Wireless Nanosensor Network with Flying Gateway

Rustam Pirmagomedov, Mikhail Blinnikov, Ruslan Kirichek, Andrey Koucheryavy

Wireless Nanosensor Network with Flying Gateway

Rustam Pirmagomedov[1], Mikhail Blinnikov[2],
Ruslan Kirichek[2], Andrey Koucheryavy[2],

[1] Peoples' Friendship University of Russia, Moscow, 117198, Russian Federation
[2] St. Petersburg State University of Telecommunication, St. Petersburg, 193232, Russian Federation
prya.spb@gmail.com, michael.blinnikov@gmail.com,
kirichek@sut.ru, akouch@mail.ru

Abstract. The use of unmanned aerial vehicles (UAVs) with a nano communication networks can significantly expand the network's capabilities. In addition, UAVs can automate the process of data collection and reduce its cost. This article expands the application that uses UAV to collect data from passive nanosensor devices. The article considers the specifics of the THz frequency range for the energy supply of nanodevices, as well as for communication with them. The paper presents a mathematical model of these processes and simulation results.

Keywords: nanonetworks, nanosensors, UAV

1 Introduction

At this point, developments in wireless sensor networks have achieved significant results. These networks consist of numerous miniature nodes, equipped with a transceiver, microprocessor, power unit, and sensor. This article considers one of the types of wireless sensor networks – passive wireless sensor networks. In this case, sensor units do not have an onboard power supply. The energy harvested from electromagnetic waves provides sufficient power for the functioning of the passive sensor unit and the signal transmission to the gateway (reader).

Passive sensor units do not require any maintenance, have a long service life, and low cost. That is why they continue to gain popularity in many industries including medicine, production processes monitoring, smart cities, etc. The development of nanotechnologies has served as an impetus for the improvement of sensor unit technologies, with many efforts being devoted to the development of devices for nano-communication networks. Several of these devices use the unique properties of graphene to transmit data in the THz frequency range, with some elements having been patented [1]. The devices have microscopic dimensions; an example is the passive acoustic graphene nanosensor [2, 3], the elements of which are placed on a graphene board with geometric dimensions of 200x200 μm.

Many problems and questions are associated with methods of data collection from passive sensor units since they do not possess a permanent communication channel with other network elements. To communicate, these devices should be provided with energy levels sufficient to both perform the measurement by integrated sensor and transference of the measured values to the network gateway. In many cases, this is done manually with the help of employees who bring readers to the sensor devices. An alternative is the use of automated means, such as UAVs.

In this article, we will consider communication aspects of data collection from the passive nanosensor devices located in a specific area, by means of UAVs, using a THz frequency range for wireless communication.

The article is organized in the following way: Section 2 describes the application, its operating principle, structure, and aims. Section 3 considers the mathematical model of data collection in the THz frequency range. Section 4 presents results of a simulation using the developed model. In conclusion, the results of the work are analyzed, with ideas for future research being considered.

2 Application description

To begin with, we can assume that there is a field (or a particular surface), which needs to be monitored. In this application, sensor devices are being used for monitoring purposes. These devices can measure physical parameters. To seed sensor devices on the field, the UAV (Fig. 1) deposits them randomly. When we are ready to take measurements from sensors, we will also use the same UAV. It is already oriented to fly over the field, utilizing the existing sensors in a predetermined route using GPS (Fig. 2) and then communicates with the sensors.

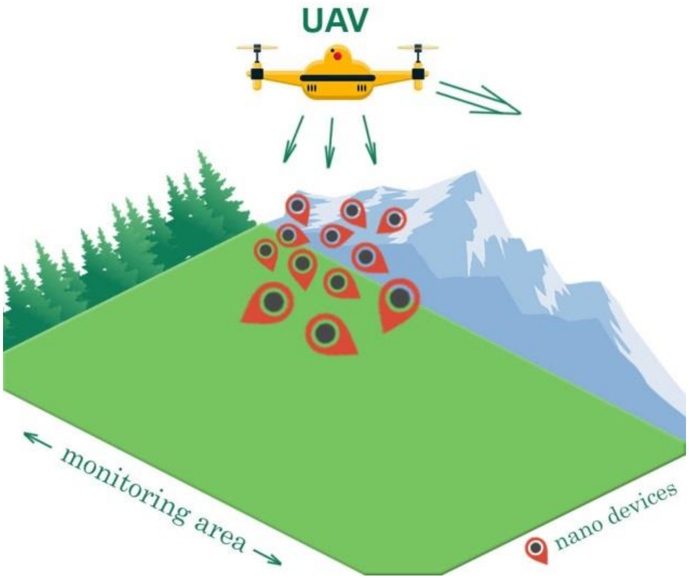


Fig. 1. Sensors installation

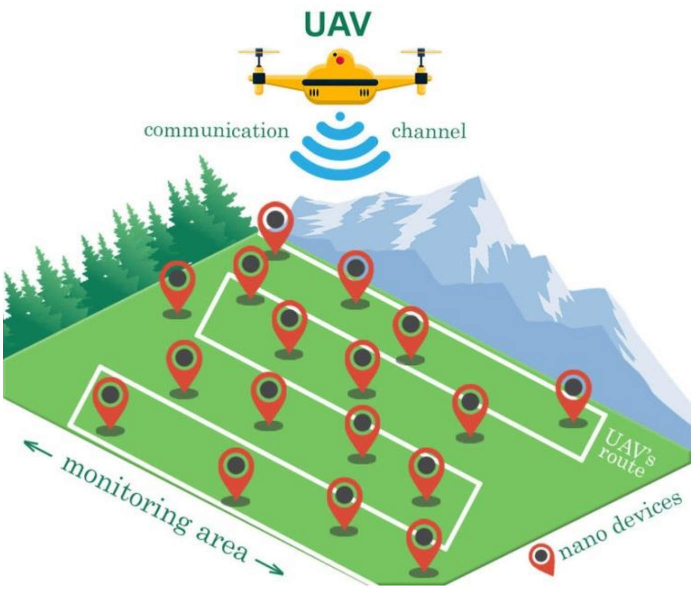


Fig. 2. Collecting data from sensors

Flying over the territory where passive nanosensor units are randomly located, the UAV emits electromagnetic (EM) waves of the THz range, the energy of these waves accumulates in the sensor devices by converting the SPP waves into electricity (NOTE: the electrical characteristics of nanosensor devices are not considered in this article). The reason of using of THz range is small size of the sensor devices, in particular plasmon nanoantenna based on graphene [1] After accumulating enough energy, the nanosensor measures a certain parameter and sends a report to the flying gateway (UAV acts as a flying gateway), using the THz frequency range. The use of THz frequency range is determined by the need to minimize the sensor device size. When collecting data, the UAV's current position is taken into account, and therefore data from sensors are identified with geographic coordinates. An example of this structure and data are shown in Table 1. The UAV then sends a report to the remote server through an Internet channel.

Table 1. Structure and data example

Type of sensor	Sensor model	Data	Location	Time	Date
Temperature	XFD3112	34.211	59.903176, 30.491099	12:32:03	22.09.2017

For the passive nanosensor unit to accumulate enough energy, it should be located in the UAV service area – an area that is determined by the propagation length of EM waves with respect to the ground plane. In this article, when developing a model, the boundaries of the UAV service area are taken nominally; in a practical situation, the boundaries can depend on parameters like the THz transmitter capacity, the opening angle and the antenna gain parameter, as well as the UAV's altitude, and flight speed among others.

The system is adaptable and can be useful for many spheres of industry. For instance, better control of the soil conditions in agriculture, monitoring environmental pollution and remediation, or control of constructed linear objects (pipelines, dams, dikes). The information obtained will allow a more exact determination of potential accidents or breakdowns, predicting them and fixing before they worsen.

3 Modeling

To determine the total delay time t_{tot} between the entry of the passive nanosensor unit into the flying gateway service area and the receipt of a sensor report, it is necessary to take into account the time t_{ch}, during which the nanosensor accumulates enough energy, as well as the delay in data transmission t_{sg}:

$$t_{tot} = t_{ch} + t_{sg} \tag{1}$$

The time for data transmission t_{sg} is an integral index that directly depends on the size of the packet being transferred, data transmission technology, time for processing and encapsulation; it is assumed as t_{sg} = 10 ms. The time spent for accumulating the energy by nanosensor can be characterized by the formula (2)

$$t_{ch} = \frac{E_{tot}}{P_{rx} r_c} \tag{2}$$

where E_{tot} – total energy demands required for transmission of the one sensor report; P_{rx} – amount of energy, being receiving by passive nanosensor per second. It is necessary to take into account the conversion coefficient of electromagnetic energy into electric energy r_c=0.5.

In order to calculate electric energy expended by the passive nanosensor unit for transmission of one sensor report to the flying gateway, it's necessary to take into account energy expended on maintaining the nanosensor in working order (until it measures the required parameter), for processing the information received, and the encapsulation of data and sending the packet to the UAV (3) [4].

$$\mathrm{E}_{tot} = \mathrm{E}_s + \mathrm{E}_p + \mathrm{E}_{packet-tx} \tag{3}$$

where E_s – energy demands of nanosensor device for measuring the indicator value; E_p – energy demands for data processing; $E_{packet\text{-}tx}$ – energy demands for sending the data packet to the flying gateway.

During modeling, the values for energy consumption of nanosensors values of the Ultra-Low-Power Smart Visual Sensor [5] were used, as its energy consumption is quite low. Thus, E_s = 1.06 μJ and E_p = 0.73 μJ.

In order to calculate energy expended for sending one data packet there is offered [6] an equation (4) depending on its volume.

$$E_{packet-tx} = N_{bits} W E_{pulse-tx} \tag{4}$$

where N_{bits} – the number of bits contained in the transmitted packet; W – the code weight, i.e., the probability of transmitting the pulse ("1") instead of keeping the mute mode ("0"), $E_{pulse-tx}$ – the energy expended for transmission of one pulse.

Using the THz range has a number of features that affect the power of received signal (5).

$$P_{rx} = \frac{\mathrm{P_{tx}G(f)}}{\mathrm{A(f)}} + N_T(f) + N_{mol}(f) \tag{5}$$

where P_{tx} – power of the transmitted signal; $G(f)$ – antenna gain parameter; $A(f)$ – total attenuation ratio; $N_T(f)$ – thermal noise; $N_{mol}(f)$ – molecular-based absorption noise.

The thermal noise of graphene antennas has yet to be fully explored, but it is suggested to be negligibly small due to the inherent features of this material [7].

For the calculation of the attenuation ratio, it is necessary to take into account not only the attenuation of the signal during propagation in the A_{fspl} space but also the molecular-based absorption A_{mol} [8-10]. Thus, the total attenuation ratio can be characterized by the formula (6):

$$\mathrm{A}(f) = A_{fspl}(f) A_{mol}(f) \tag{6}$$

Free space losses consider attenuation because of wave propagation in the environment [8]. Signal attenuation during propagation in space can be defined as follows:

$$A_{fspl}(f) = \left(\frac{4\pi f d}{c}\right)^2 \tag{7}$$

where d – distance from the transmitter to receiver; f – transmission frequency; c – light velocity.

A feature of using the THz range for wireless communication is the presence of molecular-based absorption, caused by the vibrations and rotation of molecules. Molecular-based absorption of the EM energy is an effect that occurs when the signal is transmitted at frequencies close to, or equal to, the resonance frequencies of molecules, which absorb part of the signal energy and produce noise $N_{mol}(f)$ at the same frequencies due to the internal kinetic energy of the molecules [4].

$$A_{mol}(f) = e^{k(f)d} \tag{8}$$

where k – the average absorption coefficient.

The molecular-based absorption coefficient determines the ability of a molecule to absorb energy and is determined by its physical properties (molecular communications, spatial orientation, etc.) [7]. According to [8], the losses of the molecular-based absorption are calculated depending on the transmission frequency, the distance between the receiving and transmitting antenna, and the environmental conditions where the signal propagates. In this article the molecular-based absorption coefficient was determined by means of the HITRAN database [11, 12] for ambient conditions corresponding to the "USA model, mean latitude, summer", H=0 (mixture correlations: H_2O=1.860000 %, CO_2=0.033000 %, O_3=0.000003 %, N_2O=0.000032 %, CO=0.000015 %, CH_4=0.000170, O_2=20.900001 %, N_2=77.206000 %) at a temperature of 296 K and a pressure of 1 atm.

Thus, according to (5-8), we have:

$$P_{rx} = \frac{\mathrm{P_{tx}G(f)c^2}}{(4\pi f d)^2 e^{k(f)d}} + \mathrm{N_{mol}(f)} \quad (9)$$

As a result of research [7, 8] it was determined that in some frequency ranges the absorption is excessively large and can cause a significantly reduced communication distance. However, there are transparency windows, where the absorption is much less than in other parts of the spectrum. It is worth noting that *k* does not depend on the transmission distance, but only on the ambient conditions and the frequency of the transmitted signal.

In accordance with [7] when the transmittance coefficient values are lower than 94.5% (equivalent to the absorption coefficient values of the environment higher than 5.5%), the molecular-based absorption noise N_{mol} becomes equal to the maximum value of -203.89 dB/Hz (≈10^{-20} W/Hz), which corresponds to the Johnson-Nyquist thermal noise level.

Since there is no need to use high transmission speeds for sensor reports, and therefore no current need to use a broadband channel, a bandwidth of 100 kHz per one nanodevice is used in the model. This article considers the frequency range of 0.1-0.15 THz. Consequently, taking into account that the environment transmission coefficient in the transparency windows is always above 95.5% at small and medium distances, and the molecular-based noise per 1 Hz of the used frequency band is about ≈ 10^{-20} W, we obtain N_{mol} = 1 fW, which allows considering the molecular-based noise value as negligibly small.

As mentioned above, the model considers the frequencies of the first transparency window f_1 = 0.1 THz and f_2 = 0.15 THz. It's also assumed that during the entire flight the distance between the passive nanosensor device and the flying gateway varies from the minimum distance d_{min} = 40 cm to the maximum distance d_{max} = 50 cm, and therefore, calculations are made for these two distances, and the interference capacity of the flying gateway $P_{tx}*G$ = 10 mW. The results of the calculations performed, as well as the values of the primary parameters, are presented in Table 2.

According to [13], the number of "1" and "0" bits in the packet is approximately the same, and therefore, *W* = 0.5. The energy of one pulse is equal to $E_{pulse-tx}$ = 1 pJ for transmission to a distance of 10 mm [14]. In this article, the distance from the passive nanosensor to the flying gateway *d* directly depends on the UAV's flight altitude *h*, and therefore taking *h* = 40 cm and the radius of the UAV's service area *R* = 30 cm. Consequently $E_{pulse-tx,\ min}$ = 1.6 nJ and $E_{pulse-tx,\ max}$ = 2.5 nJ. Thus, taking into account that the total packet volume containing the sensor report is taken to be V_s = 16 bytes, N_{bit} = 128 bits, [15] it became possible to calculate the energy of one packet $E_{packet-tx,\ min}$ = 0.21

μJ and $E_{packet\text{-}tx,\ max}$ = 0.32 μJ. Therefore, in accordance with (3), the total energy demands for transmission of one sensor report is about $E_{tot,\ min} \approx 2$ μJ and $E_{tot,\ max} \approx 2.11$ μJ.

Table 2. Variables, constants and their units of measure

Name	Identification	Value
THz-reader capacity	P_{tx}*G	10 mW
Transmission frequency (1st case)	f_1	0.1 THz
Transmission frequency (2nd case)	f_2	0.15 THz
Frequency band width	Δf	100 kHz
Minimum distance between the passive nanosensor and the flying gateway	d_{min}	0.4 m
Maximum distance between the passive nanosensor and the flying gateway	d_{max}	0.5 m
Absorption factor (0.1 THz)	k_1	2.58×10^{-5} m^{-1}
Absorption factor (0.15 THz)	k_2	1.01×10^{-4} m^{-1}
Energy demands of the passive nanosensor for transmitting one sensor report (40 cm)	$E_{tot,\ min}$	2 μJ
Energy demands of the passive nanosensor for transmitting one sensor report (50 cm)	$E_{tot,\ max}$	2.11 μJ
Capacity at the input of the passive nanosensor (0.4 м, 0.1 THz)	$P_{rx1,\ min}$	3.57 nW
Capacity at the input of the passive nanosensor (0.4 м, 0.15 THz)	$P_{rx2,\ min}$	1.59 nW
Capacity at the input of the passive nanosensor (0.5 м, 0.1 THz)	$P_{rx1,\ max}$	2.28 nW
Capacity at the input of the passive nanosensor (0.5 м, 0.15 ТГц)	$P_{rx2,\ max}$	1.01 nW
Time of charging the passive nanosensor (0.4 m, 0.1 THz)	$t_{ch1,\ min}$	0.011 s
Time of charging the passive nanosensor (0.4 m, 0.15 THz)	$t_{ch2,\ min}$	0.025 s
Time of charging the passive nanosensor (0.5 m, 0.1 THz)	$t_{ch1,\ max}$	0.019 s
Time of charging the passive nanosensor (0.5 m, 0.15 THz)	$t_{ch2,\ max}$	0.041 s
Time of data transmission from the passive nanosensor to the flying gateway	t_{sg}	0.010 s

4 Simulation Results

The simulation model was designed using Python software, the positioning data of the passive nanosensor is unknown and set randomly, and the UAV moves linearly at a constant speed v and a service area radius R.

The number of packets received by a flying gateway directly depends on the time of the passive nanosensor presence in the UAV's service area, t_{ex} (10):

$$t_{ex} = \frac{D}{v} \tag{10}$$

where D ($D \leq 2R$) – data exchange range.

What is more, if the condition $t_{ex} \geq (t_{ch} + t_{sg})$ is not fulfilled packet loss occurs. However, if $t_{ex} \geq n(t_{ch} + t_{sg})$, one nanodevice transmits 'n' copies of packets, the energy accumulation and report transmission cycle succeeds several times. This can result in data redundancy.

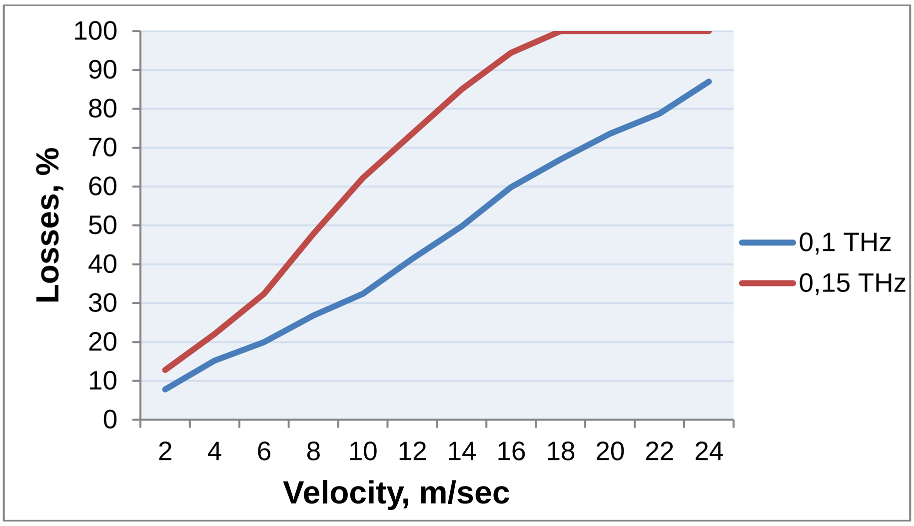
For determining the distance D, the circle line picking method is used [16]:

$$D = 2R(\frac{\pi}{2}F(s) \tag{11}$$

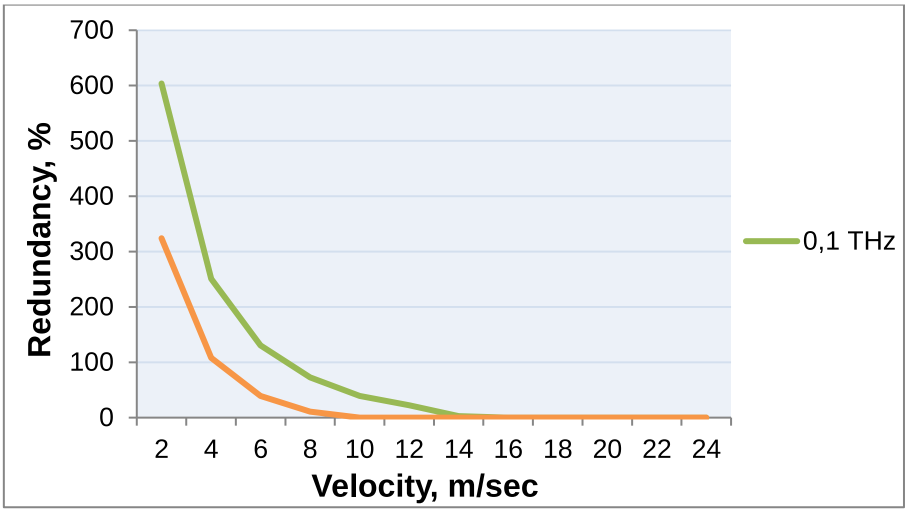
$$F(s) = \frac{2}{\pi}arcsin\left(\frac{s}{2}\right) + C \tag{12}$$

where $F(s)$ –probability density function within a circle; s – the distance between two points on the circle of the UAV's service area; C – constant.

In the capacity of the simulation results the dependency diagrams of losses and redundancy of the transmitted packets on the UAV's velocity for two frequencies (Fig. 3, 4):

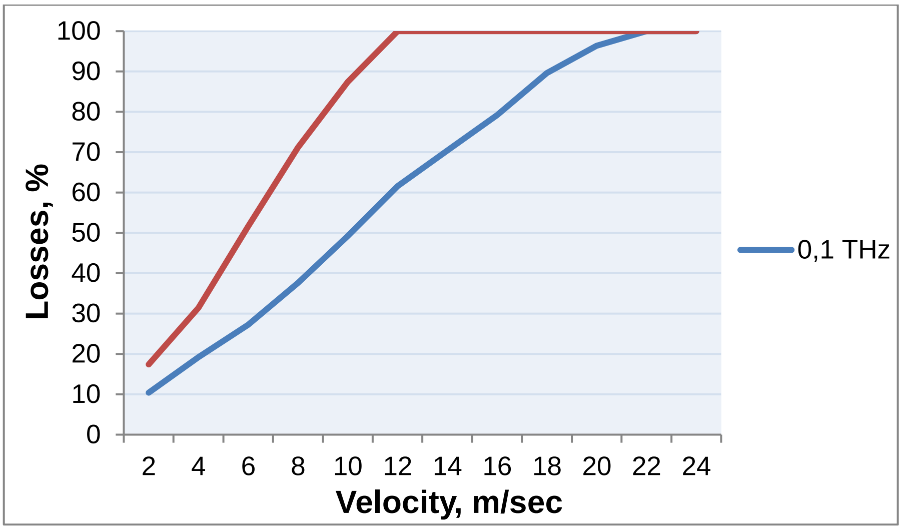


A)

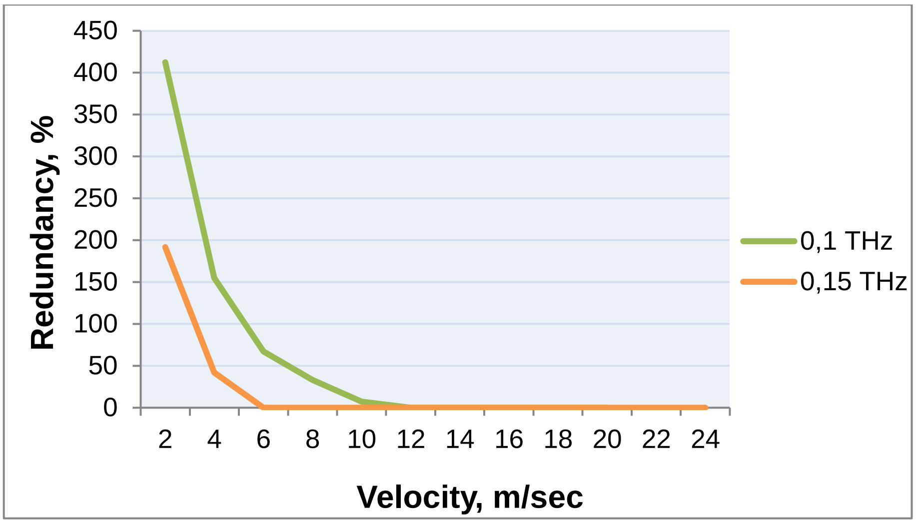


B)

Fig. 3. Dependence of packet losses (A) and redundancy (B) on the UAV's velocity at the transmission frequencies of 0,1 THz and 0,15 THz (D = 0,4 m)



A)



B)

Fig. 4. Dependence of packet losses (A) and redundancy (B) on the UAV's velocity at the transmission frequencies of 0,1 THz and 0,15 THz (D = 0,5 m)

From the simulation results it can be seen that when operating at a frequency of 0.1 THz and low UAV flight speeds (2-4 m/s), the considered data collection system has a loss of no more than 20%, which can likely be compensated by the redundancy in the number of nanosensor devices. In order to reduce losses, it is possible to have the UAV "hovering" in the air over the sensor field area. However, it should be taken into account that the UAV has a limited battery capacity and therefore a limited operating time.

Regarding the redundancy in the number of sensor reports transmitting to the flying gateway, creating high traffic in the "flying gateway – user" channel, it is possible to use an algorithm that considers data accumulation and its transmission as one large packet [17]. Such an algorithm uses the Internet connection more efficiently since it reduces the amount of transmitted signaling information (packet headers).

5 Acknowledgment

The publication has been prepared with the support of the "RUDN University Program 5-100".

6 Conclusion

Integration of wireless sensor networks and UAVs can reduce the cost and simplify the data collection process through automation. The usage of nanotechnologies will expand the scope of application of such networks for those industries where the size of the sensor devices is the primary consideration.

This article analyzed the use case of data collection from passive nanosensor devices using a flying gateway, which the UAV is an example of, and uses the THz frequency range for both energy harvesting and data transmission. The article takes into account the characteristics of signal transmission in the THz frequency range, calculates the energy expended by the sensor device, and also presents the numerical results of the simulation. The application of graphene-based components will reduce energy consumption. Since device charging will take less time, the delay time in the collection and transmission of sensor reports will also decrease, which will further reduce the resulting packet losses. At the same time, the model presented in this article does not take into account the possible influence of the weather and the presence of additional obstacles between a UAV and the sensors; these factors will be taken into account in future works. Moreover, for future research it's expected that technological enhancements will bolster the UAV's characteristics (battery capacity and energy consumption), application prototyping and practical testing.

References

1. Akyildiz, Ian F., and Josep Miquel Jornet. "Graphene-based plasmonic nano-antenna for terahertz band communication." U.S. Patent No. 9,643,841. 9 May 2017.
2. Aznakayeva, D. E., I. A. Yakovenko, and E. G. Aznakayev. "Passive acoustic graphene nanosensor modeling." Radar Methods and Systems Workshop (RMSW), IEEE. IEEE, 2016.
3. Aznakayeva, D. E., I. A. Yakovenko, and E. G. Aznakayev. "Numerical calculation of passive acoustic graphene nanosensor parameters." Radar Methods and Systems Workshop (RMSW), IEEE. IEEE, 2016.
4. M. Blinnikov, R. Pirmagomedov. "Wireless Identifying System Based on Nano-tags" Proceedings, 18th International Conference on Advanced Communication Technology (ICACT) 2018. — Phoenix Park, Korea – in publishing
5. M. Rusci, D. Rossi, M. Lecca, M. Gottardi, E. Farella, L. Benini, "An event-driven ultra-low-power smart visual sensor", IEEE Sensors Journal, vol. 16, no. 13, pp. 5344-5353, 2016.
6. J. M. Jornet, I. F. Akyildiz, "Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band", IEEE Trans. Nanotechnol., vol. 11, no. 3, pp. 570-580, May 2012.
7. Boronin P. et al. Capacity and throughput analysis of nanoscale machine communication through transparency windows in the terahertz band //Nano Communication Networks. – 2014. – Т. 5. – №. 3. – С. 72-82.
8. J. Jornet and I. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band", IEEE Transactions on Wireless Communications,, vol. 10, no. 10, pp. 3211-3221, 2011.
9. J. Kokkoniemi, J. Lehtomäki, K. Umebayashi, M. Juntti, "Frequency and time domain channel models for nanonetworks in terahertz band", IEEE Transactions on Antennas and Propagation, vol. 63, no. 2, pp. 678-691, Feb 2015.
10. K. Tsujimura, K. Umebayashi, J. Kokkoniemi, J. Lethomäki, "A study on channel model for THz band", 2016 International Symposium on Antennas and Propagation (ISAP), 24-28 Oct. 2016
11. L. S. Rothman, "The HITRAN molecular spectroscopic database and HAWKS (HITRAN atmospheric workstation): 1996 edition", J. Quant. Spectrosc. Radiat. Transfer, vol. 60, no. 5, pp. 665-710, Nov. 1998.

12. http://hitran.iao.ru/
13. J. M. Jornet, I. F. Akyildiz, "Low-weight channel coding for interference mitigation in electromagnetic nanonetworks in the terahertz band", Proc. IEEE Int. Conf. Commun., pp. 1-6, Jun. 2011.
14. J. M. Jornet, I. F. Akyildiz, "Information capacity of pulse-based wireless nanosensor networks", Proc. 8th Annu. IEEE Commun. Soc. Conf. Sens. Mesh Ad Hoc Commun. Netw., pp. 80-88, Jun. 2011.
15. Rustam Pirmagomedov, Ivan Hudoev, and Daria Shangina. "Simulation of medical sensor nanonetwork applications traffic." International Conference on Distributed Computer and Communication Networks. Springer, Cham, 2016.
16. Weisstein, Eric W. "Circle line picking." From MathWorld–A Wolfram Web Resource (2004).
17. R. Pirmagomedov , M. Blinnikov , R. Glushakov, A. Muthanna, R. Kirichek, A. Koucheryavy, “Dynamic Data Packaging Protocol for Real-Time Medical Applications of Nanonetworks”, Internet of Things, Smart Spaces, and Next Generation Networks and Systems, pp.196-205, 2017.