A Flexible Medium Access Control Protocol for Dense Terahertz Nanonetworks

ABSTRACT

The race for the miniaturization of electromechanical equipments has seen tremendous progress in recent years. In this context, nano-wireless networks composed of a large number of tiny equipments concentrated in a reduced area find multiple applications in the field of multi-core processors, programmable matter or nano-sensors networks. In order to support wireless communication between numerous millimeter-scale nodes, the radio access management protocol, a Time-Spread On-Off Keying (TS-OOK), has been proposed to operate under high density, scarce energy and miniaturized network node constraints. Despite of all the advantages provided by TS-OOK protocol, it suffers of two main drawbacks: an unbalance treatment of the active communications and a lack of adaptability. We propose to correct these defaults by adding Adaptive Symbol Rate Hopping mechanism to TS-OOK giving birth to a new protocol called Adaptive Symbol Rate Hopping TS-OOK (ASRH-TSOOK), which allows to better share the system bandwidth and to automatically readjust the radio allocation to the system load. Our protocol is based on a solid probabilistic formulation providing an accurate and a slight procedure to dynamically adjust the communication symbol rate according to the estimated system load.

1. INTRODUCTION

Nanotechnology is moving forward in many domains. The objective is the fabrication of nano-size devices dedicated to a specific basic task such as identification [1], computing [2], sensing [3]. At the same time, wireless nano-networks observe many advances due to the progress in graphene-based nano antenna fabrication [7] and the expertise in the terahertz communications. In this context the pulse based communication is seen as the most suitable modulation technique in Terahertz band [10]. Furthermore, new applications of the nano-networks are expected. One of the promising issues is the programmable material [6], where a set of nano-scale robots change their positions in order to reach a given desired shape. To represent the physical aspect of a complex object, the nano-robots should be close enough to fill the empty spaces. Therefore, a high number of nano-devices could be concentrated in the same area. The use of wireless communication between nano-robots leads to a better convergence of the shape-shifting algorithms. Another important application is in the field of high-performance computing grids. The power of the computing units reaching their limits, the use of multi-core architectures to exploit the possibilities of parallel computation is a promising track. High-speed wireless links between processors are essential to the efficient operation of these architecture.

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1.1 Contributions

Most works on nanonetworks are based on a sparse hierarchical architecture such as Wireless Nano Sensor Network (WNSN) [4] or Body Area Network (BAN) [5]. Hierarchical topology involves the use of super nodes, with higher memory, power, and computing capabilities, that control weaker slave nodes. Consequently, hierarchical topologies pose particular challenges for the manufacturing of the sub-millimeter super nodes and for the scalability of the deployed networks. Moreover, for applications such as the programmable material, the dense environment presents a real challenge to the radio channel access protocols.

In this paper, we are interested in the case of Terahertz nanonetworks composed of dense and homogeneous nodes. The absence of a hierarchical topology (absence of the super nodes), discards the possibility of using channel access protocols based on centralized management units, such as FDMA [21], TDMA [22] or RIH-MAC [23]. Carrier-sensing protocol such as CSMA/CA systems cannot be used since there is no carrier for sensing in pulse-based modulation.

The density of the network, raises a real challenge for the design of totally distributed protocol optimizing the capacity of the channel (the number of parallel communications) and the quality of the communications (throughput, energetic consumption, etc.). The TS-OOK protocol proposed by Jornet et al. [11] represents one of the few promising solutions in the context of homogeneous dense nanonetworks. TS-OOK protocol is based on pulse based modulation technique for Terahertz communications.

This paper presents an original and in-depth analysis of the performance of the TS-OOK protocol under a dense topology (billions of nodes). We show that the selection procedure of the symbol rate, in TS-OOK protocol, should be improved to allow a better repartition of the network radio capacities. We also introduce an original and light distributed protocol that provides each node with a mechanism for evaluating the network load and therefore adapting the data throughput to the traffic load fluctuation.

1.2 Paper organization

The remaining paper is organized as follow. In section 2, we give the main characteristics of the TS-OOK protocol. In section 3, we detail the nanonetwork topology and the traffic model. In section 4, we analyze the performances of TS-OOK protocol and point out two drawbacks when using it. In section 5, we present our first improved protocol called Symbol Rate Hopping TSOOK (SRH-TSOOK), which aims to equally distribute system capacity over the active communications. In section 6, we compare the standard and proposed SRH-TSOOK protocol using probabilistic modeling of Bit Error Rate (BER), Frame Error Rate (FER) and the MAC throughput of a given communication. Section 7 describes the adaptive mechanism that allows active nodes to adjust the required throughput according to the system load. In the last section, we conclude this work and give the major perspectives.

2. TS-OOK PROTOCOL

In TS-OOK [11], radio channel corresponds to a sequence of time windows during which a symbol (0/1) is transmitted using an electromagnetic pulse of a duration Tp=100 femtoseconds. The time duration between two consecutive symbols, Ts, of the same communication is negotiated (randomly chosen) during the communication establishment between the two nodes and remains constant during all data transmission session. The communication request is sent on a control channel defined by a specific inter-symbol duration note Ts_0. This proposition is similar to the Medium Access Control (MAC) protocol in Ultra Wide Band (UWB) technology [14]. Except that the electrical pulse in UWB last much longer with a picosecond range and that the covering range is about 10 meters against 1 meter for Terahertz nanonetworks.

To reduce the collision probability between communications, two solutions have been proposed [11]. First, only 1-symbol is coded by a pulse while 0-symbol is represented by a silence. The interfering impact of every communication is therefore theoretically divided by 2. This advantage is better explored in [12] using a re-encoding procedure where the transmitted symbols are more likely 0 than 1. Second, the symbol rate, β, of a given communication is selected among a list of coprime numbers for example: 1001, 1002, 1003, 1007, etc. Therefore, if a collision occurs at a receiver , the future collision between the same nodes could not occurs before a period of $\beta_1 \times \beta_2$, where β_1 and β_2 are respectively the symbol rate of transmitter and interferer node.

3. METHODOLOGY AND NOTATIONS

The analysis of the system performance is evaluated from a network node point of view. Let R be the reference node which is listening to a particular communication transmitted by the node T and let N be the average number of surrounding nodes (nodes which signal can be received by R including non active nodes). The surrounding area depicts then a sphere where the nearby nodes are randomly distributed.

We assume that communications arrivals follow a Poisson distribution of parameter λ (corresponding to the average number of new communications in a second) and we assume that the communication duration follows an exponential distribution with a mean $\frac{1}{\mu}$. The conjunction of the two distributions (arrivals and communication durations) makes the number of active nodes following a Poisson distribution with a parameter $\bar{k} = \lambda \times \mu$. The Poisson distribution represents a good model [13] for arrival phenomena when the number of communication sources (nodes) is high enough, which is the case for the studied scenarios (the number N). Indeed, the higher the number of communication sources, the more relevant the assumption about the inter-dependence of communications arrivals is. However, the assumption concerning the communication duration neglects the effect of the symbol rate selection and the interference impact on the communication.

In the remainder of the paper we will adopt the following notations to refer to the random variables describing the system: K is the number of surrounding active nodes and $\bar{k}$ corresponds to the average of K. I is the number of interfering 1-symbol received simultaneously at the reference node. D is the distance (in meters) between the reference node and a neighboring node. L is the number of lost symbols within one frame. P is the received signal power from a given node.

4. ANALYSIS OF TS-OOK

In the TS-OOK protocol, a communication, i, is carried by pulses (or silences for 0-symbol transmission) interleaved by a regular period. Let Ts_i the inter-symbol duration of the communication i and Tp the pulse duration (100 femtoseconds). The value of Ts_i is determined and announced at the beginning of the communication i. To keep the synchronization between the communicating nodes, every received pulse is used to resynchronize the receiver with the transmitter, which allows to take into account the changes in transmission distance, air composition, etc. The symbol rate β_i of the communication i corresponds to the ratio Ts_i/Tp. The symbol rate is selected among a list of coprime numbers belonging to the interval $[\beta_{min}, \beta_{max}]$. β_{min} and β_{max} represent respectively the upper and the lower data rate tolerated by the protocol.

In [18], we proposed a critical study of the TS-OOK protocol. According to this study, we conclude that:

- The co-channel probability (i.e. pulses of transmitter node T and interfering node J are received at the same time by the receiver node R) is equal to:

$$P[T,\, J \text{ are co-channel}] = \frac{1}{nbcop} \times \frac{1}{\beta} \quad (1)$$

In equation (1), *nbcop* represents the number of coprime values available in the interval $[\beta_{min}, \beta_{max}]$. For instance with $[\beta_{min}, \beta_{max}] = [1000, 5000]$ and Transmitter symbol rate $\beta = 2089$, the co-channel probability is equal to $\frac{1}{511} \times \frac{1}{2089} = 9.36 \times 10^{-7}$.

- Under the assumptions that communications arrivals follow a Poisson distribution of parameter λ and that the communication duration follows an exponential distribution with a mean of $\frac{1}{\mu}$, the probability that the number of active nodes around the node R be equal to k is expressed by the following formula:

$$P[K = k] = \frac{\theta^k}{k!} \times e^{(-\theta)} \quad (2)$$

- When the listened communication uses the symbol rate β, the probability that a listened symbol by R be in collision with an interfering symbol transmitted by another active communication, is equal to $\frac{1}{\beta}$. We call listened symbol, a symbol that belongs to the useful communication. With $p1$ the probability that transmitted symbol be 1 (a pulse and not a silence), the probability that a symbol of the listened communication be interfered by a pulse of the active communication J is expressed by:

$$P[J \text{ interferes with } T] = \frac{p1}{\beta} \quad (3)$$

The probability $p1$ could be less than 0.5 if a low-weight channel coding [12] is used. We assume that the receptor uses the correlation-based energy detector extending the reception window to $2 \times T_p$. We conclude that:

$$P[J \text{ interferes with } T] = 2 \times \frac{p1}{\beta} \quad (4)$$

In the following, we consider that $p1 = 0.5$.

The joint action of the random selection of the symbol rates among coprime values and the randomness of communications arrivals leads to a uniform distribution in time of the interfering pulses. **Momentarily, we assume that every concurrent communication is a potential interfering signal, which means that the signal powers are ignored**. Therefore, the probability that a symbol of the listened communication be interfered by a communication transmitted by one of the k active nodes can be expressed by:

$$P[I \geq 1/K = k] = \sum_{i=0}^{k} (\frac{\beta - 1}{\beta})^i \times \frac{1}{\beta} \quad (5)$$

The probability that a received symbol by R be interfered by at least another communication (whatever is the number of active nodes) is equal to:

$$BER = \sum_{k=1}^{\infty} \sum_{i=0}^{k} (\frac{\beta - 1}{\beta})^i \times \frac{1}{\beta} \times \frac{\theta^k}{k!} \times e^{(-\theta)} \quad (6)$$

The observation of the BER formula reveals two points. First, the BER is closely linked to the symbol rate used by the communication. When β is low, the value of the BER increases. We deduce that low β provides a better symbol throughput but increases the data loss when the number of active nodes augments. Secondly, the random selection of the symbol rate produces an unequal treatment between the different communications. In addition, the use of high symbol rate when the radio channel is free (low number of active nodes) is not relevant.

5. SYMBOL RATE HOPPING TS-OOK

To address the disadvantages of the standard TS-OOK protocol, we propose to dynamically change the symbol rate. Every transmitter hops over different symbol rates using a pseudo-random sequence known by both the transmitter and the receiver. The random sequence guarantees that the different symbol rates are used uniformly. Consequently, all active communications obtain the same transmission conditions expressed by the same BER and data rate averages. The Symbol Rate hopping aims to balance the observed interferences over the concurrent communications. The working scheme of the Symbol Rate hopping TS-OOK method is depicted in Figure 1.

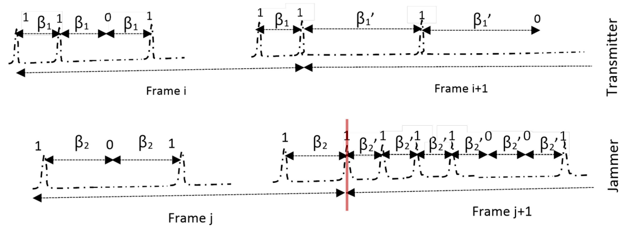

Figure 1: Symbol Rate Hopping: after each frame, a new symbol rate is used in the next frame.

The symbol rate of a communication is changed regularly after a given number of symbols corresponding to a MAC frame. The repartition of the interference depends on the shortness of this delay. The use of symbol rate hopping eliminates the effect of coprime values on reducing the pair-nodes interferences. However, this feature is relatively less important than the reduction of the interference sum.

Many random generator exists in literature [15] that can mainly expressed as a recursive function RND: $r = RND(r)$. Where r represents the current random value. When the communication is established, the transmitter and the receiver agree on the initial r value called *seed*. After each exchanged MAC frame, the next used symbol rate, β is deduced independently by the transmitter and the receiver using the new r as follow:

$$\beta = \frac{r \times (\beta_{max} - \beta_{min})}{RNDMAX} + \beta_{min} \quad (7)$$

Where $RNDMAX$ is the highest value returned by the RND function.

6. PERFORMANCE OF SRH-TSOOK

Now, we start studying the contribution of the SRH-TSOOK on the performance of the nano-networks. The co-channel probability, BER, FER and data throughput are taken as metrics to compare the standard and the proposed MAC protocols.

6.1 Co-channel analysis

Co-channel interference occurs when two communications are systematically in collision, which means that pulses sent by T to R always arrive at the same time that the interfering pulses sent by I. In SRH-TSOOK, co-channel probability is equal to the probability that the two communications use the same seed (the initial $r_current$) of the pseudo-random sequence. Since the seed is selected in the interval $[0, RNDMAX]$, the co-channel interference is equal to $1/RNDMAX$. With $RNDMAX = 2^{32}$, the co-channel interference probability is then well below the co-channel probability in standard TS-OOK protocol given in equation 1.

6.2 BER/FER analysis

Since every communication uses sequentially the different available symbol rates in random way, the BER of a communication is equal to the average BER obtained using each symbol rate; which corresponds to the following expression:

$$BER = \frac{\sum_{\beta=\beta_{min}}^{\beta_{max}} \sum_{k=1}^{\infty} \sum_{i=0}^{k} (\frac{\beta-1}{\beta})^i \times \frac{1}{\beta} \times \frac{\theta^k}{k!} \times e^{(-\theta)}}{\beta_{max} - \beta_{min}} \quad (8)$$

In Figure 2, we present the communication BER according to the average number of active nodes. We compare the estimated BER of 6 communications using different constant symbol rates with the estimated BER of a communication using SRH-TSOOK protocol. **We remind that the quality of a given communication in the standard TS-OOK protocol varies according to the selected symbol rate while this quality is smoothed over all the communications in the SRH-TSOOK approach**. Figure shows that SRH-TSOOK allows to bring the BER to average values for all communications while the BER reaches high values in standard TS-OOK for communications using a low symbol rate ($\beta = 1000$). For instance, under 900 concurrent communications, a communication with symbol rate equal to 1000 suffers from a BER that exceeds the 60%, while the BER is less than 30% when the Symbol Rate Hopping is used for all communications. By contrast, in standard TS-OOK, communication that uses the symbol rate 5000 has a better BER (less than 10% with a number of active nodes bellow 600). However by using a high symbol rate, we expect that the data rate of such communication will be low. SRH-TSOOK allows to obtain better data rate without extremely increases the BER value.

Let evaluate now the error rate at MAC frame level. Let n the number of bits composing a MAC frame (data + detection/correction Error code). We assume that the used error code offers a capability [17] of m, which means that the error code is able to fix the received frame if the number of

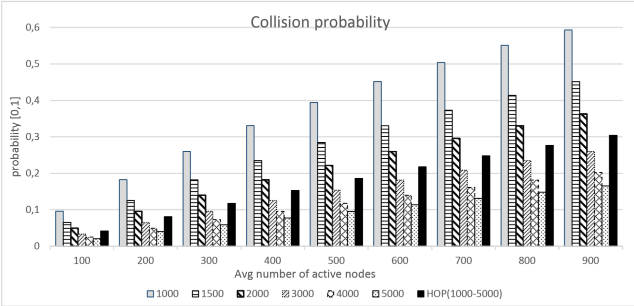

Figure 2: BER comparison between communications operating under TS-OOK with different fixed symbol rates (1000 to 5000) and any communication operating under SRH-TSOOK.

corrupted bits does not exceed m. The number of corrupted bits (number of collided bits) in a MAC frame of size n follows a Binomial distribution with a parameter BER (equation 6 or 8 according to used symbol rate allocation). Consequently, the probability that the number of corrupted bits be equal to x is:

$$P[L = x] = C_n^x \times BER^x \times (1 - BER)^{n-x} \quad (9)$$

The probability that the number of corrupted bits be higher or equal to m is:

$$P[L \geq m] = \sum_{x=m}^{n} C_n^x \times (BER)^x \times (1 - BER)^{n-x} \quad (10)$$

Where $C_n^x = n! / k! \times (n-k)!$ corresponds to the Binomial coefficient. Since the error code capability is limited to m errors, we deduce that the Frame Error Rate is equal to:

$$FER = \sum_{x=m}^{n} C_n^x \times (BER)^x \times (1 - BER)^{n-x} \quad (11)$$

Figure 3 represents the FER variation of a given communication according to the number of concurrent nodes and to the used symbol rate. The used MAC frame size is of 128 bits and m is 20. The Figure shows that SRH-TSOOK method allows a more progressive evolution of the FER contrary to TS-OOK protocol where the FER suddenly increases with the evolution of the number of active nodes. For instance, when the symbol rate is equal to 1000, the FER increases from 0% to 80% by varying the number of active nodes between 100 and 200. Whereas the FER evolution does not exceed 10% with SRH-TSOOK when the number of active nodes varies from 100 to 200. In the other side, while the standard TS-OOK presents certain communications with low FER ($\beta = 5000$) and other with high FER ($\beta = 1000$), SRH-TSOOK presents the same average FER for all the active communications.

6.3 Data rate analysis

To estimate the impact of FER on the communication throughput (a lost frame is a retransmitted frame), we assume for

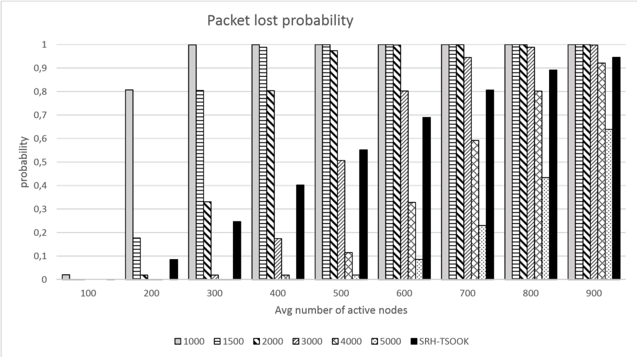

Figure 3: FER comparison between 6 communications operating under TS-OOK with different fixed symbol rates (1000 to 5000) and the FER of any communication under SRH-TSOOK.

simplification that frame acknowledgments are without errors and does not induce delay. The average number of frame retransmissions is equal to $1/(1-FER)$ times, where FER is determined using the equation 11.

The frame transmission duration is equal to $n \times \beta \times Tp$. Where n is the frame size (in bits), β is the symbol rate of the studied communication and Tp is the pulse duration. In case of SRH-TSOOK the β value changes after each frame transmission. In case of standard TS-OOK, the data throughput (TP)o f a given communication is equal to:

$$TP = (1 - FER)/(n \times \beta \times Tp)\text{Frames/s} \quad (12)$$

In case of SRH-TSOOK, the throughput is expressed as an average over available symbol rates.

$$TP = \frac{\sum_{\beta=\beta_{min}}^{\beta_{max}} (1 - FER)/(n \times \beta \times Tp)}{(\beta_{max} - \beta_{min})}\text{Frames/s} \quad (13)$$

7. ADAPTIVE SRH_TSOOK PROTOCOL

The SRH-TSOOK presents a first improvement of the TS-OOK protocol functioning allowing to equitably share the bandwidth over the active communications. However the system remains not flexible against the traffic load variation. Indeed, whatever is the system load, the used symbol rate varies within a fixed interval $[\beta_{min}, \beta_{max}]$ even if there is few active communications. It is clear that the β_{max} parameter should be adjusted according to the system load in such manner that lower is the system charge lower should be the β_{max}. For that end, we propose that every node evaluates periodically and in distributed manner the system charge in its surrounding area and uses this evaluation to determine the ideal value of the β_{max}.

7.1 Interference power

We assume that the nano-nodes are uniformly distributed over the network area. So we assume that nodes surrounding the studied node follow a uniform distribution in the 3D area. Let r the maximum coverage of a terahertz signal, the probability that the distance between the receiver node and a potential transmitter, P[dist], be less than a given value d is calculated as:

$$P[D \le d] = \frac{d^3}{r^3} \quad (14)$$

To take into account the signal powers, we consider only active node within a range r from the reference node.

By consequent, the average value of the sum of the interferences observed by the receiver node can be expressed by:

$$I = \sum_{i=0}^{k} P[I = i] \times i \times \sum_{d=0}^{r} P[D = d] \times POW(d) \quad (15)$$

$P[I = i]$ refers to the probability that the listened symbol be interfered by exactly i simultaneous signals. $P[I = i]$ is expressed according to the following formula:

$$P[I = i] = \sum_{k=i}^{\infty} P[K = k] \times C_k^i \times (\frac{1}{\widehat{\beta}})^i \times (1 - \frac{1}{\widehat{\beta}})^{k-i} \quad (16)$$

$P[K = k]$ is given in equation 2 and $\widehat{\beta}$ represents the average symbol rate: $\widehat{\beta} = \frac{\beta_{max} - \beta_{min}}{2}$.

The function $POW(d)$ measures the received signal power when the distance between the transmitter and the receiver nodes is d. Terahertz propagation model proposed in [10] provides a numerical formulation of the signal power in function of the distance:

$$POW(d) = 2 \times 10^{-13} \times (d \times \frac{\sqrt{3}}{8})^{-2.1} \quad (17)$$

Figures 4 shows how the number of simultaneous interfering nodes increases with the number of neighboring nodes and how it decreases with the B_{max} value. When the number of active nodes in the nearby area (within the radio range) is high, the use of high $Bmax$ is needed to reduce the amount of interference accumulation. For instance, when there are 10,000 active neighbors nodes, the probability of having 8 simultaneous interfering signals decreases from 14% with $B_{max} = 1500$ to 1% with $B_{max} = 9000$. On the other hand, when the number of active neighbors is low, the number of simultaneous interfering signal changes slightly with the change of B_{max}, which means that lower B_{max} provides better throughput without increasing the interferences.

7.2 BER and FER based on signal power

The formulation of the BER given in the equation 8 can now be improved by introducing the signals power. In 8, the listened symbol is considered lost when it collides with at least an interfering pulse (symbol 1) whatever the power of the interfering signal is. To introduce the interfering signal power in the BER estimation, we assume that the interfering signals corrupt the listened symbol when the interfering signals sum exceed a given threshold T_{int}. The BER of a communication in the presence of k surrounding active nodes is rewritten:

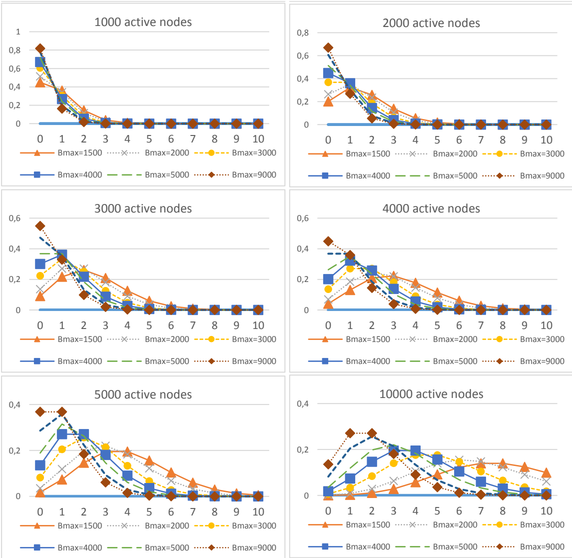

Figure 4: jamming signals number probability according to the system load and β_{max}.

$$BER = \sum_{i=0}^{k} P[I = i] \times (P_1 * P_2 * ... * P_i \geq T_{int}) \quad (18)$$

Where P_j represents the density function of the power of the j^{th} interfering signal and $P_1 * P_2 * ... * P_i$ designates the convolution of i probability functions (interfering nodes are assumed interdependent which means that the functions P_j are interdependent too). The P_j density function is directly deduced from the D density function (see equation 14) according to the following expression:

$$P[P{=}p]{=}P[D{=}d : d{=}POW^{-1}(p)] \quad (19)$$

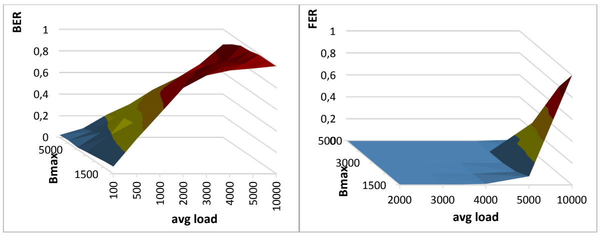

Figure 5: BER/FER evolution with system load and β_{max} (interference range=30mm).

According to equations 18 and 11, we deduce that the evaluation function of the BER and FER according to the system load and the used $Bmax$ of the listened communication. Figure 5 gives a 3D representation of the estimated BER and FER of the reference communication with an interfering range of 30mm. In order to adapt the $Bmax$ value according to system load, the receiver should be able to estimate the average system load (active nodes neighboring). This estimation will be used to renegotiate the $Bmax$ value with the transmitter over the control channel. Equations 8 and 11 represent functions returning an estimation of the BER and FER according to the used $Bmax$ and the system load. We propose then to use the inverse functions of BER and FER in order to estimate the system load according to the observed BER/FER and to the used $Bmax$. The use of the observed BER is complex since the BER can only be extracted from corrected frames. When the number of lost symbol exceeds the error code capability m, the frame can not be corrected and the number of corrupted symbols can not be deduced. Therefore, we use the inverse function of the equation 11 to compute the estimated load.

$$k_{esti} = FER^{-1}(\beta_{max}, FER_{observed}) \quad (20)$$

The new β_{max} is chosen as the minimum value that respects a threshold quality represented by a maximum tolerated FER, T_{FER}. More formally $new\beta_{max}$ is equal to:

$$new\beta_{max} = \min \beta_{max} : FER(\beta_{max}, k_{esti}) \leq T^{+}_{FER} \quad (21)$$

To avoid a periodic, energy and time consuming procedure, we propose the use of a quality table. The quality table stores pre-calculated values of recommended β_{max} in function of the system load. When a node records an FER exceeding the maximum quality threshold, T^{+}_{FER} or above the minimum quality threshold, T^{-}_{FER}, the receiver warns the transmitter of the situation and selects the $new\beta_{max}$ stored in the quality table. To prevent an excessive call for the adaptation procedure, the thresholds T^{+}_{FER} and T^{-}_{FER} should be significantly different. A minimum duration between two consecutive β_{max} readjustments could be also defined.

The quality table is calculated using the algorithm 1. The stored table allows more effective adjustment than a progressive adaptation (i.e. the nodes adjust their β_{max} by increasing or decreasing its value depending on whether the FER exceeds or is above the quality thresholds). The progressive adjustment leads to several negotiation messages between nodes and overloads the control channel.

Algorithm 1: Quality table generation for β_{max} adaptation

```
for every possible current βmax and FERobserved do
    Use equation 20 to compute kesti;
    Use equation 21 to compute newβmax;
    Store (current βmax; FERest; newβmax) in the table;
end
```

8. CONCLUSION AND PERSPECTIVES

In this paper, a MAC protocol for Terahertz based nanonetworks have been studied. We provided an analysis of TS-OOK technique, that shows that standard TS-OOK suffers of two major drawbacks. First, the random selection of the symbol rate induces an unequal distribution of network ressources between communications using a high symbol rate and those using a low symbol rate. Secondly, TS-OOK presents a lack of adaptability against traffic load.

We proposed the symbol rate hopping technique to overcome these drawbacks. In ASRH-TSOOK, every transmitter changed periodically the symbol rate used by the communication in a pseudo-random way, which leads to spread the generated interference over the communications and offers the same radio access conditions to all active nodes. The probabilistic analysis proves the relevance of the proposed techniques in terms of BER, FER and Throughput gain.

ASRH-TSOOK protocol presents an adaptive mechanism that allows each active node to estimate the surrounding load of the network. The traffic estimation is then used to establish the optimal upper limit of the symbol rate range, β_{max}, and therefore adapt the node throughput to reduce the FER value to acceptable threshold. The adaptive mechanism presents no additional exchanged messages and simply uses the observed FER on the concerned node. In addition, the distributed implementation of this mechanism leads the smart use of the radio resources over the network.

The adaptive mechanism makes the system hard to model since the behavior of every node is a response to the neighboring nodes behavior. We project then to use a terahetz network simulator developed by Boillot et al. [19] to evaluate the impact of the ASRH-TSOOK on the terahertz network.

9. REFERENCES

[1] R. Pathak and S. Joshi, *Multi-scale Modeling and Analysis of Nano-RFID Systems on HPC Setup*, Series Communications in Computer and Information Science, Vol. 40, pp 649-659, Springer, 2009.

[2] M. A. Bounouar, D. Drouin and F. Calmon, *Towards nano-computing blocks using room temperature double-gate single electron transistors*, IEEE 12th International Conference on New Circuits and Systems (NEWCAS), pp 325-328, IEEE, 2014.

[3] C. K. Sung, M. Egan, Z. Chen; I. B. Collings, *Performance of Wireless Nano-Sensor Networks with Energy Harvesting*, IEEE 79th Vehicular Technology Conference (VTC Spring), pp 1-5, IEEE, 2014.

[4] V. Upadhayay and S. Agarwal, *Application of Wireless Nano Sensor Networks for Wild Lives*, International Journal of Distributed and Parallel Systems (IJDPS), Vol.3, No.4, pp 173-181, 2012.

[5] R. Zhang et al. *Analytical Characterisation of the Terahertz In-Vivo Nano-Network in the Presence of Interference Based on TS-OOK Communication Scheme*, IEEE Access, Vol. 5, pp 10172-10181, IEEE, 2017.

[6] J. Bourgeois et al., *Programmable matter as a cyber-physical conjugation*, IEEE International Conference on Systems, Man, and Cybernetics, pp. 2942-2947, IEEE, 2016.

[7] X. Qin, J. Chen, C. Xie, N. Xu and J. Shi, *A tunable THz dipole antenna based on graphene*, IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), pp 1-3, IEEE, 2016.

[8] M. Ye. Ilchenko, S. E. Kuzmin, T. N. Narytnik and V. N. Radzikhovsky, *Tranceiver for digital radiorelay system in terahertz frequency band*, 23rd International Crimean Conference in Microwave and Telecommunication Technology (CriMiCo), pp 318-319, IEEE, 2013.

[9] I. F. Akyildiz and J. M. Jornet, *Electromagnetic wireless nanosensor networks*, Journal of Nano Communication Networks, N 1, pp 319, Elsevier, 2010.

[10] J. M. Jornet and I. F. Akyildiz, *Femtosecond-long Pulse-based Modulation for Terahertz Band Communication in Nanonetworks*, IEEE Transactions on Communications, vol. 62, no. 5, pp 1742-1754, IEEE, 2014.

[11] J. M. Jornet, J. Capdevila-Pujol and J. Sole-Pareta, *PHLAME: A Physical Layer Aware MAC Protocol for Electromagnetic Nanonetworks in the Terahertz Band*, Journal of Nano Communication Networks, vol. 3, no. 1, pp. 74-81, Elsevier, 2012.

[12] J. M. Jornet, *Low-weight Channel Codes for Error Prevention in Electromagnetic Nanonetworks in the Terahertz Band*, 1st ACM International Conference on Nanoscale Computing and Communication (NANOCOM), ACM, 2014.

[13] D. Huo, *Generalized Erlang-B formula for mobile and wireless radio channels*, Global Telecommunications Conference, Communication Theory Mini-Conference, (GLOBECOM), pp 38-41, IEEE, 1995.

[14] M. S. I. M. Zin and M. Hope, *A Review of UWB MAC Protocols*, 6th Advanced International Conference on Telecommunications (AICT), pp 526-534, IEEE, 2010.

[15] L. Blum, M. Blum, M. Shub, *A Simple Unpredictable Pseudo-Random Number Generator*, SIAM Journal on Computing, 15(2), pp 364383, 1986.

[16] M. Franceschini, G. Ferrari, R. Raheli, *LDPC Coded Modulation*, Springer-Verlag Berlin, ISBN 10 3642088961, 2010.

[17] S.K. Chilappagari, B. Vasic, M.W. Marcellin, *Guaranteed Error Correction Capability of Codes on Graphs*, IEEE Information Theory and Applications Workshop, pp 50-55, IEEE, 2009.

[18] H. Mabed, *Enhanced Spread in Time On-Off Keying Technique for Dense Terahertz Nanonetworks*, IEEE Symposium on Computers and Communications, pp 1-7, 2017.

[19] N. Boillot, D. Dhoutaut, J. Bourgeois, *Large scale MEMS robots cooperative map building based on realistic simulation of nano-wireless communications*, Nano Commun. Netw. 6(2), pp 5173, 2015.

[20] H. Mabed, J. Bourgeois, *Scalable distributed protocol for modular micro-robots network reorganization*, IEEE Internet of Things Journal, 3(6), pp 1070-1083, 2016.

[21] A; Afsharinejad, A. Davy, B. Jennings, *Dynamic channel allocation in electromagnetic nanonetworks for high resolution monitoring of plants*, Nano Commun. Netw. Vol. 7, pp 2-16, 2016.

[22] J. Suzuki, H. Budiman, *Robustness in TDMA Scheduling for Neuron-based Molecular Communication*, Body Area Networks (BodyNets'13), pp 478-483, 2013.

[23] S. Mohrehkesh, M. C. Weigle, *RIH-MAC: Receiver-Initiated Harvesting-aware MAC for NanoNetworks*, Nanoscale Computing and Communication, pp 180-188, ACM, 2014.