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Wireless Real Time Temperature Measurement for Process Control in High Temperature Environments

Dr.-Ing. Michael Marx[1], Frederic Meyer[1], Kai Grundmann[1], Prof. Dr. rer. nat. Anton Grabmaier[1,2]
[1] Fraunhofer IMS, Finkenstr. 61, 47057 Duisburg, Germany
[2] University of Duisburg-Essen, Bismarckstr. 81, 47057 Duisburg, Germany
{michael.marx, frederic.meyer, kai.grundmann}@ims.fraunhofer.de

Abstract:
In inductive soldering processes, it is crucial to accurately control the temperature of the workpieces moving through the process. In conventional systems, the actual temperature is measured by multiple thermocouples (TCs) with wired connections to the process controller. In this paper, a wireless temperature measurement system for industrial applications is presented. The solution consists of multiple mobile wireless sensor nodes (SNs). To each SN, up to four TCs can be connected. The SNs are designed for operating temperatures of up to 125 °C, while TCs can easily measure temperatures of 2,500 °C. To save battery power, the SNs are active only when they are within a running production process. Therefore, before entering a part of the process where their measurement values are required, the SNs are woken up by LF antennas placed at suitable locations. Up to 84 SNs transmit their measurement values to a base station (BS) via a deterministic real time protocol. The BS communicates with the process controller via a USB interface (optional: Ethernet, CAN or Profibus).

Key words: Industrial Process Control, Wireless, Real Time, Low Power, Thermocouple

Introduction and Example Application

In many industrial manufacturing processes, a high product quality can only be achieved, if the temperature of the workpiece is controlled with high accuracy. Examples of such manufacturing processes can be found in the food industry (e.g. industrial bakeries) as well as in industrial production companies, e.g. for drying and hardening, gluing or soldering processes. The actual temperature required by a process controller is typically determined by means of wired temperature sensors. However, in situations where sealed chambers do not allow for an easy installation of cables or where the point of measurement moves with the workpiece, the installation of cables is often complicated or not feasible.
For these cases, Fraunhofer IMS has developed a wireless real time temperature measurement system. Fig. 1 illustrates the integration of this system into a production process that is characterized by four vacuum chambers through which the workpiece travels.

System Architecture

The system consists of a base station, multiple wireless sensor nodes and antennas for the LF (133 kHz) and UHF (868/900 MHz) bands.

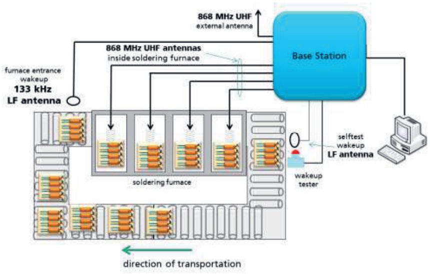

Fig.1. Schematic view of an industrial process with integrated wireless real time temperature measurement

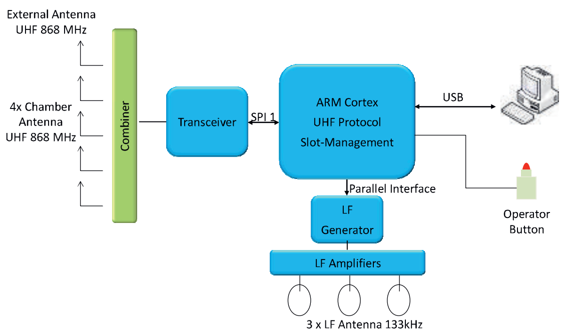

Fig.2. Block diagram of the base station

Fig. 2 summarizes the most important components of the base station. The ARM Cortex controller is responsible for managing the sensor nodes. It provides measurement data and system status information at a USB port. Optionally, the base station can be directly integrated into a field bus (Ethernet, CAN or Profibus).

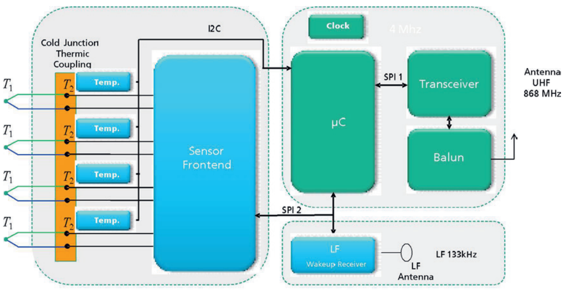

Fig.3. Block diagram of the sensor node

The sensor nodes are designed for operating temperatures of up to 125 °C. Up to four thermocouples as external temperature sensors can be connected to one sensor node (Fig. 3).

Efficient Resource Utilization

Wireless systems for industrial applications require an efficient use of sparse resources. One of these limited resources is the available amount of energy – whether it is supplied by a battery or an energy harvester. When a battery is employed, it is necessary to keep the maintenance interval (i.e. the time between battery changes) as long as possible even for small sized primary cells. For thermal energy harvesters that supply power as a result of a temperature difference, it is usually necessary to minimize the temperature difference required for the sensor to operate to a few Kelvins.

In wireless sensor systems, a considerable amount of energy is consumed by the radio communication transceiver. Tab. 1 exemplarily shows the influence of the transmission interval on the run time of a battery operated sensor node. E.g., the time between battery changes can be more than doubled by reducing the transmission interval from 1 Hz to 1/5 Hz.

Tab. 1: Battery run time in days over transmission interval in seconds

	Transmission Interval		
Bat. Capacity	1s	5s	10s
800 mAh	39.8 d	83.8 d	97.2 d
1800 mAh	89.5 d	188.5 d	218.8 d
7500 mAh	373.0 d	785.6 d	911.7 d

Thus, it is essential to keep the transceiver in a sleep mode where its energy consumption can be considered negligible for a predominant part of the operation time. In the presented system, the transceiver is in active mode only for a few milliseconds per second.

In industrial environments with a large amount of data points to be measured and a multitude of wireless sensor nodes per unit area, another sparse resource that needs to be used efficiently is the available frequency spectrum. This especially holds true for systems that operate in the 868/900 MHz ISM band. Because of this, simple medium access protocols like pure Listen-Before-Talk (LBT) are out of the question because of their poor spectrum utilization.

Deterministic Wireless Communication

The presented solution relies on a proprietary wireless communication protocol developed at Fraunhofer IMS. This communication protocol is optimized towards low power demand, high spectrum efficiency and deterministic real time capability. These requirements are fulfilled by means of a Time Division Multiple Access scheme (TDMA).

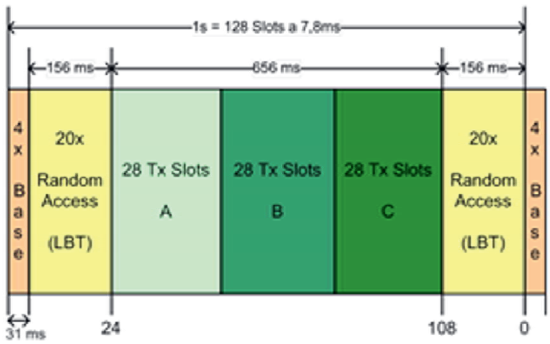

Fig.4. Basic TDMA frame structure

Fig. 4 illustrates the basic TDMA frame structure. This structure is repeated once per second. The frame starts with four downlink slots, in which the base station can send messages to the sensor nodes. This way, the user may alter the configuration of the sensor nodes even during operation. This includes the frequency channel, TX powerand transmission interval.

The downlink slots are followed by a random access channel, through which sensor nodes that are not yet associated with their base station can register themselves.

Therefore, the new sensor node listens for so called beacon messages sent by the base station in the first downlink slot. As these beacon messages are sent at well-defined points in time, the sensor node can synchronize its local timing with the base station on receiving a beacon message.

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After the sensor node has synchronized its local clock to the base station, it randomly chooses one of the random access time slots and sends an association request in the chosen slot. For this purpose, the sensor node still uses Listen-before-Talk as a collision avoidance strategy.
The base station reacts to a valid association request by sending a configuration message to the sensor on the downlink channel. By means of the configuration message, the sensor node learns – besides other configuration parameters – the numbers of the TDMA uplink slots now reserved for it. Now, all preconditions are met so that the sensor node can enter its operating mode and start measuring. The sensor sends its measurement results only in the TDMA slots reserved for it. This ensures a collision-free, fast and reliable transmission of the measurement values.
As the time pattern of the TDMA frame repeats exactly once per second, communication is carried out in an absolutely deterministic way.

Time-Synchronized Sampling Points

As the data measured by the presented system are used as input for a complex control loop, it is beneficiary for the controller if the points in time at which measurements are taken are synchronized as well, i.e. if all temperature measurements are performed at exactly the same points in time.
In the presented system, such a synchronization of measurement timing can be easily achieved: As the local clocks of the sensor nodes are already synchronized to the base station and, thus, synchronized to each other, all sensor nodes can start their measurements at the same time slot in the TDMA frame (e.g. shortly before the downlink).

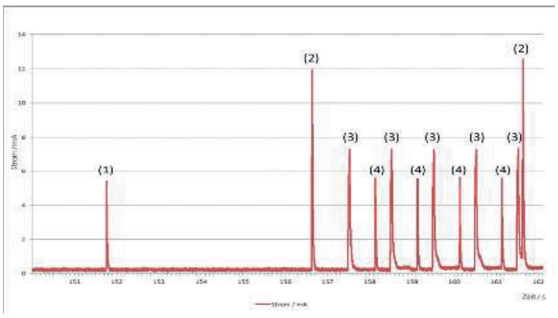

Fig. 5. Measured current consumption of a sensor node

Fig. 5 exemplarily illustrates the current consumption of one wireless sensor node. One can recognize the following peaks in current consumption:

(1) Association Request TX
(2) Downlink RX
(3) Measurement
(4) Uplink TX

Between these peaks, the sensor node is in a low power sleep mode with a current consumption of just a few µA. Another means of saving power lies in the fact that the sensor node skips downlink messages, i.e. it does not turn on the receiver for every downlink slot.

Scalability

The presented system scales in multiple dimensions. E.g., one base station can manage 84 uplink time slots on one carrier frequency at a transmission rate of 1 Hz. This means that up to 84 sensor nodes can be connected to a base station. If a faster transmission rate of e.g. 3 Hz is required, each sensor node is assigned 3 equidistant time slots in the TDMA frame. This way, the latency can be balanced against the number of sensors per base station: At a transmission interval of 3 Hz, one base station can only manage 84/3=28 sensor nodes.
For a transmission rate of 0.5 Hz, the base station can assign time slots in even TDMA frames to different sensor nodes than in odd frames. This way, the number of maximum sensor nodes per base station can be doubled to 84*2=168.
If even more sensor nodes are required, multiple base stations can be operated in parallel. In this scenario, each base station operates on a different frequency channel, so that it does not interfere with other base stations. This way, radio cells as known from mobile cellular networks can be formed [1].

Mobile Sensor Nodes

For the application presented in the first section of this paper, the sensor nodes can be shelved together with the workpieces to be processed during different phases of the entire production process. During shelf time, the sensor nodes are not required to take measurements. Therefore, they can remain in a deep sleep mode where only an ultra-low power LF radio receiver stays active. For waking up the sensor nodes, a short range LF transmitter antenna as known from RFID technology is placed at the location of entrance into the next process step. The short messages periodically sent by such an LF antenna contain the UHF frequency on which to register at a base station. This way, the network cell in which the sensor node registers itself for the next process step is determined by the LF antenna passed by at the entrance of the production step.

Test Wakeup

In addition to the wakeup procedure at the start of a process step as described in the previous

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section, there is a second scenario in which a sensor node can be woken up by an LF message: at an operator test station. At such a test station, the operator can check if all thermocouples are correctly connected to the sensor node and if the measurement values sent by the sensor node are plausible. Furthermore, the operator can check the battery status and, if necessary, replace the battery. This way, the operator can make sure that only fully functioning sensor nodes enter the production process.

Temperature Measurement Using Thermocouples

The system design considers a temperature measurement using thermocouples. A system of two conductors of dissimilar metallic materials, forming electrical junctions, is called a thermocouple (TC). Exploiting the thermoelectric effect, such a system is suitable for temperature measurements. TCs can be applied for temperatures of up to 2500 °C. Further, TCs exhibit a strong resistance against mechanical stress and allow cheap and spatial compact assemblies.

Cold Junction Compensation

Fig. 6 shows a TC schematically. The two dissimilar metallic conductors are sketched in the colors green and blue. In the application, the electrical junction between the two conductors is applied to the actual temperature to be measured, T_{wp} (workpiece). The conductions with the electrical contacts of the subsequent signal analysis are called cold junction, the temperature at these junctions (assumed to be equal) will be termed T_{CJ}. If these two temperatures differ, the TC produces a thermo-voltage V_{Th}, which is approximately proportional to the difference of the both temperatures (T_{wp}, T_{CJ}).

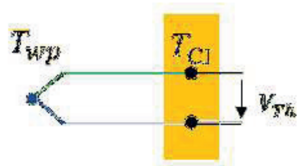

Fig.6. Principle of a thermocouple.

Thus, to determine the absolute temperature T_{wp}, the temperature at the cold junction has to be captured by a separate sensor. This process is called cold junction compensation (CJC). This is done by the use of a second temperature sensor, that measures the absolute temperature T_{CJ}. Fig. 7 shows the signal processing chain in a functional view. The sensor frontend converts, besides others, the analogue thermo-voltage to the digital domain.

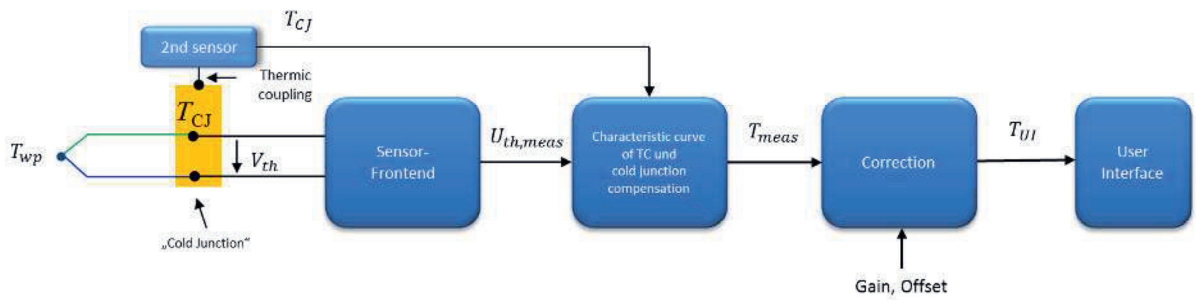

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Fig.7. Block diagram of the functional signal processing chain.

Standardized Characteristics

The thermo-voltage V_{Th} is approximately proportional to the difference between both temperatures (T_{wp}, T_{CJ}). The standard DIN EN 60584 describes the characteristic of the non-linear relationship between thermo-voltage and temperature. This information is stored in the memory of the SN and considered in the cold junction compensation function. Measurement series, conducted at our institute, showed a maximal measurement error of +/- 1°K for the entire measurement chain (Type K sensors and signal processing chain, but still without calibration).

Calibration

In practice, deviations between the real characteristic of an individual thermocouple and the standardized characteristic have strong impact on measurement accuracy. Thus the standard allows appropriate deviations for thermocouples. For instance, for a new TC of type K, the standard allows in the highest accuracy class 1 for temperatures up to 1000 °C still a deviation of up to +/-4°C from the standardized characteristics. Due to aging, the deviations can further increase. Thus the signal processing chain includes a correction function. To apply the correction step, the individual characteristics of each TC have to be captured (e.g. using so called block calibrators) at dedicated calibration points. Thus for each TC, an individual set of calibration points is collected and stored in the memory of the SN. The correction step then corrects the deviations by linear (in case of one calibration point) or non-linear curve fitting approaches (in case of multiple calibration points).

Packaging

The temperature profile of the workpiece contains gradients of up to 100 Kelvin/min. Since in the application the SNs are mounted on workpiece holders, the cold junction (CJ) is thermally linked to the workpiece. Fig. 8 shows an example of the temperatures (T_{wp}, T_{CJ}) over time in the application. It shows temperature changes of the cold junction T_{CJ} of about 10 °K during the process.

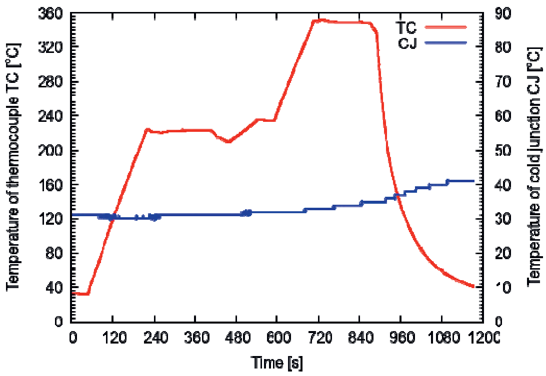

Fig.8. Process temperature as measured by a thermocouple (TC) and cold junction temperature (CJ) for a typical process over time

Since the spatial temperature gradient between the cold junction itself and the sensor for measuring T_{CJ} directly affects the total measurement error, measures are required to position this sensor thermally close to the cold junction. In the described system, a dedicated mechanical construction of the CJ satisfies a very close thermal coupling between CJ and the sensor for T_{CJ} measurement.

Conclusion

A wireless real time temperature measurement for process control in high temperature environments has been presented.
The sensor nodes (SNs) are designed for operating temperatures of up to 125 °C, while the thermocouples can measure temperatures up to 2,500 °C.
Without calibration step, the system exhibits a maximum measurement error of +/- 1°K for the entire measurement chain (Type K sensors and signal processing chain.
With a calibration step with multiple calibration points the measurement error can be further reduced.

A dedicated collision free wireless transmission protocol with deterministic behavior guaranties a real time transmission of the measured data at a measurement frequency of up to 3 Hz.

With multiple power saving mechanisms (beside others, wake up and dedicated wireless protocol) the battery runtime can be driven to more than 2 years.

References

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