Wireless SAW passive tag temperature measurement in the collision case

A. Sorokin¹, A. Shepeta¹, M. Wattimena¹

¹Major Problem-Oriented Computer Complexes Department, State University of Aerospace Instrumentation (SUAI), St. Petersburg, Russia

E-mail: mauritswattimena@yahoo.com, ultramagnus88@gmail.com

Abstract. This paper describes temperature measurement in the multisensor systems based on the radio-frequency identification SAW passive tags which are currently applied in the electric power systems and the switchgears. Different approaches of temperature measurement in the collision case are shown here. The study is based on the tag model with specific topology, which allows us to determine temperature through the response signal with time-frequency information. This research considers the collision case for several passive tags as the temperature sensors which are placed in the switchgear. This research proposal is to analyze the possibility of using several SAW passive sensors in the collision case. We consider the using of the different typical elements for passive surface acoustic wave tag which applies as an anticollision passive sensor. These wireless sensors based on the surface acoustic waves tags contain specifically coded structures. This topology makes possible the reliability of increasing tag identification and the temperature measurement in the collision case. As the results for this case we illustrate simultaneous measurement of at least six sensors.

1. Introduction

Modern solutions in the field of monitored parameters should meet the requirements of increased noise immunity. In addition, they should have high speed, resistance to external climatic influences, high reliability and durability in operation. Modern monitoring based on radio frequency systems should be passive (without any energy source). Such requirements are met by radio frequency identification (RFID) technology, based on the use of passive acoustoelectronic devices on surface acoustic waves (SAW) [1], [2].

For temperature monitoring, RFID reader interrogates several passive SAW tags which are placed on the monitored object. However, in the simultaneous monitoring of several temperature sensors is limited to the problem of collision for passive acoustoelectronic RFID devices. In the case when several sensors are interrogated simultaneously, their response signals can overlap each other in the time domain, making it impossible to read the code of each device and obtain information about the temperature.

The last analysis shows that solutions cannot satisfy the actual tasks of monitoring and control objects with a wide temperature range and certain operating conditions in the collision case. This problem is the most evident in multisensory systems which are using the electric power systems. The temperature is the most important indicator of the electrical equipment current status. It makes possible to provide information about the emergency and electrical fire caused by short circuit or overheating of the equipment in the switchgear. Monitoring systems which are applied for temperature measurement would increase reliability and safety of high-voltage equipment.
The monitoring of contact connections status can be carried out with the thermal imager. However, this method has a number of disadvantages which are related to the lack of automation.

![Figure 1. Contacts overheat in switchgears. Left picture illustrates temperature of three contacts. Overheating impacts are demonstrated in the right picture.](image)

2. **Basic approaches to temperature measurement using passive SAW tags**

As a rule, for temperature measurement time impulse coded passive SAW tad are applied. Increase in the number of the tags which are simultaneous interrogated by RFID reader causes collision for one or more group of code. It makes impossible to identify each tag. For this reason several approaches are applied:

1. Signal separation using matched filtering is the basic method for accomplishing the required signal based anti-collision processing methods.
2. Time domain separation.
3. Spatial separation.
4. Processing technique based on the fractional Fourier transform (FrFT).

All common anticollision techniques and schemes are proposed in [3]. But all approaches are restricted by the information capacity which defines total number of tags which could be interrogated by RFID reader simultaneously. In order to enlarge the number of tags we propose specific topology of RFID SAW tag which aims to expand possibilities for anticollision processing signal approaches.

3. **Temperature measurement of passive SAW RFID tag**

The RFID SAW temperature sensors application helps to achieve an increase in the level of automation of control over the status of the main parts of the electrical installations and other electric power units, as well as to increase the level of efficiency in obtaining information on the mode of operation of power facilities and preventing supernumerary situations [4], [5].

![Figure 2. Simplified illustration of the SAW tag as the temperature sensor](image)
Passive SAW anticollision temperature sensor with frequency-time code difference is presented in Figure 2 [6]. It consists of a piezoelectric substrate, where are consistently located a unidirectional broadband interdigital transducer (IDT) with antenna and four orthogonally frequency-coded reflecting structures which are located in the time slots. The OFC structures position defines the identification code of the temperature sensor [7], [8], [9]. The three consecutive reflectors make possible the obtaining information about temperature.

Slots are located at a certain distance \( R \), and they have \( n \) variants of OFC structure position. The number of slots on the entire label is defined as \( M \). In each slot, only one orthogonally frequency-coded structure can be placed. The reflection coefficients of the structures are determined by different frequencies that are not repeating for subsequent structures. Reflectors 6 are located at a distance \( X' \) between themselves.

To obtain information about the temperature of the sensor, the reader emits an interrogation signal which is represented by expression:

\[
S_m(t) = \left[ h(t - T_1') - h(t - T_2') \right] \cdot \left[ A \cdot \left( \sum_{k=1}^{M} \sin \left( 2\pi w_k t - \varphi_k \hat{\tau}_k \right) \right) + A \cdot \sin \left( 2\pi f_c + \varphi_0 \right) \right]
\]

Where \( T_1' \) and \( T_2' \), the initial and final time of the interrogation signal, \( A \) - is the amplitude of the signal, \( w_k \) - frequency of \( k \)-th pulse, \( \varphi_k \) - phase of \( k \)-th pulse, \( N' \) - is the number of pulses during the period of the interrogation signal duration, \( f_c \) – is the carrier frequency the last pulse in the interrogation signal, \( \varphi_0 \) – is the initial phase of the frequency \( f_c \) for the last pulse.

The incoming interrogated electromagnetic signal is converted by the IDT into the surface acoustic waves, which completely repeats the shape of the interrogation signal. Acoustic pulses propagate along the surface of the piezoelectric substrate. In the case where the carrier frequency of the \( k \)-th pulse coincides with the frequency that determines the reflection coefficient of the \( k \)-th reflecting structure - this pulse is reflected back to the IDT. The remaining pulses continue their propagation until they reach the reflecting structures in which the frequency that determines the reflection coefficient coincides with the carrier frequency of the acoustic pulse. The reflected pulses come back to the IDT, and thus the response of the identification tag is formed in the form of consecutive pulses.

A pulse with a carrier frequency \( f_c \) that does not coincide with any of the orthogonally coded structures 3 continues to propagate until it encounters an inhomogeneity in its path in the form of reflectors. The part of the acoustic wave is reflected back into the IDT 2, and the part continues to propagate to the next reflector 6, where part of the wave is reflected, and the part passes to the last reflector, reflected from it.

The response signal from the anticollision passive temperature sensor on surface acoustic waves can be represented as:

\[
S_{out}(t) = \left( \sum_{k=1}^{M} \left[ h(t - T'_{1k}) - h(t - T'_{2k}) \right] \cdot A_k \cdot \sin(2\pi w_k t - \varphi_k \cdot \hat{\tau}_k) \right) + x(t)
\]

Where: \( T'_{1k} \) and \( T'_{2k} \) are the initial and final time point of each pulse duration. Each pulse reflects from the orthogonally frequency-coded structure (OFC). \( A_k \) is the amplitude of the reflected \( k \)-th pulse of the OFC structure, \( w_k \) is the frequency of the \( k \)-th pulse of the OFC structure, \( \varphi_k \) is the \( k \)-th reflected pulse from the OFC structure, \( M \) is the number of response pulses from the surface acoustic wave of the tag, \( x(t) \) is the signal reflected from the reflectors 5.

The frequency values for the reflecting structures are selected from \( w_k \) to \( w_k = M \). Thus, from the IDT, a signal is sent to the RFID reader in the form of a sequence of delayed pulses. Each pulse has own carrier frequency. The last three response pulses, reflected from the reflectors, have the same carrier frequency.

The pulses which come from the reflecting structures 3 are delayed relative to each other in time proportional to the distance determined by the tag topology. Thus, the topology of the passive SAW tag allows obtain a time and frequency information for further time-frequency coding of each tag and its identification in the collision tags case. The signal reflected from the tag can be expressed as:
Where $A_i$ is the attenuation coefficient of the amplitude due to propagation loss of acoustic waves, $\tau_c$ and $\tau_a$ are the propagation delay of the electromagnetic wave and acoustic wave in free space, respectively, $\theta_i$ is the phase shift of the central frequency related to the reflection characteristics from the $i$-th reflector, $f_c$ is the carrier frequency, $\phi_0$ is the initial phase of the carrier frequency, $h(t)$ is the envelope function.

The propagation delay of the acoustic wave $\tau_i$ and the phase delay $\phi_i$ for the $i$-th reflector can be represented as [10]:

$$
\tau_i = \tau_c + \tau_a + \frac{\theta_i}{2\pi f_c}
$$

$$
\phi_i = 2\pi f_c (\tau_c + \tau_a) + \theta_i
$$

At different ambient temperatures, the propagation delay of the acoustic wave $\tau_i$ will change due to a change in the distance between the reflectors. The ambient temperature $T$ is determined by means of reflectors 6 as:

$$
T = \frac{\Delta \phi_{ij}}{T_{CD} \phi_{ij,0}} + T_0
$$

where $\Delta \phi_{ij}$ is the phase difference, defined as: $2\pi f_c (\tau_a + \tau_a)$, $T_{CD}$ – temperature coefficient of delay, $\phi_{ij}$ is the difference between the phase delays between the reflections reflected from the $i$-th and $j$-th reflector of pulses corresponding to the $i$-th and $j$-th reflector, $\phi_{ij,0}$ design value at ambient temperature, $T_0$ - reference temperature [10].

4. **Anticolision encoding of passive SAW RFID temperature sensors**

The RFID SAW temperature sensors application helps to achieve an increase in the level of automation of control over the status of the main parts of the electrical installations and other electric power units, as well as to increase the level of efficiency in obtaining information on the mode of response pulse.

Let’s consider the solution described in [5] where radio-frequency reader interrogates tags using the signal

$$
S(t) = N \left[ h(t - T_1' - h(t - T_2')) \right] \cdot A \cdot \sum_{i=1}^{N} \sin \left( 2\pi \cdot F_i \cdot t - \phi_i \right)
$$

where $T_1'$ and $T_2'$ are the initial and finite times of the interrogation pulse, $A$ is the pulse amplitude, $F_i$ is the carrier frequency of the pulse, $\phi_i$ is the phase of the pulse, and $N$ is the number of pulses for one period of the interrogation signal.

The tag’s response is formed in the IDT in the form of a pulse sequence:

$$
S(t) = \sum_{i=1}^{N} \left[ h(t - T_{1i}') - h(t - T_{2i}') \right] \cdot A \cdot \sin \left( 2\pi \cdot F_i \cdot t - \phi_i \right)
$$

where $T_{1i}'$ and $T_{2i}'$ are the initial and finite times of the response pulse.

**Figure 3.** SAW RFID model as a time delay in the Simulink
This research takes a simple model with four slots and one reference reflective structure. This model uses time slots \(T_1-\ T_{12}\), as shown in Figure 5.

![Figure 4. Passive tag with reflective structures in the slots](image)

In this model, the position of the reflective structure in the time slot is matched with a certain frequency; it determines the binary code. The first slot has durations from \(T_1\) to \(T_3\), second from \(T_4\) to \(T_8\), third from \(T_7\) to \(T_9\), fourth from \(T_{10}\) to \(T_{12}\). Time slots \(T_{11} = T_4 - T_2\), \(T_{12} = T_7 - T_6\), and \(T_{13} = T_{10} - T_9\), are set between slots containing reflective structures [11-15]. The time–frequency attributes allow build a time–frequency matrix for tag \(A\), which is shown in Figure 5.

![Figure 5. Time–frequency matrix for tag A](image)

Thus, using information about time and frequency of the first tag, the RFID reader forms the binary code \(A_2 = 01001000000\). Zeros fill spacing between slots. Placement of the reflective structure in a certain position denotes either “0” or “1.” The reflected signal from tag \(A\) in the time domain is shown in Figure 6.

Here, \(T_d\) is the pulse length, \(T_{slot}\) is the time slot boundary, \(T_s\) is the shift time of the reflective structure. Using time intervals and frequencies of pulses at the collision situation moment allows building the time–frequency matrix. Then, shifting both matrices in the time domain with a given step allows them to be separated.

![Figure 7. Time–frequency matrix of tags A and B](image)
Similarly, we obtained the code of tag $B_2 = 01001001001$. Forming two time–frequency arrays $A$ and $B$ allows us to create a model of the tags’ collision.

A shift of matrices $A$ and $B$ relative to each other with the pitch $T_{slot}$ creates the $A$ and $B$ tag codes.

The code bits that trapped the separation intervals $T_{i1} = T_4 - T_3$, $T_{i2} = T_7 - T_6$, $T_{i3} = T_{10} - T_9$, $T_{i4} = T_{12} - T_{13}$, determine the place of the reflective structure of tag $B$. The presence of a reference pulse makes it possible to separate tags in the given frequency range from $F_1$ to $F_2$.

Specific passive SAW tag topology allows us to get time–frequency information for coding, which is represented in Equation 8. It provides the possibility to build a time–frequency matrix in the reader and measure temperature of each tag. The reader processes the response signals and executes the anticollision algorithm.

**Figure 8.** A simplified model of the passive SAW RFID temperature sensor with time–frequency information

For this case we consider the collision case between two passive sensors $A$ and $B$, with the same number of reflecting structures and different identification codes.

**Figure 9.** Collision case for two SAW temperature sensors.
As is shown in Figure. 9 [6], the first and the second structures of sensors A and B are placed in the same time slot places. In this way, these structures have different central frequencies but similar time delays. The reader receives reflected signals from the passive sensor, which contain information about frequencies and time delays. As a result, the reader creates matrix as is similar to the matrix which is illustrated in the Figure. 7.

The reader uses this information and makes a shift of columns in the time domain. This shift is equal to the $T_{12} - T_1$ interval. Thus, information about frequency and time delays allows highlighting the identification code of each tag in the collision case. For sensor $A$, the code is 01 10 10 10. For second, sensor $B$, the code is 01 01 10 01 [16, 17].

Thus, such an approach could be possible for consider in the temperature encoding of passive SAW RFID temperature sensors in collision case.

Reader measures temperature through time delay measurement of last three reflectors as it is shown in the expression (6).

![Figure 10. Temperature measurement of two passive SAW RFID sensors](image)

5. Results
For results illustration we review of application anticollision identification approach for temperature measurement in the switchgears and other high-voltage devices. SAW RFID based on devices allows us to carry out monitoring of temperature. Temperature alters correlation properties of the tag response. As a rule, response signal modulation allows us to get a temperature value from each tag. As an example, we consider the innovative technology of wireless passive temperature sensors, which have already been used for a real-time online monitoring system. Passive wireless temperature sensors are installed in the contact point of the distribution equipment to measure the contact temperature. An antenna is installed in the line of sight from the sensors to provide wireless communication with the temperature sensor. The temperature reader is placed in the compartment of the automatic devices. If the sensor temperature exceeds the specified threshold level, the reader indicates the event on the LED panel and sends a message to the automation system by the commutation relays. The reader transmits the temperature data to the industrial computer by an RS-485 interface. The industrial computer is connected to a local network. In this case, the operator can view and analyze the temperature data by web access.
Let’s consider the solution described in [5] where radio-frequency reader interrogates tags using the signal from the passive SAW tag comes to the reader.

After shifting the columns of the matrix, we get identification codes (Figure 11). Thus, we can separate the labels from each other using time-frequency information. As a result of the separation of the identification codes, we use the information on the modulation of the signals of each tag, that is, obtain the temperature value of each tag [5]. Therefore, for the collision case, this solution can be implemented in monitoring systems and control the temperature of high-voltage parts of electric power equipment.

![Figure 11. Matrices with IDs of two RFID SAW sensors. Due to specific topology RFID reader gets ID of each sensor and determines temperature in collision case](image)

Based on the modern existing solutions in the field of RFID SAW technology we consider using intelligent sensors for monitoring the temperature of the switchgear. It makes possible to increase the number of simultaneously interrogated sensors. Our anticollision approach increases the reliability and accuracy of the system, that makes it attractiveness for large-scale application in the electricity industry.

The innovative technology of wireless temperature sensors is already used today in the real-time monitoring systems [5, 18, and 19]. Passive temperature sensors are installed at the contact point of the distribution equipment for measuring the contact temperature.

The reader's antenna is installed at a distance of up to 10 meters from the sensors to provide wireless communication. The RFID SAW temperature sensor reader is placed in the switchgear cell. If the temperature sensor exceeds the specified threshold level, the reader indicates an event on the LED panel and sends a message to the automation system using switching relays. The reader transmits temperature data to the industrial computer via the RS-485 interface. The industrial computer is connected to the local network. In this case, the operator sees and analyzes the temperature data using web access (Figure 12).

![Figure 12. PC software interface which illustrates temperature measurement for several sensors](image)

Considered system is used for wireless monitoring and temperature monitoring. The offered approach allows solving a tag collision problem at the reading of codes and temperature values in multisensory systems, which are applied for the control of temperature in the electric equipment.

The collision problem is illustrated by the fact that in one cell of the switchgear there can be more than a dozen sensors and their temperature varies from -40 °C to 200 °C (Figure 12, 13, 14).
Figure 13. The example of SAW RFID temperature sensors placement in the switchgear

The proposed technology, which has the industrial name "RFSens", increases the number of simultaneously sampled sensors, the temperature range and the accuracy of this parameter. This becomes especially relevant for equipment with a large number of bends. Sensors for SAW technology are absolutely passive and consist of a metal antenna and a chip. The resulting solution is very important for the energy market.

In general, such systems use only one sensor for wireless monitoring. Our solution expands the possibilities for RFID wireless temperature monitoring systems based on the passive SAW sensors [5]. SAW RFID tags with time–frequency information provide the possibility of increasing number of passive temperature sensors for one switchgear. In this case, we could potentially use at least seven tags.

With compare general anticollision approaches like signal separation using correlation methods and time-spatial separation we assume that suggested anticollision algorithm significant increases information capacity each tag and enlarge the number of possible interrogated tags.

Thus, the temperature measurement example explains real-world measurement results. In addition, it illustrates the basic idea of how to realize our solution in practice.

6. Conclusion
In this paper, we propose a model that allows solving the collision problem using the frequency–time separation of passive SAW temperature sensor. Specific reflective OFC structures, which are placed in time slots on the surface of the piezoelectric substrate, make it possible to get a unique identification code, which contains time–frequency information. Reflectivity structure positioning and its placement in the time slots determine the total number of codes and decrease the possibility of incorrect identification.

Our approach is based on a combined coding method including orthogonal-frequency coding and encoding of the pulse time position. The combined coding method allows us to increase the number of temperature that are interrogated simultaneously in the electric power system and switchgears.

Anti-collision algorithm increases the number of any passive SAW RFID wireless smart sensors due to increasing of the number of variants for placing reflective structures in time slots, the number of slots, as well as the technological capabilities of producing SAW devices and the dimensions of the piezoelectric material substrate determine the number of identified sensors.
Our research covers the application of the SAW RFID temperature sensors in temperature measurement in the electrical industry.

Acknowledgment
The authors wish to acknowledge continuing support from RF SAW R&D Center in St. Petersburg, Russia, which operates with SAW RFID technology in the smart sensors domain. This company is developing smart wireless passive temperature sensors based on SAW RFID technology.

The authors express thanks to all the current and past colleagues for their varied contributions to this research.

References

[1] Jalal A S 2015 Passive RFID Tags *Wulfenia Journal* **22** 12 415-35
[2] Plessky V P and Reindl L M 2010 Review on SAW RFID tags *Proc.IEEE Trans Ultrason Ferroelectr Freq Control* **57** 3 654-68
[3] Karmakar NC, Koswatta R, Kalansuriya P and Rubayet E 2013 Chipless RFID reader architecture *Artech House*
[4] Malocha D C, Gallagher M, Fisher B, Humphries J, Gallagher D and Kozlovski N Passive 2013 Wireless Multi-Sensor SAW Technology Device and System Perspective *Sensors* **13** 1 1-27
[5] Sorokin AV and Shepeta AP Anti-collision radio-frequency identification system using passive SAW tags *InSmart Sensors, Actuators, and MEMS VIII* **10246** 1024613 International Society for Optics and Photonics
[6] Podoplekin Y F, Sorokin A V and Shepeta A P 2017 Anticollision passive radio frequency tag with time–frequency information *Marine Radio Electronics* **1** 59 41
[7] Sharma M and Singh S K Orthogonality Measurement of OFDM Signal *Indonesian Journal of Electrical Engineering and Computer Science* **9** 3 595-598
[8] Rafiqul I M, Rafiq S, Yasmin MS and Habaebi MH 2017 A 2X2 MIMO Patch Antenna for Multi-Band Applications *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)* **5** 4 383-389
[9] Habaebi M, Rosli R and Islam M R 2017 RSSI-based Human Presence Detection System for Energy Saving Automation *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)* **5** 4 339-350
[10] Kang A, Zhang C, Ji X, Han T, Li R and Li X 2013 SAW-RFID enabled temperature sensor. *Sensors and Actuators A: Physical* **201** 105-113
[11] Harma, S., Plessky, V. P. “Surface Acoustic Wave RFID Tags,” Development and Implementation of RFID Technology 1(1), 145-158 (2009).
[12] Plessky VP and Reindl LM 2010 Review on SAW RFID tags *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, **57** 3 654 - 68
[13] Harma S, Arthur W G, Hartman C S, Maev R G and Plessky V P 2008 Inline SAW RFID Tag Using Time Position and Phase Encoding *Proc. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* **55** 8 145-158
[14] Binder G 2011 SAW Transponder–RFID for Extreme Conditions *Deploying RFID – Challenges, Solutions and Open Issues* **1** 1 303-318
[15] Stelzer A, Scheiblhofer S, Schuster S and Brandl M 2008 Multi-Reader/Multi-Tag SAW RFID Systems combining Tagging, Sensing, and Ranging for Industrial Applications *IEEE Frequency Control Symposium* **1** 2 263-272
[16] Koygerov A S and Dmitriev V F 2010 Radiomarker on surface acoustic waves with noise-proof frequency-manipulated code *Proc. Modeling of processes and systems Information management systems* **4**
[17] Sorokin A V, Shepeta A P and Smirnov Y G Passive anticollision radiofrequency identification tag on surface acoustic waves with frequency–time difference Patent 2616342
[18] Malocha DC, Puccio D and Gallagher D 2004 Orthogonal Frequency Coding for SAW
Device Applications In Proceedings of the IEEE Ultrasonics Symposium, Montreal, Canada 1082–1085.

[19] Malocha D C, Gallagher D and Hines J 2004 SAW Sensors Using Orthogonal Frequency Coding In Proceedings of the 2004 IEEE International Frequency Control Symposium and Exposition, Montreal, Canada 307–310