ON APPLICABILITY OF ENERGY HARVESTING TECHNOLOGIES FOR EMERGENCY VICTIMS DETECTION SYSTEM BUILDING

In this paper we propose a technique for a potential distance calculation for a system of detection emergency situation victims equipped with passive radio-tags. This calculation is performed for three channel models: open territories, forest and snowy field. For every model a level of a reader signal received by radio-tag is estimated as a function of distance. Basing on characteristics of state-of-art systems-on-crystal used for radio-tags building an average energy consumption is estimated with a few polling rates. An quantitative characteristics of harvested electromagnetic energy generated by reader in a far field is calculated via electric model of harvester. Our study shows that a potential distance of investigated system based on energy harvesting technology doesn’t exceed 50 meters for typical scenarios.

Keywords: devices for energy collection, harvesting, victim detection system, channel budget.

Introduction
Sensing elements, primary transducers, and detectors based on these devices form the basis of all automated information processing systems and industrial control systems. The task for the organization of a decision support system at emergencies can be considered as a special case of the processing procedure at the emergency monitoring system. The development of passive wireless detectors is one of the promising directions for the development of monitoring systems [1].

The increase in the range of detectors and the provision of the required accuracy for them are the main problems during the development of such devices. The range depends on the power and waveform of the challenging signal radiated by the reader (readout device), the ratio between the spectral densities of the signal reradiated by the detector and interference (signal to noise ratio), the shape of the impulsive admittance function for the sensing element, etc. [2].

It is possible to mark two competitive trends evolving in the area of implementation of remote monitoring systems:

• systems with the use of semiconductor detectors (chip sensors, tags);

• systems based on detectors realizing the principles of functional electronics (chipless sensors, tags) [3].

Generally, one of the important elements of a semiconductor detector is the harvester; this is a device for the collection and conversion of the energy of external electromagnetic fields designed for the power supply of the detector.

Each trend has its own specific strengths and shortcomings which are taken into account by the system designers depending on the system application features. The range of tag operation under different signal propagation conditions is an important criterion of quality.

Further, three different application scenarios typical for the case of emergencies will be considered in the article with regard to semiconductor detectors (radio tags):

• open spaces (fields, flatlands);

• woodlands;

• snowbound territories.

The computation of the system operation range with the standard parameters of the semiconductor tag will be implemented for each scenario.
The model of a channel for energy transfer from the reader to the harvester

Signal propagation along the Earth at the open spaces

The PE (Plane Earth) model analyzed in the paper [4] is the typically encountered formula describing the signal attenuation during its propagation along the Earth’s surface without additional obstacles:

\[ L_{PE}^{dB} = 40 \log(d) - 20 \log(h_T) - 20 \log(h_R), \]

where \( L_{PE}^{dB} \) is attenuation (dB); \( d \) is the distance between the relaying and receiving points, m; \( h_T, h_R \) are the transmitter and receiver antenna suspension heights, m, respectively.

Woodlands

The LITU-R attenuation model for woodlands proposed in the paper [5] was used for the computation of radio signal parameters in these conditions. This model is based on the PE model and is distinguished from it by the supplementing of a summand into the formula (1) with the requirement that this summand accounts for additional attenuation contributed by the shadowing with tree trunks and rereflections:

\[ L_{LITU}^{dB} = 0.48 f^{0.43} d^{0.13} + 40 \log(d) - 20 \log(h_T) - 20 \log(h_R). \]

where \( L_{LITU}^{dB} \) is attenuation, dB; \( f \) is frequency, GHz.

Snowbound territories

The paper [6] shows the series of experiments which have been conducted for the development of a model for signal propagation over the snow surface (SNOW model). It has been demonstrated that the presence of snowpack strongly influences the attenuation in the channel. The standard log-model of propagation [7] is used as a basis; the factors of this model are taken for three values of antenna suspension height:

\[ L_{LG}^{dB} = L(d_0) + 10 n \log \left( \frac{d}{d_0} \right). \]

The evaluation of mean power received by the radio tag

Let us take an assessment of power received by the radio tag. The parameters of the system selected for this calculation are presented in Table 2.

The graphs for the dependence of received power on the distance for three models of propagation are presented in Fig. 1.

Analyzing Fig. 1, one can conclude that the received power level at 100 m distance is in the range from –45 dBm to –35 dBm depending on the selected scenario.

The calculation of power consumed by the radio tag

Let us use the standard parameters of low-power systems-on-the-chips equipped by the microcontroller and transceiver [8] (Table 3).

The represented data testify that the energy consumption of the radio tag in the active mode with 3.3 V standard supply voltage is

\[ P_a = 3.3 \cdot 16 \cdot 10^{-3} = 52.8 \cdot 10^{-3} \text{W} \]

which is \( 17.2 \text{ dBm} \), respectively.

If it is necessary to encourage the working conditions for the tag within the intervals between the inquiries (e.g., for the on-line monitoring of biometric indicants in the same way that it was described in the paper [1]), one should also take into account the energy consumption in the sleep mode for the calculation of average power consumption:

\[ P_{avg} = \frac{T}{T} P_a + \left( 1 - \frac{T}{T} \right) P_s, \]

The resulting energy consumption of the device \( P_{avg} \) will depend on the period of frames readout:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency (MHz)</td>
<td>433</td>
</tr>
<tr>
<td>Power radiated by the reader (W)</td>
<td>2</td>
</tr>
<tr>
<td>Antenna power gain for the reader (dB)</td>
<td>10</td>
</tr>
<tr>
<td>Antenna power gain for the tag (dB)</td>
<td>0</td>
</tr>
<tr>
<td>Antenna suspension height for the reader (m)</td>
<td>1</td>
</tr>
<tr>
<td>Antenna suspension height for the tag (m)</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1. The model factors from the paper [7]

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>( L(d_0) )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>65.83</td>
<td>3.51</td>
</tr>
<tr>
<td>1.00</td>
<td>66.76</td>
<td>1.26</td>
</tr>
<tr>
<td>1.50</td>
<td>65.16</td>
<td>1.87</td>
</tr>
</tbody>
</table>

Table 2. Parameters of the system
where $T$ is the total time for information acquisition (sec), and $\tau$ is the duration of readout (sec).

Fig. 2 shows the dependence of the power consumed by the radio tag on the message retrieval period in the following cases:

- the radio tag is in the sleep mode during the pauses between the messages;
- the radio tag is switched off during the pauses between the messages.

It should be noted that in the case of keeping the tag in the on-line state, the resulting energy consumption goes to the sleep mode energy consumption (~30 dBm) with the enlargement of the message retrieval period. Using the presented calculation, one can conclude that the average energy consumption would be ~20 dBm with a 5 min tag inquiry period. Then, analyzing Fig. 1, one can conclude that the coverage range of the system is equal to 15–40 m even with 100% efficiency of the harvester. When the message retrieval period continues for 3 hours, the values of energy consumption would be in the range from ~35 dBm (the tag is switched off within the pauses between the inquiries) to ~25 dBm (keeping the sleep mode within the pauses between the inquiries), and the coverage range would be in the range from 20 to 100 m depending on the scenario.

Следует иметь в виду, что данный расчет является приближенным, т.к. не учитывает реальный КПД харвестера, существенно влияющий на результатирующие характеристики системы [9, 10]. Более точные вычисления будут проведены далее.

It should be kept in mind that this calculation is approximate because it does not take into account the real efficiency of the harvester having the significant influence on the resulting characteristics of the system [9, 10]. More exact calculations will be provided later.

### The efficiency of the harvester

Generally, modern highly-effective harvesters are developed based on Schottky diodes with extra low cutoff voltages (about 30–40 mV). The reviews [11, 12] note the following main factors influencing the effectiveness of harvesting.

The cut-off voltage affects directly the minimum level of the rectified signal. The corresponding graphs of harvester efficiency are presented in Fig. 3 which is plotted using the procedure considered in the paper [12].

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**Table 3. The radio tag digital unit parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The consumption current in the relaying mode at –6 dBm radiated power (mA)</td>
<td>16</td>
</tr>
<tr>
<td>The consumption current in the sleep mode (µA)</td>
<td>0.3</td>
</tr>
<tr>
<td>The data flow rate (kbit/sec)</td>
<td>2.4</td>
</tr>
<tr>
<td>The dimensions of the preamble and synchronous sequence (bits)</td>
<td>64</td>
</tr>
<tr>
<td>The dimension of the message (bits)</td>
<td>96</td>
</tr>
<tr>
<td>The duration of the message (msec)</td>
<td>67</td>
</tr>
</tbody>
</table>
It is interesting to note that the 0.04 V value of cut-off voltage is the standard for modern high-specification Schottky diodes, while the graph characterized by the 0.004 V cut-off voltage is hypothetical at the state-of-the-art level. The $P_{\text{min}}$ input level (W) where the harvester efficiency reaches the 50–60% levels, can be estimated approximately by the formula

$$P_{\text{min}} = 2\frac{V_T^2}{R},$$

where 2 is the multiplier characterizing the loss at the antenna with the ideal matching; $V_T$ is the cut-off voltage (V); $R$ is the antenna resistance (Ohm).

Generally, the minimum power where the efficiency is non-zero (at a level of percent proportions) is lower for 30 dB. Therefore, the minimum power with the $V_T = 0.005$ V will be equal to $-63$ dBm; with the $V_T = 0.05$ V it will be will be equal to $-43$ dBm; and with the $V_T = 0.5$ V it will be about $-23$ dBm, respectively (that will be in agreement with the modeling results presented in Fig. 3).

Another harvesting efficiency factors are the parasitic capacitances and spurious inductances of Schottky diode packages used for harvesters development. The dependencies of idealized harvester efficiency on the input power level with three frequencies of the received signal are presented in Fig. 4.

It is apparent that the harvester efficiency starts to decrease considerably with higher frequencies (from 10 GHz).

### Quantitative implications

Let us implement the quantitative analysis for the system operation range with different requirements to the rate of message retrieval from the tag using the available dependencies.

For example, the acceptable delay level for energy storage with the response is 10 minutes. One can conclude from Fig. 2 that the power required for the operation of the tag would be $-25$ dBm herewith. For example, such level of effective (accumulated) power can be provided with $-21$ dBm input signal level and 40% efficiency that corresponds to $-4$ dB loss (see Fig. 3, 0.04 V cut-off voltage). One can also conclude from Fig. 1 that such power can be provided depending on the scenario at 15–40 m distance.

Likewise, the average power with 10 sec storage time would be $-5$ dBm (see Fig. 2), which is provided with the $-4$ dBm input power and 90% efficiency (see Fig. 3). Then, the coverage range of the system will not exceed 20–30 m.

The presented values agree completely with the characteristics of the tag sample which is up to now one of the best from the developed using the harvesting technology. The 25 m distance was achieved with 1.78 W reader transmitter power that was described in the series of natural experiments [13].

It should be noted that the 100 m operational range is inaccessible practically for reference scenarios: then, the accepted power would not exceed $-35$ dBm (see Fig. 1) and, consequently, the 5% efficiency (Fig. 3 for $V_T = 0.04$ V), which would lead to the fact that the effective accumulated power would not exceed $-48$ dBm (insufficient level for operation of semiconductor devices).

### Results

The conducted computation shows that the semiconductor detectors have significant restrictions for the
operational range. The expected value of this system parameter does not exceed 50 m for standard application scenarios.

If one needs the enhancement of the range to 100 m and more, it is necessary to consider the variants of chipless devices based on the surface acoustic waves (SAW) technology [14, 15].

**Conclusion**

This article has detected the important interrelations between the operational range for the information acquisition system about the people in the emergency zone and such parameters of the system as the characteristics of the environment for signal propagation, harvester efficiency, the data update rate at the collection point, etc.

The obtained results can be used for the development of similar networks (e.g., for the selection of the element base, reader transmitter power, the optimum rate of inquiry).

The further directions of work can be the origination of closed formulas connecting the above-mentioned characteristics, as well as the statement of optimization tasks aimed at maximizing the selected key indicator for the network quality depending on the constructive and technological constraints.

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