The Effects of Nanosensors Movements on Nanocommunications

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ABSTRACT

Nanonetworks expand the capability of a single nanosensor in computational complexity and transmission range. If information provided by sensors is to be transferred to the end system in a multi-hop fashion, nanodevices movement during transmission process would cause some effects to the received signal. Correct symbol detection is necessary to avoid the interference between sub-sequence symbols. In this paper, we propose a mobility model for nanonetworks. We investigate the effects of nodes movements in terms of pulse time-shift, Doppler effect, information rate reduction, error rate increase, and signal shape for correct detection. The results show that pulse time-shift introduce inter-symbol interference (ISI) for large data transmission, while the movement speed has significant impacts on the maximum information rate and on the achievable bit error rate.

1. INTRODUCTION

Nanosensors based on graphene nanomaterial have size in the scale of several hundreds nanometers, that allow to do the sensing functions at nanoscale, i.e. detect the chemical compounds in concentrations as low as one unit per billion or the presence of virus and bacteria. According to its small dimension, it has limitation in computational complexity, energy consumption, and transmission coverage. Connecting nanosensors could enhance the complexity and operational range of a nanosensor [1]. Wireless nanosensor networks will enable novel advance applications, such as health monitoring [9], multimedia communications, and surveillance systems against Nuclear, Biological and Chemical (NBC) attacks at nanoscale [5].

Many applications will force nanosensors to have movement activity due to the environment. For example, in health monitoring, Body Area Networks (BAN) could use nanosensors in blood circulation. The movement speed and coverage area are defined by the speed of blood and location within the patient body. This means that that the distance among nodes changes during communication.

Electromagnetic communication among nano-devices has been investigated by Jornet et al. [5], who show that the operating frequency will be at Terahertz band (0.1–10 THz). They proposed the TS-OOK modulation which uses very small duration pulses (100 femtoseconds) as a base for information exchange within the network.

TS-OOK needs a high synchronization among nodes, whereas node movement changes the communication distance. In this paper, we investigate some parameters such as pulse time-shift, Doppler effect, information rate reduction, and error rate increase during node movement to provide correct signal detection. The results can be used to check the effectiveness of nanocommunication when nodes move, and have more accurate nanocommunication simulation parameters [2, 9].

The rest of the paper is organized as follows. In Sec. 2, we describe TS-OOK. In Sec. 3, we present the effect of node movement in the time domain which introduces pulse time-shift, the effect of node movement in frequency domain (Doppler effect), information capacity reduction, and bit error rate increase. In Sec. 4, we provide the simulation results. Finally, the paper is summarized in Sec. 5.

2. TS-OOK MODULATION IN TERAHERTZ BAND

Electromagnetic communication among nanosensors must specify the ability of nanomaterials to radiate and receive electromagnetic waves. In [6], the authors show that nanoantenna based on a derivative of graphene, carbon nanotube (CNTs) and graphene nanoribbons (GNRs), resonate at the Terahertz band (0.1–10 THz). Furthermore, they investi-

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gate the channel capacity based on different power allocations through analytical and numerical results.

Path-loss and noise at Terahertz band depend on the molecular compositions and the transmission distances. The path-loss in Terahertz band is composed by the spreading loss and the molecular absorption loss [5]. The spreading loss is the attenuation when a wave propagates through the medium, while absorption loss is the attenuation due to absorbed wave's energy by molecules along the transmission path, which converts the part of wave energy into internal kinetic energy at the molecule level.

In order to investigate the channel capacity, Jornet et al. [6] use HITRAN (HIgh resolution TRANsmission molecular absorption database), an online catalog [12] for absorption loss computation. As shown in Fig. 1, the absorption loss is function of distance and frequency. For transmission distance below 1 mm, the attenuation is very small. As the distance increases, the path-loss greatly increases too. For example, when the transmission distance is above 1 m, the path-loss is more than 200 dB for frequencies above 10^{12} Hz. The total path-loss is the sum of the spreading loss and the absorption loss as follows:

$$A_{\text{total}}(dB) = A_{\text{abs}}(dB) + A_{\text{spread}}(dB) \quad (1)$$

$$A_{\text{abs}}(f,d) = \frac{1}{\tau(f,d)} \quad (2)$$

$$A_{\text{spread}}(dB) = 20 \times log10\left(\frac{4\pi f d}{c}\right) \quad (3)$$

where f is the operating frequency, d the transmission distance, and τ the transmittance of the molecular composition in the channel along the transmission path. This parameter measures the ability of the channel to pass the electromagnetic wave. The characteristic of this parameter is described by the Beer-Lambert Law as [3]

$$\tau(f,d) = e^{-k(f)d} \quad (4)$$

where k is the medium absorption coefficient. Molecules in the channel not only absorb the energy of the transmitted waves, but they also introduce noise. This noise has a correlation with the last transmitted signal. Absorption noise is characterized with the parameter emissivity of channel ε as

$$\varepsilon(f,d) = 1 - \tau(f,d) \quad (5)$$

The absorption noise can be modeled as an additive Gaussian noise, with zero mean and the variance as the noise power [6]. The total noise power can be counted using:

$$N = \int_B k_B\, T_0\, \varepsilon\, \frac{P_m(f)}{P_T}\, df \quad (6)$$

where B refers to channel bandwidth, k_B to the Boltzmann constant, T_0 to the reference temperature, k to the medium absorption coefficients, P_m to the power spectral density, and P_T refers to the total maximum transmitted power. The noise is only produced when a pulse is transmitted through the channel N_1. Noise for silence transmission N_0 is considered as background noise by the relaxation time for the molecules to stop vibrating. The amount of N_0 is relatively small compared to N_1 ($N_0 \ll N_1$).

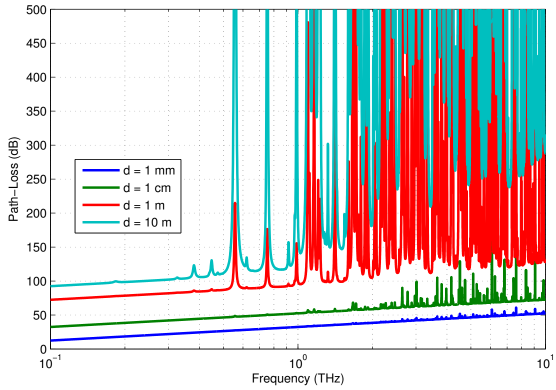

Figure 1: Path loss in Terahertz band using the HITRAN molecular composition database.

Due to the small size of nanomachines, the power, coming probably from energy harvesting, will be a scarce resource. It is necessary to design the nanotransceivers with very small energy specification. In [5], Jornet et al. proposed the TS-OOK modulation based on very short pulses (one hundred femtoseconds per Gaussian pulse). During the transmission process, binary 1 is presented as a pulse transmission, while binary 0 as silence (no energy required). A pulse with very small energy, just a few aJ, is possible to generate [7, 16]. The Gaussian pulse can be written as follows:

$$p(t) = \frac{a_0}{\sqrt{2\pi}\sigma} e^{-(t-\mu)^2/(2\sigma^2)} \quad (7)$$

where a_0 refers to the normalizing constant, σ stands for the standard deviation, and μ is the delay from original time 0. The transmitted pulse usually uses the derivative of the Gaussian pulse due to limitation of transceiver components for DC signal [8]. In TS-OOK, pulses are spread during the transmission. The ratio between a pulse period T_s and a pulse duration T_p is the spreading factor β. In TS-OOK design, the spreading factor is preferred to be large, e.g. $\beta = 1000$. A large value of β has several advantages, it provides:

- A relaxation on the energy harvesting process, which gives enough time for harvesting energy for the next transmission.
- A channel relaxation, where molecules in the channel have enough time to fully release the absorption energy (absorption noise) from the previous transmitted pulse [4].
- A fine time resolution, where the probability of nearby located nodes transmitting pulse at the same time is smaller.

3. THE EFFECTS OF NODE MOVEMENT

In this section, we present the effects of node movement such as pulse time-shift, Doppler effect, information capacity reduction, and error rate increase.

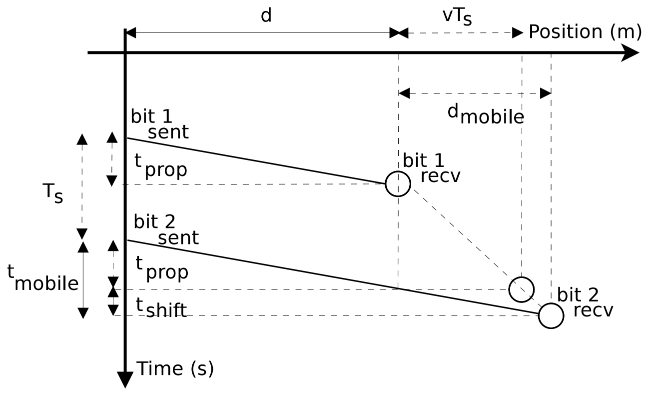

Figure 2: Time-shift due to receiver movement during two bit transmission.

3.1 Pulse time-shift

TS-OOK modulation needs a receiver highly synchronized to the transmitter. Indeed, during communication, transmitter sends at fixed intervals T_s and receiver listens the channel at the same interval T_s. This type of communication works as long as the receiver listens at the right times. Since distance between transmitter and receiver changes, the time when the signal is received changes too. Pulse time-shift is defined as the difference in time between the *actual* arrival of the signal and its estimated arrival (in case the receiver is static).

We consider that transmitter is stationary while receiver moves away from it with a speed v. Transmitter sends a pulse each T_s seconds. The various parameters used to compute the pulse time-shift are shown in Fig. 2. It could be noticed that the same distance d_{mobile} (between position when first bit is received and when second bit is received) is travelled by the receiver:

$$d_{\text{mobile}} = v(T_s + t_{\text{shift}}) \tag{8}$$

and also by the signal when transmitting the second bit (assuming that it propagates in the channel with speed of the light):

$$d_{\text{mobile}} = ct_{\text{shift}} \tag{9}$$

Putting on one equation the right side of both formulas, we obtain:

$$ct_{\text{shift}} = v(T_s + t_{\text{shift}}) \tag{10}$$
$$(c - v)t_{\text{shift}} = vT_s \tag{11}$$
$$t_{\text{shift}} = \frac{1}{\frac{c}{v} - 1} T_s \tag{12}$$

Since $c/v \gg 1$, equation becomes:

$$t_{\text{shift}} \approx \frac{v}{c} T_s \tag{13}$$

The effect of the receiver movement is important in order to investigate the percentage of pulse time-shift according to the pulse duration T_p. If the value of the pulse time-shift percentage $t_{\text{percentage}}$ is greater than 100%, the symbols could not be correctly detected, and in some cases the received symbols overlap, effect known as Inter-Symbol Interference (ISI). This effect increases as the size of a packet data increases. The pulse time-shift percentage $t_{\text{percentage}}$ can be computed as follows:

$$t_{\text{percentage}} = \left(\frac{t_{\text{shift}}}{T_p}\right) \times 100\% \tag{14}$$

3.2 Information capacity reduction

The channel capacity is the maximum allowable transmission rate (in the channel) to have reliable communications (very small error rate) [10]. The channel capacity depends on the source and channel statistical properties. The channel capacity is derived from the maximum mutual information as follows:

$$C = \max\{I(X,Y)\} = \max\{H(X) - H(X|Y)\} \tag{15}$$

where X is the input symbol, Y the output symbol, $H(X)$ the source entropy, and $H(X|Y)$ the channel equivocation. The source entropy $H(X)$ is denoted by:

$$H(X) = \sum_i P_i \log_2\left(\frac{1}{P_i}\right) \tag{16}$$

where P_i is the probability of symbol $i = \{0, 1\}$ to be transmitted. For example, P_1 is the probability to transmit the pulse, while P_0 is a silence. The channel equivocation is denoted by:

$$H(X|Y) = \sum_{i,j} P(x_i, y_j)\ \log_2\left(\frac{1}{P(x_i|y_j)}\right) \tag{17}$$

where $P(x_i, y_j)$ is the probability of having a symbol x_i in the input and the symbol y_j at the ouput, and $P(x_i/y_j)$ is the probability of having transmitted an x_i given by the output y_j. Since the preferred parameter is $P(y_j/x_i)$, the parameters in the channel equivocation can be replaced using:

$$P(x_i, y_j) = P(y_j|x_i)P(x_i) \tag{18}$$
$$P(x_i|y_j) = \frac{P(y_j|x_i)P(x_i)}{\sum_i P(y_j|x_i)P(x_i)} \tag{19}$$

and equation (17) can be denoted by:

$$H(X|Y) = \sum_{i,j} P(y_j|x_i)P(x_i) \times \log_2\left(\frac{\sum_i P(y_j|x_i)P(x_i)}{P(y_j|x_i)P(x_i)}\right) \tag{20}$$

The received signal is the pulse of the TS-OOK modulation that have been attenuated by the total path loss and the absorption noise. The probability density function (PDF) of the received signal is based on a statistical model of the molecular absorption noise [7] given by the input i. It can be written as follows:

$$P(Y|X = x_i) = \frac{1}{\sqrt{2\pi N_i}} e^{-\frac{(y-a_i)^2}{2N_i}} \tag{21}$$

where N_i is the total noise power for the transmitted symbol x_i and a_i is the amplitude of the received symbol. By combining equations (15), (16), (20) and (21), the channel capacity becomes:

$$C = \max\Bigg\{ \Bigg[\sum_{i=0}^{1} P_i \times \log_2\left(\frac{1}{P_i}\right) \Bigg] - \Bigg[\int \sum_{i=0}^{1} \frac{1}{\sqrt{2\pi N_i}} e^{-\frac{(y-a_i)^2}{2N_i}} P_i \times \log_2\left(\sum_{j=0}^{1} \frac{P_j}{P_i} \sqrt{\frac{N_i}{N_j}} e^{-\frac{(y-a_j)^2}{2N_i} + \frac{(y-a_i)^2}{2N_j}} \right) dy \Bigg] \Bigg\} \quad (22)$$

The information rate IR (bit/sec) for TS-OOK modulation can be obtained as follows:

$$IR = C \times \frac{B}{\beta} \quad \text{(bit/second)} \quad (23)$$

We investigate the effect of movement speed on the achievable information rate during the movement.

3.3 Error rate increase

An important measurement in digital communication system is the probability of error in terms of bit error rate [14]. The probability of error is the sum of the probabilities of all the ways that errors can occur, as follows:

$$P_E = \sum_{i=0}^{1} P(e, x = i) = \sum_{i=0}^{1} P(e|x = i)P(x = i) \quad (24)$$

For the case where the input has equal probability for bit 0 and bit 1, $(P(x = 1) = P(x = 2) = 1/2)$, then

$$P_E = \frac{1}{2}(P(e|x = 0) + P(e|x = 1)) \quad (25)$$

Using asymmetric Terahertz band channel [4], the error transition probabilities are:

$$P(e|x = 0) = P(y = 1|x = 0) = 1 - \int_A^B P(Y|x = 0)\, dy \quad (26)$$

$$P(e|x = 1) = P(y = 0|x = 1) = \int_A^B P(Y|x = 1)\, dy \quad (27)$$

where:

$$A, B = \frac{a_1 N_0}{N_0 - N_1} \pm \frac{\sqrt{2N_0 N_1^2 log(N_1/N_0) - 2N_0^2 N_1 log(N_1/N_0) + a_1^2 N_0 N_1}}{N_0 - N_1} \quad (28)$$

where A is the lower threshold level, B is the upper threshold level, a_1 refers to the amplitude of the received signal, N_0 and N_1 stand for the distance dependent noise power.

Since the THz band has characteristics such as the frequency selection and a very high attenuation, the received signal will be much distorted for longer transmission distances. The hop distance between a source node to the sink node should take into account the distortion experienced by the signal. In this case, we will investigate the effect signal quality reduction during receiver movement. This step is important for signal detection at receiver side, i.e., if the received signal is very distorted, the receiver will need an additional signal processing either equalizer, rake receiver, or orthogonal frequency division multiplexing (OFDM).

3.4 Doppler effect

The moving receiver will receive the electromagnetic waves from a transmitter with different frequencies, event known as the Doppler effect. The amount of frequency shifting depends on the relative velocity v between transmitter and receiver. For movement relatively small to the velocity of the waves, the shifting frequency is formulated [11] as:

$$\Delta f = \frac{v}{c} f_0 \quad (29)$$

where f_0 is the operating frequency.

4. SIMULATION RESULTS

In order to get the data, we have done simulations using MATLAB.

4.1 Pulse time-shift

In order to see the effects of receiver movements, we suppose that nanosensors are embedded into a human body for a health monitoring application. The fastest blood speed in vessel is inside the aorta which is 0.4 m/s [15]. We also consider that the patient moves with speed 2 m/s. In the worst case, no matter the motion (e.g. Brownian or linear), the total relative speed between fixed transmitter and moving receiver is the sum of the two speeds, i.e. 2.4 m/s = 8.64 km/h. For TS-OOK modulation we are using the following parameters [7]: pulse duration $T_p = 10^{-12}$ (1 picosecond) and pulse period $T_s = 10^{-9}$ ($\beta = 1000$). Using equation (13), pulse time-shift is therefore:

$$\begin{aligned} t_{\text{shift}} &= \frac{v}{c} T_s \\ t_{\text{shift}} &= \frac{2.4}{(3 \times 10^8)} \times 10^{-9} \\ t_{\text{shift}} &= 0.8 \times 10^{-17} (s) \end{aligned}$$

Next, we take into account the percentage of pulse time-shift to pulse duration:

$$\begin{aligned} t_{\text{percentage}} &= \left(\frac{t_{\text{shift}}}{T_p}\right) \times 100\% \\ t_{\text{percentage}} &= \left(\frac{0.8 * 10^{-17}}{10^{-12}}\right) \times 100\% \\ t_{\text{percentage}} &= 8 \times 10^{-4}\% \end{aligned}$$

The result shows that pulse time-shift is very small compared to the pulse duration for a 1 bit transmission. But, since the effect is cumulative, the movement will introduce ISI ($t_{\text{percentage}}$ exceeds 100%) at the 125,000-th bit, i.e. 16-th kbyte or after $125k \times T_s = 0.125$ ms, in the binary sequence if the pulses are transmitted in burst. In this case, we conclude that the pulse time-shift can introduce ISI for not so large (tens of kbytes) of data transmission if countermeasures are not taken.

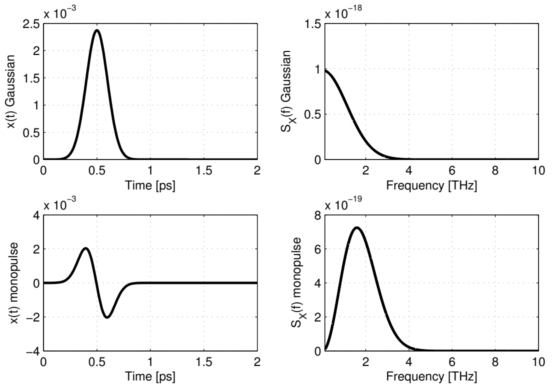

Figure 3: Signal and PSD of Gaussian pulse and Gaussian monopulse.

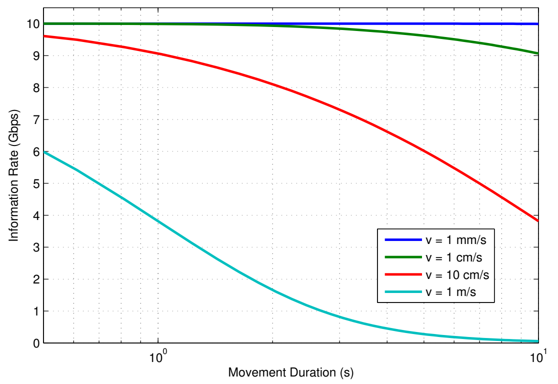

Figure 4: Information rate reduction during the receiver movement.

4.2 Information capacity reduction

In this simulation, we are using parameters such as an energy per pulse of 1 aJ, a variant $\sigma = 100$ femtoseconds, and a delay $\mu = 500$ femtoseconds. The graph of the Gaussian pulse and of the Gaussian monopulse (first derivative of the Gaussian pulse) and their power spectral density (PSD) are shown in Fig. 3. It shows that the monopulse is able to eliminate the DC component from the Gaussian pulse. Moreover, the pulse duration for monopulse signal becomes 1 picosecond (instead of 100 femtoseconds).

The achievable information rate of TS-OOK modulation in Terahertz band (0.1–10 THz) can be obtained using equation (23). The setup parameters are the distance range from 0.1 mm – 10 m, $B = 10^{13}$ (all the spectrum are in THz band), $\beta = 1000$, the initial distance d is 1 mm, the receiver movement speed v is ranging from 1 mm/s to 1 m/s, and the movement duration t_{mobile} is $0 \leq t_{\mathrm{mobile}} \leq 10$ s. The achievable information rate during the movement for various speed is shown in Figure 4.

The results show that the receiver movement has significant effects on the allowable maximum information rate. For example, when the receiver speed is equal to 1 m/s, the allowable maximum information rate is 6 Gbps (60% reduction

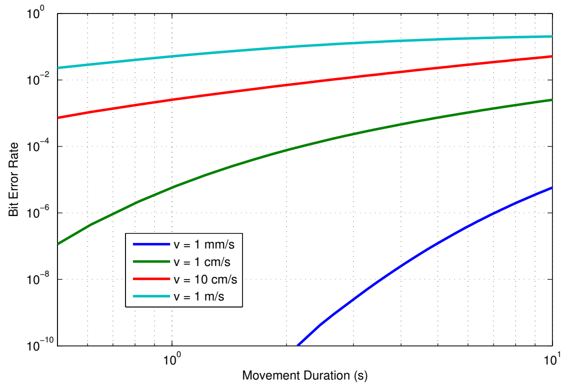

Figure 5: Bit error rate for various receiver speed.

from the information rate of the stationer receiver).

4.3 Error rate increase

Node movement also has an effect on the bit error rate. A larger transmission distance between a transmitter and a receiver yields a higher bit error rate, due to larger signal attenuation and absorption noise in the THz band. The bit error rate for various movement speed is shown in Fig. 5. The results show that the movement speed influences the achievable bit error rate. In multimedia services, e.g., video streaming, a bit error rate less than 10^{-4} is required [13]. If nanonetworks are used to provide such services, the speed must not exceed 1 cm/s. For larger speeds, for example 1 m/s, the achievable bit error rate would be larger than 10^{-2}. It would then require error correction codes to fix errors.

Furthermore, we can investigate the signal quality at certain distances using the model presented in [4]. As shown in Fig. 6, the received signal is spread during propagation. Larger distances result in a larger signal spread, which introduces ISI at the receiver side. In addition to very high attenuation in higher frequency signal, the signal's component in these frequencies is eliminated, so in frequency domain the signal is compressed. According to Fourier transform, if the signal is compressed in frequency domain, then in the time domain the signal is being spread [10]. As shown in Fig. 6 when a receiver moves away from a transmitter, higher frequencies in received signal are getting more distorted along the propagation. For example, when the transmission distance is 1 meter, the received signal is spread 3 times of the pulse duration. This phenomenon restricts the value of the spread factor in TS-OOK modulation, i.e., $\beta \geq 3$.

4.4 Doppler effect

By using first derivative of the Gaussian pulse as the transmitted signal in TS-OOK modulation, the spectrum is centered at 1.6 THz. Using equation (29), for a stationary transmitter and a moving receiver with a speed of 1 m/s,

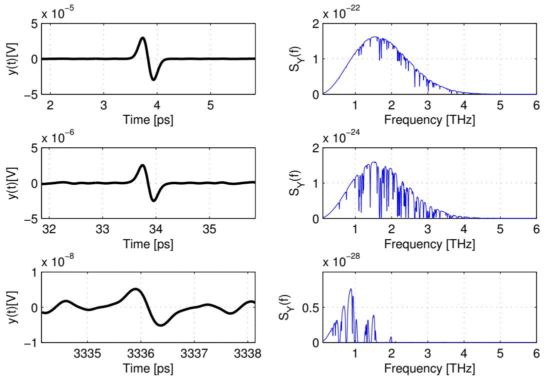

Figure 6: Received signals and their spectrum at various distances. Top: distance 1 mm, middle: distance 1 cm, bottom: distance 1 m.

the shifting frequency will be:

$$\Delta f = \frac{v}{c} \times f_0$$
$$\Delta f = \frac{1}{3 \times 10^8} \times 1.6 \times 10^{12}$$
$$\Delta f = 5333 \text{ Hz}$$

The movement of the receiver will shift the spectrum of the received signal around 5 kHz lower (higher if get closer) than the transmitted signal at the transmitter side. As shown in Fig. 3, the spectrum of transmitted signal is around 4 THz, while the spectrum shift is only 5 kHz. As a result, the node movement will have a small impact in the signal detection. We conclude that the Doppler effect in nanonetworks is negligible.

5. CONCLUSION AND FUTURE RESEARCH

Wireless nanonetworks consist of numerous nanosensors that cooperate to transmit sensing information to an end-system. The mobility of nanosensor nodes have some effects in nanocommunication. In this paper, we presented the effects of node mobility in terms of pulse time-shift, Doppler effect, information reduction, and error rate increase. The results show that pulse time-shift can introduce inter-symbol interference (ISI) for not so large (tens of kB) data transmission, while the movement speed has significant impacts on maximum information rate and achievable bit error rate. Due to the large available bandwidth in the THz band (0.1–10 THz) as well as the large signal bandwidth (4 THz), the Doppler effect is negligible. Future research includes investigation of massive nano-antennas to compensate channel capacity reduction due to node movement, and OFDM technique to improve signal quality.

6. REFERENCES

[1] I. F. Akyildiz, F. Brunetti, and C. Blázquez. Nanonetworks: a new communication paradigm. *Computer Networks*, 52(12):2260–2279, 2008.

[2] E. Dedu, J. Bourgeois, and M. A. Zainuddin. A first study on video transmission over a nanowireless network. In *ACM Nanocom*, 1, pages 1–6, Atlanta, GA, USA, May 2014.

[3] R. Goody and Y. Yung. *Atmospheric Radiation: Theoritical basis*. Oxford University Press, 2 edition, 1989.

[4] J. M. Jornet. Low-weight error-prevention codes for electromagnetic nanoneworks in the Terahertz band. *Nano Communications Networks*, 5(1–2):35–44, Mar–Jun 2014.

[5] J. M. Jornet and I. F. Akyildiz. Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the Terahertz band. *IEEE Transactions on Wireless Communications*, 10(10):3211–3221, Oct. 2011.

[6] J. M. Jornet and I. F. Akyildiz. Information capacity of pulse-based wireless nanosensor networks. In *Proc. of the 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pages 80–88, Salt Lake City, Utah, USA, June 2011.

[7] J. M. Jornet and I. F. Akyildiz. Femtosecond-long pulse-based modulation for Terahertz band communication in nanonetworks. *IEEE Transactions on Communications*, 62(5):1742–1754, May 2014.

[8] H. Nikookar and R. Prasad. *Introduction to Ultra Wideband for Wireless Communication*. Springer, 2009.

[9] G. Piro, L. A. Grieco, G. Boggia, and P. Camarda. Nano–Sim: Simulating electromagnetic-based nanonetworks in the network simulator 3. In *Proceedings of the 6th International ICST Conference on Simulation Tools and Techniques*, SimuTools '13, pages 203–210, ICST, Brussels, Belgium, 2013.

[10] J. G. Proakis. *Digital Communications*. McGraw-Hill International, 4 edition, 2001.

[11] J. Rosen and L. Q. Gothard. *Encyclopedia of Physical Science*. Infobase Publishing, 2009.

[12] L. Rothman, I. Gordon, A. Barbe, D. Benner, P. Bernath, M. Birk, V. Boudon, L. Brown, and A.Campargue. The HITRAN 2008 molecular spectroscopic database. *Quantitative Spectroscopy and Radiative Transfer*, 110(9–10):533–572, June 2009.

[13] O. I. Sheluhin, A. A. Atayero, Y. A. Ivanov, and J. O. Iruemi. Effect of Video Streaming Space-Time Characteristics on Quality of Ttransmission over Wireless Telecommunication Networks. In *World Congress on Engineering and Computer Science*, volume 1, pages 1–6, San Francisco, USA, Oct. 2011.

[14] B. Skalar. *Digital Communications, Fundamentals and Applications*. Pearson Education Asia, 2001.

[15] G. J. Tortora and B. Derrickson. The Cardiovascular System: Blood Vessel and Hermodynamics. *Principles of Anatomy & Physiology*, 13:816, 2012.

[16] L. Vicarelli, M. S. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini, V. Pellegrini, and A. Tredicucci. Graphene field-effect transistors as room-temperature terahertz detectors. *Nature Materials*, 11:865–871, Oct. 2012.