the microcontroller AD converter. Cold junction compensation has been performed in the digital domain; the absolute reference temperature has been retrieved from a monolithic temperature sensor (formerly LM60 from National). This section is directly connected to an XBee module from Maxstream [14] that hosts microcontroller (uC) and RF transceiver (HCS08GT60 and MC13192 from Freescale). Both temperature signals are acquired with the uC internal 10-bit ADC; temperature is computed as the average value of 8 consecutive readouts. Reference compensation and thermocouple linearization is performed through a look-up table of 32 entries. The achieved overall accuracy is in the order of 1°C. The sensor node block diagram is shown in Fig.4 while a prototype is visible in Fig.7b.

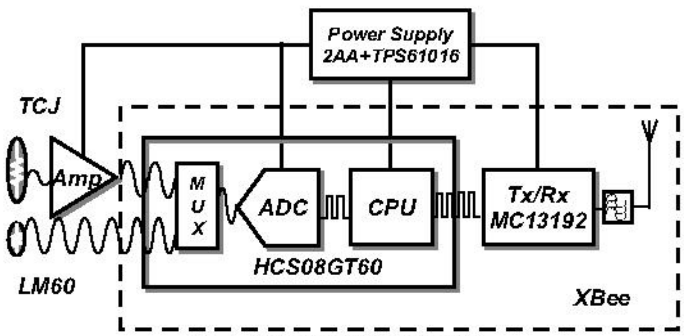

Fig. 4. Sensor node block diagram .

Concerning low power strategies, the most efficient approach seems to be the adoption of the Doze and STOP2 mode of the transceiver and the microcontroller, respectively. The former consumes about 35μA and only 330μs are needed to turn on the modem in the idle state; the advantage is that the internal oscillator is always running allowing for the shortest recovery time. On the other hand, the STOP2 modality absorbs about 1μA, still ensuring data and I/O retention. The RF modem internal timer is used to wake up both devices with a time resolution of up to 1μs. Since the RF-modem is compliant with IEEE802.15.4 [4] specifications, it includes a 40-ppm quartz crystal, that greatly reduces synchronization troubles due to the short Tcycle duration.

Authors have also considered the use of alternative strategies, such as the Hibernate mode of the transceiver and the internal Real Time Interrupt (RTI) offered by the uC, but no advantages arises when a so short cycle time must be ensured. In fact, the smallest time resolution of the RTI is 8ms, forcing a longer microcontroller on time.

Also the coordinator is realized using an XBee module together with an optocoupler for RS485 interface.

IV. EXPERIMENTAL RESULTS

A purposely designed "sniffer" has been realized to analyze traffic over the air. It collects data and sends them over a serial link toward a host PC (@ 57.6kbps). A timestamp is added for each packet with a time resolution of 125μs. Link quality (a.k.a. LQI according to IEEE802.15.4) feature offered by the RF transceiver is exploited to quantify incoming signal strength.

Some metrological characterizations have been done in the SIT (the Italian calibration system) facility at the Gefran plant in a room with controlled temperature using a thermocouple furnace and a calibrator. Two measurement points were analyzed: T=room temperature set at 23.2°C and T=200°C. Results in terms of mean value and standard deviation of one node are reported in Table I (observation time = 5 min).

TABLE I
METROLOGICAL CHARACTERIZATION [°C]

T reference	T, Mean Value	T, Standard Deviation
23.2	22.9	0.3
200.0	199.9	0.3

Transceiver only current consumption is measured as the voltage drop across a 1.8Ω shunt resistor amplified by an instrumentation amplifier (TI INA110, Gain=100) and acquired by an oscilloscope (LeCroy LT374M). Fig.5 shows the current absorption in transmitting (TX) and receiving (RX) phases. Output power amplifier level strongly affects consumptions in TX phase: data refer to maximum output gain, (P_{out}≈3.6 dBm).

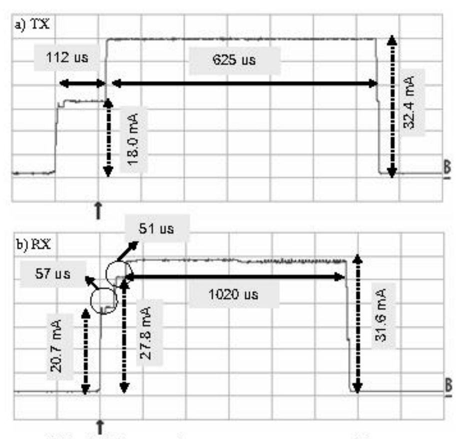

Fig. 5. Transceiver power consumption.

The same acquisition has been done for the uC only, which shows an average consumption of 10mA in the active state (that lasts less than 10ms). Rest of electronics has power consumption in the order of 200μA and it is in the on state for only 1ms. Since Tcycle=128ms, the average current of the RF section is $I_{RF,AVG}$=0.5mA while other circuitries (uC and sensor conditioning) require $I_{OTHER,AVG}$=0.8mA. It means that if no retransmissions occur, the node life is about 2 months (considering DC/DC efficiency and a power source of 2.3Ah).

Fig.6 is an acquisition done with the LT374M that shows transmitting phases of three nodes allocated in consecutive time slots (channel 2, 3 and 4) and the coordinator answers (channel 1), respectively.

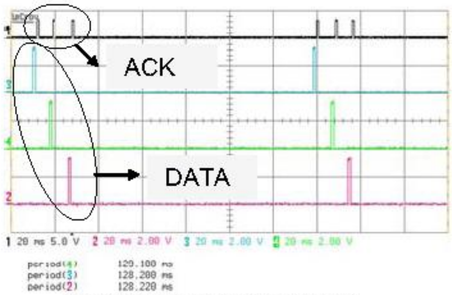

Fig.6. Network temporal evolution.

In order to evaluate performances in a real application, some additional measurements have been conducted in a factory building (refer to Fig.7a). Four wireless thermocouples were installed on a plastic injection moulding machine. In particular, there was no direct line-of-sight between some thermocouple nodes and the coordinator.

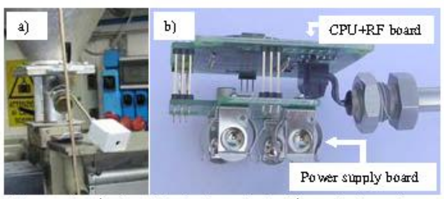

Figure 7. a) A node in the plant; b) node boards

As explained in Section 2, each sensor sends its data together with a progressive sequence number. This feature has been used to furnish an indication of the QoS offered by the proposed system. Traffic "on the air" was sniffed for an hour, corresponding to N_{CYCLE}=28125 at T_{CYCLE}=128ms. Fig.8 reports a histogram showing the frequency distribution of lost packets. The horizontal axis represents the number of consecutive lost packets (lack of information interval), while the vertical one represents the percentage of the number of occurrences with respect to N_{CYCLE}. As a final remark, it must be said that the maximum number of consecutive lost packets is equal to 7, and occurs only one time.

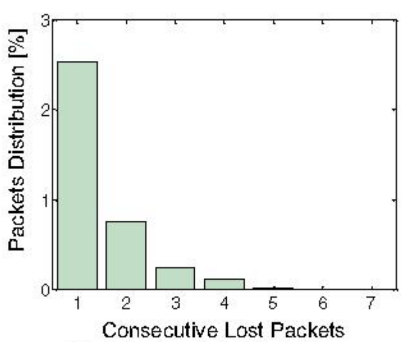

Fig.8. Lost packets distribution.

V. CONCLUSION

In conclusion, this paper presents a wireless thermocouples network to be employed in plastic machinery. Notwithstanding its extreme simplicity, which allows to employ simple devices and software protocols lowering cost, the whole system has been successfully tested in a typical real environment. Battery life, actually limited to about 2 months, could be improved with a suitable components and battery choice, despite a cost increase.

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