Relay-assisted nanoscale communication in the THz band

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The bit error rate (BER) performance of a cooperative relaying transmission scheme for wireless nanosensor networks in the terahertz (THz) band is investigated. Nanosensor networks comprising several graphene-based devices deployed at the nanoscale are considered. Both amplify-and-forward (AF) and decode-and-forward (DF) relaying modes are studied. A line-of-sight (LOS) channel model in the THz band is considered which takes into account both spreading loss and molecular absorption loss. Given the high path loss and level of noise from significant random fluctuations through the THz channel, relay-assisted schemes offer advantages in terms of significant performance improvements. To quantify the likely benefits, the predicted BER of the proposed scheme is derived. A simulation of the proposed relay schemes based on the THz LOS channel model utilising a Monte Carlo method is conducted. The results obtained show that a performance improvement of 2.2 dB for AF and of 5 dB for DF is achievable at a target BER of 10^{-5}.

1. Introduction: Nanotechnology is expected to advance the continuing technological revolution driven by engineering and science in many fields. Novel devices at the nanoscale provide an opportunity to equip any environment or set of objects with a plethora of molecular scale sensors. Recent developments in nanoscale sensors have led to increasing interest in the interconnection of such devices with established macroscale networks to form the Internet of nanothings (IoNT) [1]. In an IoNT system, a number of nanosensors equipped with fundamental computing and communication abilities can be distributed in the environment for data processing and exchange in the monitoring system [2, 3]. As the size of such nanosensors is estimated to be in the range of approximately hundreds of nanometres to tens of micrometres, the application potential of a single nanosensor is quite limited [3]. However, communication among nanosensors is capable of expanding their abilities to accomplish considerably more complex tasks. The connected nanosensor network will enable the application of the IoNT in healthcare, military and environmental applications [3, 4].To realise these envisioned nanosensor networks, electromagnetic (EM) communication in the terahertz (THz) band is one of the promising paradigms. Recent advanced materials such as the carbon nanotube and graphene have opened the door to the manufacturing of vital components for nanosensors [5–8]. In this Letter, we consider the performance of graphene-based EM nanosensor networks. One of the advantage of graphene-based devices is that they enable operation in the frequency range of 0.1–10.0 THz (the target THz band) at the nanoscale [5]. However, the most important characteristic of the THz channel is the high path loss and noise due to the molecular absorption of EM waves [9]. Moreover, the resulting noise is frequency selective, which makes the channel depart significantly from the ideal flat band and greatly decreases transmission performance and subsequently the transmission distance. These are the main bottlenecks that limit the application of THz communications at the nanoscale. In traditional EM communications, cooperative diversity has been introduced as a way to achieve significant data transmission performance improvements [10]. The proposed relay-assisted transmission scheme in the THz band thus seems a promising approach to overcome the channel limitations resulting in significant transmission performance improvements. This Letter investigates for the first time a possible configuration for a nanoscale THz relaying scheme.

2. THz propagation channel model: As an EM wave propagates, its power reduces as the channel is traversed due to path loss and noise. In the THz channel, molecular absorption is the most important factor which introduces path loss and random noise. In this Letter, the propagation model used in the THz band is [9, 11]

$$H(f,\ d) = \mathrm{PL}_{\mathrm{spread}}(f,\ d)\mathrm{PL}_{\mathrm{abs}}(f,\ d) \tag{1}$$

where $\mathrm{PL}_{\mathrm{spread}}$ refers to the free space spreading loss and $\mathrm{PL}_{\mathrm{abs}}$ represents the molecular absorption loss. The spreading loss can be obtained based on the Friis equation as

$$\mathrm{PL}_{\mathrm{spread}}(f,\ d) = \left(\frac{4\pi f d}{c}\right)^2 \tag{2}$$

where f is the frequency, d is the transmission distance and c is the speed of light in a vacuum.

The absorption loss is caused by molecular absorption and is determined by the transmittance of the medium τ. According to the Beer–Lambert law, we have

$$\mathrm{PL}_{\mathrm{abs}}(f,\ d) = \frac{1}{\tau} = \mathrm{e}^{k(f)d} \tag{3}$$

where $k(f)$ is the absorption coefficient of the transmission medium, i.e. air [9]. Moreover

$$k(f) = \sum_q \frac{p}{p_0}\frac{T_{\mathrm{STP}}}{T} Q^q \sigma^q(f) \tag{4}$$

where p is the system pressure, p_0 is the reference pressure, T_{STP} represents the standard temperature, Q^q refers to the number of molecules per unit volume of gas q and σ^q is the absorption cross-section of gas q. More details are given by Jornet and Akyildiz [9].

The impulse response of the THz channel is therefore the inverse Fourier transformation of the channel frequency response

$$h(t,\ d) = \mathbb{F}^{-1}\{H(f,\ d)\} \tag{5}$$

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which gives

$$h(t,\ d) = \left| \left(\frac{4\pi f d}{c} \right)^2 \mathrm{e}^{k(f)d} \right| \bullet \delta(t - t_p) \tag{6}$$

where $t_p = d/c$ is the arrival time of the EM wave.

Considering the energy dissipation and transceiver complexity for nanoscale communication systems, differential binary phase shift keying (DBPSK) modulation was used as the channel access scheme due to its low energy consumption and non-coherent demodulation process [12].

3. System model: The relay model for nanoscale communications in the THz band under consideration is a single relay system with one source, one relay and one destination. As shown in Fig. 1, ***S*** is the source node which transmits information both to the destination node ***D*** directly and via the relay node ***R***, which assists the information transmission via the ***S*** to ***R*** and ***R*** to ***D*** links over the same THz band. The system models based on amplify-and-forward (AF) and decode-and-forward (DF) relaying are introduced in the following paragraphs.

3.1. AF relaying: Here, the transmission process can be divided into two steps. First, the source node broadcasts its signal x_{S} to destination and the relay node simultaneously in the first step. Therefore, the received signal at the relay node is given by [10]

$$y_{\mathrm{S,R}} = \sqrt{P_{\mathrm{s}}} h_{\mathrm{S,R}} x_{\mathrm{S}} + n_{\mathrm{S,R}} \tag{7}$$

while the received signal at the destination node is

$$y_{\mathrm{S},D} = \sqrt{P_{\mathrm{s}}} h_{\mathrm{S},D} x_{\mathrm{S}} + n_{\mathrm{S},D} \tag{8}$$

where P_{S} is the transmitted power from the source, h represents the corresponding channel gain of the two paths, $n_{\mathrm{S,R}}$ and $n_{\mathrm{S,D}}$ are the noises within the source to relay and source to destination paths, respectively. The molecular absorption noise is considered as the main noise factor within the THz propagation channel. According to Yu *et al.* [13] and Jornet [14], the absorption noise is given by

$$n_{\mathrm{abs}}(f,\ d) = k_{\mathrm{B}} T_{\mathrm{STP}} \left(1 - \mathrm{e}^{-k(f)d}\right) \tag{9}$$

where k_{B} refers to the Boltzmann constant. As communications among different nodes are operated in the same frequency band, we assume that the absorption noise within the three channels ***S*** to ***R***, ***R*** to ***D*** and ***S*** to ***D*** are independent instantly of the same distribution.

Interference occurs when symbols arrive at the destination from different nanosensors concurrently and overlap. According to Jornet and Akyildiz [15], the overall interference can be modelled

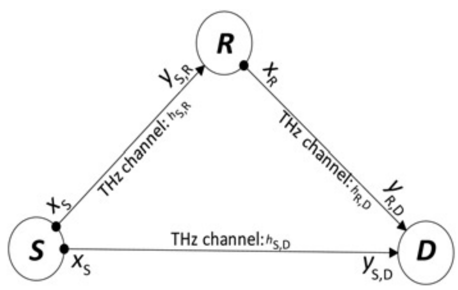

Fig. 1 *System model of single relay-assisted data transmission in the THz band at the nanoscale*

as a Gaussian distribution, which gives

$$\mathbb{N}_{\mathrm{I}}\left(\mu_{\mathrm{I}} = E[I];\quad \sigma_{\mathrm{I}}^2 = N_{\mathrm{I}}\right) \tag{10}$$

where

$$E[I] = \sum_{u=2}^{U} \frac{A^u}{\zeta} \tag{11}$$

$$N_I = \sum_{u=2}^{U} \left(\frac{(A^u)^2 + N}{\zeta} \right) p(x_1) + 2 \sum_{u=2<v}^{U} \left(\frac{p(x_1)}{\zeta} \right)^2 A^u A^v - \left(\sum_{u=2}^{U} \frac{A^u}{\zeta} p(x_1) \right)^2 \tag{12}$$

where U is the number of nanosensors, A^u is the amplitude of signal transmitted from u to destination and N refers to the channel noise power from nanosensors to destination. $P(x_1)$ refers to the probability of sending a pulse. ζ is the ratio of symbol duration and pulse duration, for DBPSK in this Letter we set it to 1. Therefore, the total noise and interference is

$$n = n_{\mathrm{abs}} + n_{\mathrm{I}} \tag{13}$$

During the next step, the received signal at the relay, i.e. $y_{\mathrm{S,D}}$ is amplified with gain β, in order to comply with the relay power constraint, the amplifying gain should satisfy [10]

$$\beta \leq \sqrt{\frac{P_{\mathrm{s}}}{P_{\mathrm{s}} |h_{\mathrm{S,R}}|^2 + n_{\mathrm{S,R}}}} \tag{14}$$

As maybe seen from (14), the amplification gain depends on the THz channel gain from source to relay, the source power and the noise power. Therefore, the received signal at the relay is now amplified to be

$$y_{\mathrm{AF}} = \beta y_{\mathrm{S,R}} \tag{15}$$

As a result, the received signal from relay at destination is

$$y_{\mathrm{R,D}}^{\mathrm{AF}} = h_{\mathrm{R,D}} y_{\mathrm{AF}} + n_{\mathrm{R,D}} \tag{16}$$

where the power of the transmitted signal from relay is P_{r} and is equal to P_{s}.

The signal from the source $y_{\mathrm{S,D}}$ is then combined with the signal from the relay $y_{\mathrm{R,D}}$ at destination, to obtain

$$y = a_1 y_{\mathrm{S,D}} + a_2 y_{\mathrm{R,D}}^{\mathrm{AF}} \tag{17}$$

where a_1 and a_2 are the parameters when we use the maximal ratio combining (MRC) method to combine the two received signals so as to achieve a maximised *signal-to-interference-noise ratio (SINR)* at the destination.

As was mentioned previously, we assume that the absorption noise within the three channels follows the same distribution; therefore, the two signals at the destination are affected equally by the channel noise n with a power density of N. In this case, the combined signal at the destination can also be expressed as

$$y = \sum_{i=1}^{2} \alpha_i \mathrm{e}^{-\mathrm{j}\phi_i} y_i \tag{18}$$

where $y_i = h_i \mathrm{e}^{\mathrm{j}\emptyset_i} x_i + n$ and α_i represents the MRC coefficients.

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The MRC output *SINR* of (14) is given by

$$\gamma = \frac{\left(\sum_{i=1}^{2} \alpha_i h_i\right)^2}{N \sum_{i=1}^{2} \alpha_i^2} \tag{19}$$

This can be maximised by using the Cauchy–Schwartz inequality

$$\left(\sum_{i=1}^{2} \alpha_i h_i\right)^2 \le \left(\sum_{i=1}^{2} \alpha_i^2\right)\left(\sum_{i=1}^{2} h_i^2\right) \tag{20}$$

The maximal *SINR* in (19) can be obtained when the equality of (20) is achieved by making

$$\alpha_i = \frac{h_i}{\sqrt{N}} \tag{21}$$

By substituting (8) and (12) into (13), we obtain

$$\begin{aligned} y = {} & a_1\left(\sqrt{P_s} h_{S,D} x_S + n_{S,D}\right) \\ & + a_2\left(\beta\sqrt{P_r} h_{S,R} h_{R,D} x_S + \left(\beta h_{R,D} n_{S,R} + n_{R,D}\right)\right) \end{aligned} \tag{22}$$

where $n_{S,D} = n_{S,R} = n_{R,D}$ with the same noise power density, i.e. $N_{S,D} = N_{S,R} = N_{R,D}$.

To achieve the maximal *SINR*, the optimal values of the parameters in (18) are designed similarly to [16] as

$$a_1 = \frac{\sqrt{P_s} h_{S,D}^*}{N_{S,D}} \tag{23}$$

and

$$a_2 = \frac{\beta\sqrt{P_r} h_{S,R}^* h_{R,D}^*}{\left(\beta^2 |h_{R,D}|^2 + 1\right) N_{R,D}} \tag{24}$$

where h^* represents the complex conjugate of h; this is designed to make the two received signals equal.

The corresponding MRC output *SINR* at the destination for the system is given by [17]

$$\gamma = \gamma_{S,D} + \gamma_{S,R,D} \tag{25}$$

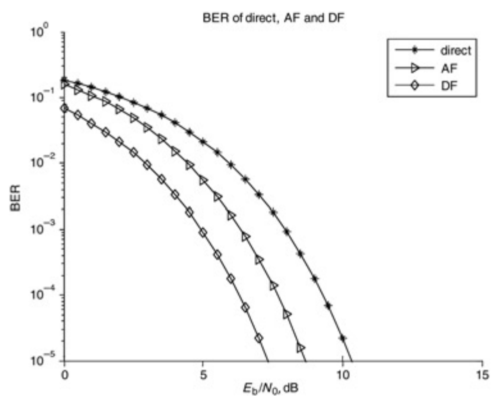

Fig. 2 *BER against E_b/N_o simulation results of AF, DF and direct data transmission over the THz band*

For AF model, the *SINR* expressions for the two paths are

$$\gamma_{S,D} = \frac{\left|a_1\sqrt{P_s} h_{S,D}\right|^2}{|a_1|^2 N_{S,D}} = \frac{P_s |h_{S,D}|^2}{N_{S,D}} \tag{26}$$

and

$$\begin{aligned} \gamma_{S,R,D} &= \frac{\left|a_2 \beta \sqrt{P_r} h_{S,R} h_{R,D}\right|^2}{|a_2|^2 \left(\beta^2 |h_{R,D}|^2 + 1\right) N_{R,D}} \\ &= \frac{1}{N_{S,D}} \frac{P_r^2 |h_{S,R}|^2 |h_{R,D}|^2}{P_r |h_{S,R}|^2 + P_r |h_{R,D}|^2 + N_{S,D}} \end{aligned} \tag{27}$$

3.2. DF relaying: In this case, the relay decodes (demodulates) the received signal from the source node and then forwards the encoded (modulated) signal to destination. The received signal at the destination after DF relaying is therefore [18]

$$y_{R,D}^{DF} = \sqrt{P_r} h_{R,D} y_{DF} + n_{R,D} \tag{28}$$

This signal is then combined with the direct signal from the source node at the destination which gives

$$y = b_1 y_{S,D} + b_2 y_{R,D}^{DF} \tag{29}$$

b_1 and b_2 are the relevant MRC optimal parameters given as

$$b_1 = \frac{\sqrt{P_s} h_{S,D}^*}{N_{S,D}} \tag{30}$$

$$b_2 = \frac{\sqrt{P_r} h_{R,D}^*}{N_{R,D}} \tag{31}$$

Recalling (29), in DF model *SINR* for the two paths can be calculated as

$$\gamma_{S,D}^{DF} = \frac{\left|b_1\sqrt{P_s} h_{S,D}\right|^2}{|b_1|^2 N_{S,D}} = \frac{P_s |h_{S,D}|^2}{N_{S,D}} \tag{32}$$

and

$$\gamma_{S,R,D}^{DF} = \frac{\left|b_2\sqrt{P_r} h_{R,D}\right|^2}{|b_2|^2 N_{R,D}} = \frac{P_r |h_{R,D}|^2}{N_{R,D}} \tag{33}$$

4. Simulation results: The simulations were conducted using DBPSK modulation to access the single AF and DF THz channel. The channel gain is based on the THz line-of-sight channel model. For a target minimum error probability of 10^{-5}, Monte Carlo simulations were implemented. For simplicity, no channel codes were used to encode the raw data in either relaying case meaning that the decoding process was therefore simply demodulation. Fig. 2 shows the simulated bit error rate (BER) performance of the two relay schemes compared with direct transmission without a relay. In this figure, we plot the BER of AF and DF relay protocols as a function of E_b/N_0 and it can clearly be seen that both AF and DF relay-assisted transmissions have improved the BER performance significantly. Moreover, DF has much better performance than AF in line with expectations based on established cooperative communications principles. The relaying gain at $10^{-5}$is ~2.2 dB for AF and 5 dB for DF. The extra 2.8 dB represents the benefit for the complexity of DF compared with AF.

5. Conclusions: In this Letter, a single relay-assisted communication scheme in THz band for nanoscale networks has been introduced. Both AF and DF relays are studied in the THz channel employing DBPSK modulation to reduce the complexity and lower the power dissipation in the system. The simulation results have shown that relay-assisted transmission provides significant improvement over the original direct transmission. The application of the DF scheme provides better performance than that of AF because the latter not only amplifies the signal but also the noise in the channel. Given the energy and transceiver limitations for nanoscale operation, we have not considered any channel coding in this first investigation. Furthermore, due to the complexity of the system at the nanoscale we only considered the single relay scheme in this Letter; channel coding and multi-hop schemes are the subjects of ongoing study.

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