

SBN: Simple Block Nanocode for nanocommunications

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ABSTRACT

Nanonetworks consist of nanomachines that perform simple tasks (sensing, data processing and communication) at molecular scale. Nanonetworks promise novel solutions in various fields, such as biomedical, industrial and military. Reliable nanocommunications require error control. ARQ and complex Forward Error Correction (FEC) are not appropriate in nano-devices due to the peculiarities of Terahertz band, limited computation complexity and energy capacity. In this paper we propose Simple Block Nanocode (SBN) to provide reliable data transmission in electromagnetic nanocommunications. We compare it with the two reliable transmission codes in nanonetworks in the literature, minimum energy channel (MEC) and Low Weight Channel (LWC) codes. The results show that SBN outperforms MEC and LWC in terms of reliability and image quality at receiver. The results also show that a nano-device (with nano-camera) with harvesting module has enough energy to support perpetual image transmission.

1. INTRODUCTION

Nanotechnology is providing us with a set of novel tools, i.e. nano-devices to perform simple tasks (sensing, data processing and communications) at molecular scale. The size of an individual nano-device is in the order of a few cubic micrometers [10], which allows it to detect chemical compounds in very low concentrations (even a single molecule) [15], or the presence of cancer cells [19] and infectious agents such as virus and harmful bacteria [18].

Nanodevices are devices whose edge size is less than $1\ \mu\text{m}$, i.e. a surface of less than $1\ \mu\text{m}^2$. In comparison, currently an Intel processor of 22 nm technology has a die size of $160\ \text{nm}^2$, i.e. 160000 times more. This means that nanodevices have

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a very small computational complexity. The energy is also a constraint, since a state of the art nano-battery has a capacity of 800 pJ [9]. A complete system has not yet been built.

In wireless sensor networks, information from the observed phenomenon should be reliably transmitted to the end system, in order to initiate the right actions [2]. Terahertz band (0.1–10 THz) is characterized by high molecular absorption and high molecular noise, which makes it vulnerable for data transmission. Thus, for reliable communication, nanonetworks require error control, such as automatic repeat request (ARQ) and Forward Error Correction (FEC). Complex and powerful FEC techniques cannot be directly implemented in nano-devices due to their limitations presented above. ARQ technique is prohibited due to limited energy (battery capacity) in nano-devices [6]. When the channel error is high, re-transmissions must be done frequently, which increases the delay and consumes more energy. Therefore, low complexity (simple) error correction coding is the best solution for nanocommunications.

In this paper, we propose Simple Block Nanocode (SBN) to provide reliability in electromagnetic nanocommunications in terahertz band. We investigate the performance of SBN in terms of bit error rate and robustness against transmission error in image transmission. In [1], the authors compare ARQ, Hamming and Low Weight Channel (LWC [6]) codes at Terahertz band in terms of bit error rate (BER) and conclude that LWC is the best one. Terahertz band is modeled as BAC, where transition probability for bit 1 and bit 0 are different. In this paper we simulate the theoretical BER and simulation BER using different transitional probability of bit 1 and bit 0.

Additionally, we investigate the energy consumed for image transmission using a sensor application whose goal is to detect cancer cells. We also investigate the feasibility, from energy point of view, of a perpetual image transmission using the state of the art in nano-battery and energy harvesting process in nano-power-generator [9]. The results show that our proposed code outperforms minimum energy channel (MEC) [11] and LWC codes in terms of reliability.

We called our code a *nanocode*. By extension of the meaning of the word nano, by nanocode we mean a code appropriate to nanocommunications. Indeed, SBN provides simplicity in the (de)coding process together with robustness and energy efficiency. Simplicity is important due to limitation in nano-devices. Simplicity for robustness comes from

simple block code, while energy efficiency comes for NME code for TS-OOK based modulation nano-devices. Comparing to Hamming code for example, SBN is flexible and more robust: Hamming code has fixed input size n and output size m , with $m = 2^n - 1$ and $n = 4, 5, 6, \dots$, while SBN allows any $m > n$. Hamming code perfectly corrects 1 bit error, while SBN (6,3) also perfectly corrects 1 bit error, and SBN (16,3) perfectly corrects 2 error bits and up to 7 error bits.

The rest of paper is organized as follows. In Sec. 2 we present some background on nanonetworks by describing the channel model for Terahertz band, TS-OOK modulation, LWC, MEC and Nanonetwork minimum energy (NME) codes. In Sec. 3 we describe the proposed SBN code. In Sec. 4 we analytically investigate the BER of MEC, LWC and SBN. We also numerically investigate the code performance in energy consumption and received image quality for an image transmission related to the detection of cancer cell. Finally, we conclude the paper in Sec. 5.

2. ELECTROMAGNETIC NANOCOMMUNICATIONS

Several source and channel codes have been proposed so far for nanonetworks. The only codes with error correction and reliability proposed in the literature are MEC and LWC. Our method aims to increase reliability, therefore we present MEC and LWC in the following, and later compare them with our method.

2.1 Terahertz propagation model

Jornet et al. [7, 10] developed a novel propagation model for Terahertz channel based on radiative transfer theory [4] and validated it using COMSOL Multi-physics. The result shows that Terahertz band with large available bandwidth (almost 10 THz) supports very high transmission rate, in the order of a few Terabits per second (Tbps) for transmission distances below 1 m.

In Terahertz band, the electromagnetic propagation is affected by molecular absorption and molecular noise. The path-loss in Terahertz band is mainly characterized by the spreading loss and the molecular absorption loss. The molecular absorption loss can be computed as [6, 1]:

$$H_{abs}(f, d) = \exp\left(-\frac{\alpha(f)d}{2}\right) \quad (1)$$

where f is the operating frequency, d is the transmission distance and α is the molecular absorption coefficient, which depends on the molecular composition in the channel along the transmission path.

The electromagnetic nanocommunications can be modeled as discrete input X and continuous output Y . The total molecular absorption noise S_N affecting the transmission of symbol $i \in \{0, 1\}$ consists of the background atmospheric noise S_{N_B} and the self-induced noise $S_{N_i^X}$ [10]. The power spectral density of total molecular noise can be obtained by:

$$S_{N_i}(f, d) = S_{N_B}(f) + S_{N_i^X}(f, d) \quad (2)$$

$$S_{N_B}(f, d) = \lim_{d \rightarrow \infty} k_B T_0 (1 - |H_{abs}(f, d)|^2) |H_{ant}^R(f)|^2 \quad (3)$$

$$S_{N_i^X}(f, d) = S_{X_i}(f) (1 - |H_{abs}(f, d)|^2) |H_{ant}^T(f)|^2 |H_{spread}(f, d)|^2 |H_{ant}^R(f)|^2 \quad (4)$$

Input sym.	Sym. freq.	NME	MEC	LWC
111	80	000	0...0011	10011
110	70	010	0...1100	01101
101	60	001	.	10101
100	50	100	.	11001
011	40	101	.	01110
010	30	011	.	10110
001	20	110	0011...0	11010
000	10	111	1100...0	11100

Table 1: Mapping table for all compared codes.

where k_B is the Boltzmann constant, T_0 is the room temperature, S_X is the power spectral density of the transmitted pulse, H_{ant}^R and H_{ant}^T are the antenna frequency response at receiver and transmitter for an antenna that satisfies $|H_{ant}^T H_{ant}^R| = \lambda_0^2 / 4\pi$, where $\lambda_0 = c/f_0$ and f_0 is the center frequency of the pulse (around 1.6 THz).

2.2 TS-OOK modulation

For the time being, the only feasible way for electromagnetic nanocommunications is pulse-based modulation. Jornet and Akyildiz [10] proposed the time-spread on-off keying (TS-OOK) modulation based on very short pulses (one hundred femtosecond-long per Gaussian pulse). Such pulses have been used in Terahertz imaging and biological spectroscopy [20]. During the transmission process, binary 1 is considered as a pulse transmission, while binary 0 as silence (no energy required). The time T_s between two consecutive symbols is much longer than the pulse duration T_p , i.e. $\beta = T_s/T_p \gg 1$. A pulse with very small energy, just a few aJ, was proposed in [10].

2.3 Minimum energy channel (MEC) code

Kocaoglu and Akan [11] proposed MEC to provide energy efficient and robustness in nanocommunications. The encoding process is done by simple mapping from symbols to their corresponding codewords; the decoding process uses Maximum Likelihood Decoding (MLD). In MLD, minimum distance d_{min} is used to control robustness; larger d_{min} provides better error correction capability. MEC code is denoted by MEC (m, n, d_{min}), where m is the output and n the input size. For example, MEC (16,3,4) is shown in Table 1.

2.4 Low Weight Channel (LWC) code

Jornet [6] proposed Low Weight Channel (LWC) code for transmission error prevention in nanosensor networks. Codeword weight (the number of bits 1 in the codeword) in LWC is constant. The lower the probability of bit 1, the lower the interference power in the network. LWC code is denoted by LWC (m, n, w), where m is the output size, n the input size, and w the codeword weight. For example, LWC (5,3,3) is shown in Table 1.

2.5 Nanonetwork minimum energy (NME) code

In [21] we proposed NME code. Most frequent symbols are mapped to codewords with fewer bits 1. In coding table, input symbols are sorted in decreasing order of their frequency, while codewords are sorted in increasing number of their weight. For codewords with the same weight, the sorting is done in increasing order of the number of sequential bits 1, which is a characteristic of terahertz band communi-

cations. For example, NME 3 bits is shown in Table 1.

NME saves energy depending on input data distribution, in some tests more than 50%, and in theory up to 100%. Results also show that NME “is more vulnerable to channel errors, therefore it needs to be combined with error correction code” [21]. Our paper pursues this idea and combines it with an error correction code.

3. SIMPLE BLOCK NANOCODE (SBN)

Due to peculiarities of terahertz band (high path loss and high molecular noise) and limited computational complexity in nano-nodes, the design and implementation of channel coding in nanocommunications should take into account at least these characteristics:

- The information must be transmitted as fast as possible, which requires fast encoding and decoding time.
- The information must be reliably transmitted to the receiver, which requires low probability of decoding error.
- The number of hardware components should be minimized in order to fulfill the size requirement and to reduce the energy consumption in hardware.

In order to fulfill the above requirements, SBC uses NME code followed by a simple block code. Reliability is obtained from additional parity bits in the transmitted codewords, which increases the data size. NME is used as a countermeasure to the increased data size due to block code.

The SBN encoding algorithm is as follows:

- Binary stream from data source is processed by NME code to reduce the number of bits 1. The NME encodes the input symbol size n to NME n bits (i.e. the output size is equal to the input size). This process reduces the transmission energy in TS-OOK modulation.
- Next, the output of NME coding is processed by block encoder with preferable code rate (i.e. ratio between input size and output size) to provide reliability in data transmission. The smaller the code rate, the better the error correction capability.

The decoding process is reversed: the block decoder followed by NME decoder.

Formally, SBN code is characterized by two parameters, SBN (m,n) , where m is the codeword size and n the input symbol size.

3.1 Block encoder

In binary transmission, the output of source encoder is the information sequence of bits 0 and 1. In block coding, the information sequence is segmented into n bits symbols u .

After NME step, block code encodes each n bits NME output u into m bits codeword v , where $m > n$, $R = n/m$, R is the code rate. Block code in SBN is defined by an $n \times m$ generator matrix G . The transmitted codeword $v = u \times G$.

We have created four matrix generators, using random block codes. For SBN (6,3), the matrix generator is:

$$G = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

NME bits u	Codewords v
000	000000
001	011001
010	111010
011	100011
100	110100
101	101101
110	001110
111	010111

Table 2: Mapping table for SBN (6,3).

and the mapping table is as shown in Table 2. The matrix generator for SBN (16,3) is:

$$G = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

The matrix generator for SBN (16,5) is:

$$G = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

The matrix generator for SBN (16,7) is:

$$G = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

3.2 Block decoder

If error occurs during data transmission, then the received data is $r = v + e$, where $e = \{e_1, e_1, \dots, e_n\}$, $e_i = 1$ if $r_i \neq v_i$, and $e_i = 0$ if $r_i = v_i$. In order to correct errors, the receiver uses syndrome $s = r.H^T = e.H^T$ to obtain the error pattern \hat{e} . The errors in r can be corrected by computing the estimated codeword $\hat{v} = r + \hat{e}$. For example, for the symbol $u = (101)$, the transmitted codeword is $v = (101101)$, and the second transmitted bit is received in error due to the channel error, so the received word is $r = (111101)$. The receiver computes the syndrome $S = r.H^T = (010)$, which generates the error pattern $\hat{e} = (010000)$ given by Table 3. The output of decoder becomes $\hat{v} = r + \hat{e} = (101101)$, then the estimated symbol can be obtained from the last k bits of the estimated codeword $\hat{u} = (101)$. As a result, the symbol is transmitted reliably to the receiver ($\hat{u} = u$), even if the channel introduced an error.

The ability of Block code to correct i errors in received word r is defined by the weight distribution α_i . α_i is defined as the number of error patterns in syndrome table with weight i . The weight distribution of SBN (6,3) is $\alpha_0 = 1$, $\alpha_1 = 6$ and $\alpha_2 = 1$. SBN (n,k) is capable to perfectly correct i error bits if the following condition is fulfilled:

$$\alpha_i = \binom{n}{i} = \frac{n!}{(n-i)! i!} \quad (9)$$

Syndrome S	Error patterns \hat{e}
000	000000
100	100000
010	010000
001	001000
110	000100
111	000010
011	000001
101	101000

Table 3: Syndrome table for SBN (6,3).

The syndrome and error patterns for SBN (6,3) are shown in Table 3. SBN (6,3) has the ability to perfectly correct one bit error in received word. SBN (n, k) is capable to correct 2^{n-k} error patterns, where $\sum_{i=0}^{n-k} \alpha_i = 2^{n-k}$.

SBN is a simple process. It involves one mapping corresponding to NME and one mapping corresponding to block encoder. These two mappings can be combined into one mapping. Mapping process is very simple, hence appropriate for nanodevices.

In order to further minimize the encoding and decoding complexity of both hardware and computation process, it is better to use small values for the symbol block length n and codeword length m . For example, in the next section we will use message block length $n = 3, 5$ and 7 bits and codeword length $m = 6$ and 16 bits. The weight distributions for the blocks with $m = 16$ ($m = 6$ has already been presented) are the following:

- SBN (16,3): $\alpha_0 = 1, \alpha_1 = 16, \alpha_2 = 120, \alpha_3 = 550, \alpha_4 = 1635, \alpha_5 = 3030, \alpha_6 = 2480$ and $\alpha_7 = 360$.
- SBN (16,5): $\alpha_0 = 1, \alpha_1 = 16, \alpha_2 = 120, \alpha_3 = 511, \alpha_4 = 964, \alpha_5 = 428$ and $\alpha_6 = 8$.
- SBN (16,7): $\alpha_0 = 1, \alpha_1 = 16, \alpha_2 = 111, \alpha_3 = 273, \alpha_4 = 110$ and $\alpha_5 = 1$.

According to (9), SBN (16,3) and SBN (16,5) are able to perfectly correct 1 and 2 error bits in a received word and up to 7, respectively 6 error bits (depending on error patterns), while SBN (15,7) is able to perfectly correct up to 2 error bits and up to 5 error bits.

4. PERFORMANCE ANALYSIS

In this section, we numerically investigate the performance of MEC, LWC and SBN codes in terms of BER. We also investigate the feasibility of image transmission through a sensor application in biomedical field, with additional performance analysis such as energy consumption per information bit and received image quality.

In our model, the energy consumption to transmit a pulse is $E_p^{tx} = 1$ aJ and the energy to receive a pulse is 10 times smaller $E_p^{rx} = E_p^{tx}/10 = 0.1$ aJ [9]. Also, we use a simple point-to-point communication, which means there is no multi-user interference. For simulation we use MATLAB®.

4.1 Bit error rate

The propagation effects at Terahertz band (high attenuation and molecular noise) result in many bits received in error, especially for large transmission distance. The Bit Error Rate (BER) is defined as the ratio between the number

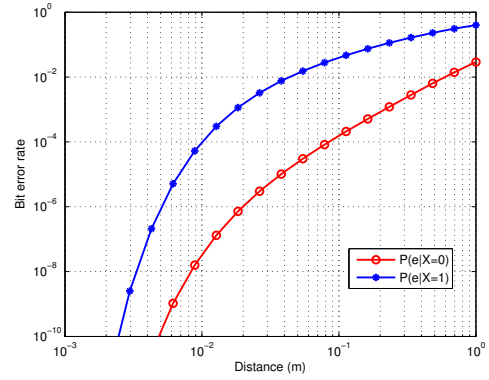


Figure 1: Transition probabilities in terahertz band.

of bit errors and the number of transmitted bits. The BER can be computed as follows:

$$P_E = \sum_{i=0}^1 P(e, X_i) = \sum_{i=0}^1 P(e|X=i) P(X=i) \quad (10)$$

where $P(e|X=i)$ is the probability of bit error when bit i is transmitted and $P(X=i) = P_i$ is the probability to transmit bit i .

Due to the complexity limitation in a nano-device, currently the feasible modulation is TS-OOK, which is binary modulation. Bit detection in binary modulation is based on 1-bit hard decision [3, 6, 1], in which, if the amplitude of received signal is larger than a threshold, it is detected as bit 1, elsewhere as bit 0. Transmission channel is modeled as an asymmetric Terahertz channel with the following error transition probabilities [6]:

$$P(e|X=0) = P(Y=1|X=0) = 1 - \int_A^B f_Y(Y|X=0) dy \quad (11)$$

$$P(e|X=1) = P(Y=0|X=1) = \int_A^B f_Y(Y|X=1) dy \quad (12)$$

where A and B are two threshold values. These values can be computed from the intersection of two Gaussian distributions $\mathcal{N}(0, N_0)$ and $\mathcal{N}(a_1, N_1)$ as follows:

$$A, B = \frac{a_1 N_0}{N_0 - N_1} \pm \frac{\sqrt{2N_0 N_1^2 \log(N_1/N_0) - 2N_0^2 N_1 \log(N_1/N_0) + a_1^2 N_0 N_1}}{N_0 - N_1} \quad (13)$$

where a_1 is the amplitude of the received pulse, and N_i the total molecular absorption noise power at the receiver when symbol i is transmitted [6].

The results in this paper are obtained using HITRAN (High resolution TRANsmission molecular absorption database) [14], an online catalog for path-loss computation at terahertz band. Based on (11) and (12), Fig. 1 shows that the transition probability of bit 0 is much smaller than of bit 1.

In MEC, the decoding error occurs when the number of bit errors in a received word is larger than $t = (d_{\min} -$

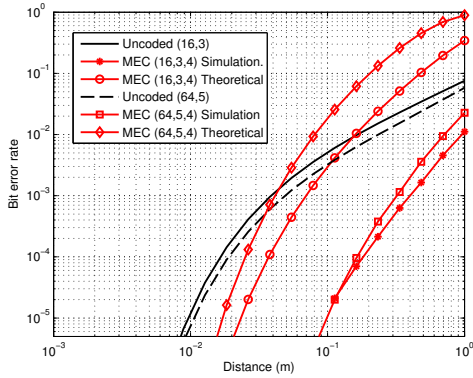


Figure 2: Bit error rate for MEC.

1)/2, where d_{\min} is the minimum distance. Therefore, the theoretical BER for MEC is obtained by [17]:

$$P_E^{MEC} = \sum_{i=t+1}^n \binom{n}{i} P_E^i (1 - P_E)^{n-i} \quad (14)$$

In LWC, the theoretical BER is equal to uncoded transmission, which can be obtained from (10).

In SBN, the decoding error occurs when the errors are not in error patterns. The theoretical BER for SBN is [12]:

$$P_E^{SBN} = 1 - \sum_{i=0}^n \alpha_i P_E^i (1 - P_E)^{n-i} \quad (15)$$

where P_E is BER given by (10).

4.1.1 Simulation results

In the simulation, 10^6 random bits are generated and transmitted through the Terahertz channel.

The BER for MEC with various input symbol sizes and constant $d_{\min} = 4$ is shown in Fig. 2. BER is a function of transmission distance (i.e. the larger the distance, the larger the number of received error bits). MEC with $d_{\min} = 4$ can correct $t = 1$ error bit. So, if the received error bits is larger than t , then MEC is unable to correct the error, which causes error symbol detection. As a result, the theoretical BER for MEC is worse than uncoded at certain distance. For example, the theoretical BER is worse than uncoded when transmission distance is larger than 3 cm. In theoretical BER, each bit (0 or 1) is transmitted with the same BER (14). In fact, BER for bit 0 is much smaller than bit 1 (i.e. terahertz channel is BAC). In simulation, transition probabilities for bits 0 and bits 1 are computed using (11) and (12), respectively. Since MEC mostly contains bits 0, then the number of received error bits is much smaller than its theoretical BER. Therefore, the BER for MEC simulation is much better than its theoretical. In MEC, output size is exponential function of input size. So, larger input symbol sizes require very large output size, which potentially increases the number of received error bits. Therefore, the larger the input symbol size, the larger the BER.

The BER for LWCs are shown in Fig. 3. Since receiver uses hard decision in bit detection, LWC has no error correction capability. Thus, if the received codeword is not in the mapping table (there are bit errors in the codeword), the

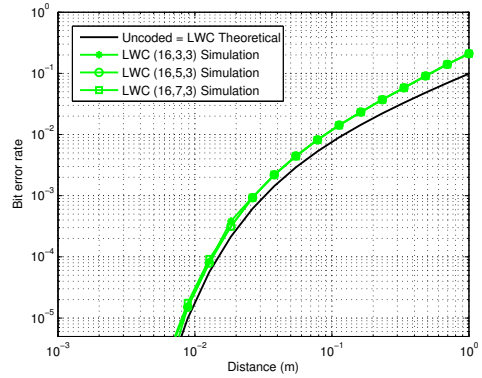


Figure 3: Bit error rate for LWC.

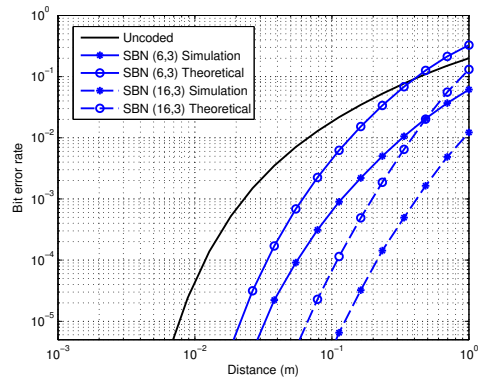


Figure 4: Bit error rate for SBN with input symbol 3 bits.

receiver produces all zero codeword. This process causes a greater BER than theoretical.

The BER for SBN with symbol size 3 bits is shown in Fig. 4 and SBN with output symbol size 5 and 7 bits is shown in Fig. 5. The theoretical BER for SBN using (15) is larger than the simulation BER. BER for bits 0 in (11) is much smaller than (15), which makes the number of received bit 0 error in simulation to be much smaller than its theoretical BER. In SBN, the smaller the code rate (i.e. constant codeword size ($m = 16$) and smaller input symbol size), the smaller the BER obtained.

Note that, however, LWC could have error correction capability by using soft-value in bit detection. Constant weight codeword allows LWC decoder to find the estimated codeword. For example, in LWC (22,16,6) [1], if the received codeword has 12 bits 1 then receiver can estimate the transmitted codeword by taking 6 highest power/amplitude bits as bits 1. But this process requires additional complexity (e.g. additional memories, adder circuit, comparator (to compare bits) circuit, etc.), which increases processing delay, circuit size and computational energy.

4.2 Sensor application

In this section we investigate the energy consumption, especially the feasibility of an image transmission application from energy point of view, and measure received image quality.

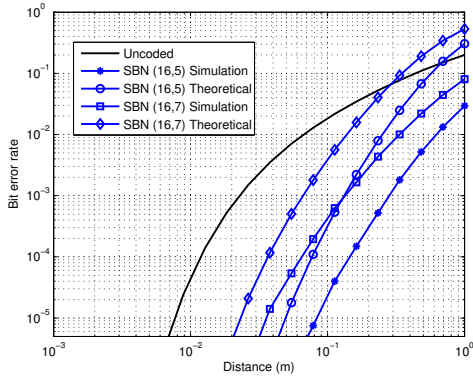


Figure 5: Bit error rate for SBN with input symbol 5 and 7 bits.

Jornet et al. [8] envisioned the Internet of multimedia nano-things in Terahertz band. In the future, nano-devices will be able to generate multimedia contents at molecular scale. High resolution nano-cameras based on nano-photodetectors [5, 13] can be built with very low power consumption. The pixel size is very small (several nm per pixel), which is easy to be embedded into a nano-devices.

In advanced health monitoring system, nano-devices can be used to detect infectious agents, such as virus and harmful bacteria [18], and sick cells. For example, cancer cells detected [19] at early stage are easier to cure. We believe that this method will revolutionize the way to cure these diseases. A nano-camera captures cell images, then transmits them to the end system for the physician diagnostic. As such, a fundamental requirement for these applications is the detection accuracy (get clear images).

In our application, nano-camera has 128x128 pixels resolution, so if the pixel size is 1 nm, then the size of nano-camera is around 128x128 nm², which still fulfills the size requirement for nano-component. In this section we simulate the transmission of a cancer cell image (`cancer.bmp`), retrieved from an electron microscope, with a resolution of 128x128 pixels, and a distance between transmitter and receiver of 10 cm.

4.2.1 Energy consumption

For the time being, the energy consumption of graphene-based nano-machine remains unknown. Therefore, we focus on the energy consumed in the communication part. In TS-OOK modulation [10], the energy consumption at transmitter is equal to the number of transmitted bits 1 multiplied by the energy to transmit a pulse (1 aJ) and the energy consumption at receiver it is equal to the number of received bits (0 and 1) multiplied by the energy to receive a pulse 0.1 aJ [9]. In Table 4, MEC (16,3,4) and LWC (16,3,3) consume more energy since the number of bits 1 is larger than uncoded (e.g. symbols 000, 001, 010 and 100 are mapped to codewords with weight 2 in MEC and weight 3 in LWC). SBN consumes more energy than the others; this is the price to pay for more reliability.

It should be noted that the SBN increases the energy consumption, but increases the reliability. For example, in Table 4, SBN (16,3) increases the transmission energy by a factor of $323,797/73,126 = 4.4$, and improves the reliability

Code	Energy consumption (aJ)			BER	PSNR (dB)
	Tx	Rx	Tx + Rx		
Uncoded	73 126	13 107	86 233	1.0×10^{-2}	25.40
MEC (16,3,4)	87 382	69 906	157 288	9.9×10^{-4}	33.74
MEC (64,5,4)	52 430	167 776	220 206	4.5×10^{-3}	28.02
MEC (256,7,4)	37 450	479 360	516 810	1.1×10^{-2}	23.98
LWC (16,3,3)	131 073	69 906	200 979	8.2×10^{-2}	12.27
LWC (16,5,3)	78 645	41 944	120 589	8.1×10^{-2}	11.89
LWC (16,7,3)	56 175	29 960	86 135	8.1×10^{-2}	11.71
SBN (6,3)	125 376	26 215	151 591	8.2×10^{-4}	37.27
SBN (16,3)	323 797	69 906	393 703	0	∞
SBN (16,5)	200 273	41 944	242 217	1.5×10^{-5}	48.13
SBN (16,7)	140 789	29 960	170 749	5.0×10^{-4}	40.41

Table 4: Energy consumption, BER and PSNR for cancer image.

(probability of decoding error) by a factor of $BER_{uncoded}$ divided by $BER_{coding} = 1.0 \times 10^{-2}/1.5 \times 10^{-5} = 667$.

Alternatively, one could prefer a coding gain instead of a higher reliability. For example, the energy consumption of SBN (16,3) can be reduced to 7.0×10^{-3} aJ to get the same BER value as uncoded (1.0×10^{-2}), and this results in $10 \times \log_{10}(1/(7.0 \times 10^{-3})) = 21.55$ dB coding gain, i.e. two orders of magnitude less than uncoded in energy used.

4.2.2 Feasibility of image transmission from energy point of view

We now compute the number of images a nano-camera without a harvesting module can send until depletion. As presented in Table 4, the transmission of the cancer image uses $N_1 = 73,126$ aJ. The number of images which can be sent with a battery initially fully charged is $800\text{pJ}/N_1 \approx 11,000$ images.

We now compute the number of images per second a nano-camera with a harvesting module can send. Recently, novel energy harvesting mechanisms have been proposed allowing perpetual (infinite life time) nanonetworks. One such mechanism is described in [9]. The nano-battery capacity is approximately 800 pJ when the 9 nF nano-capacitor is charged at 0.42 V and there are 2,500 vibration cycles. For a vibrator of 50 Hz, such as the vent of air conditioner in offices, the time needed to fully charge the nano-battery is 50 seconds.

The energy harvesting rate E_{hr} can be obtained from the nano-battery capacity 800 pJ divided by time to fully recharge it 50 seconds, which is 16 pJ/sec. The energy to transmit the cancer cell image is $E_{tx} = E_p^{tx} N_1^{Uncoded} = 73,126$ aJ for uncoded and $E_{tx} = E_p^{tx} N_1^{Block} = 323,797$ aJ for SBN (16,3). Therefore, the number of images per second in a perpetual operation is $E_{hr}/E_{tx} \approx 220$ images/second for uncoded and 50 for SBN (16,3), which is sufficient for classical uses.

4.2.3 Received image quality

In order to assess the quality of received images we use the classical peak signal to noise ratio (PSNR) metric [16]. The larger the value of PSNR, the closer the received image to the transmitted one.

In order to investigate code capability to correct errors, we generate noise with BER for bit 0 and bit 1 using (11) and (12) respectively at distance 10 cm, and use it for all codes with input symbol size 3. For example, we use MEC

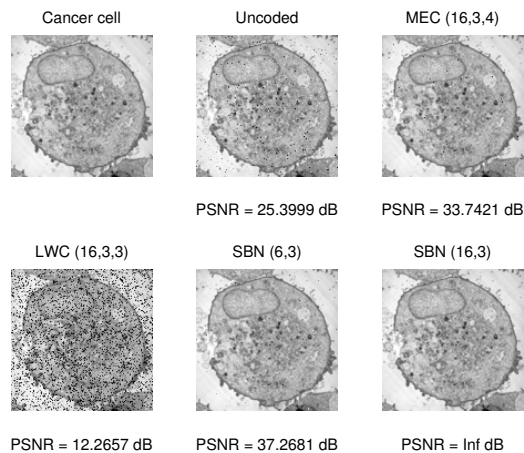


Figure 6: Reconstructed image at receiver for various codes for cancer file.

(16,3,4) since it has the smallest BER in MEC (as shown in Fig. 2). The reconstructed images at receiver are shown in Fig. 6. SBN (16,3) perfectly corrects all errors, which makes receiver reconstruct the same image as in transmitter. Knowing that SBN has a better BER, this result confirms that SBN outperforms MEC and LWC in terms of PSNR.

5. CONCLUSIONS

We presented SBN, an error correction code to provide reliability in electromagnetic nanocommunications at terahertz band. SBN outperforms the two other error correction codes found in the literature, MEC and LWC, in terms of bit error rate (reliability) at the expense of more energy. However, the energy consumption factor is much smaller than the reliability factor. Alternatively, SBN allows a coding gain over uncoded with less transmission energy for the same BER. However, we show that a nanosensor can harvest enough energy to continuously transmit images: In an example scenario and using state of the art nano-battery and harvesting process, SBN code allows to transmit up to 50 images per second with a bit error rate less than 10^{-5} .

Future work will focus on joint source-channel coding to further reduce the energy consumption at transmitter while maintaining the communication reliability.

6. REFERENCES

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