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Simultaneous Wireless Information and Power Transfer for AF Relaying Nanonetworks in the Terahertz Band

Abstract

A nanonetwork is comprised of nanoscale sensors and communicating devices facilitating communication at the nanoscale, which is a promising technology for application in health applications such as intra-body health monitoring and drug delivery. However, **the communication performance** within a nanonetwork is substantially limited by the energy loss as the Electromagnetic (EM) wave propagates along the channel. Energy harvesting for nanosensor networks can provide a way to overcome the energy bottleneck without considering the lifetime of batteries. Moreover, relaying protocols for nanoscale communications have been proposed to improve the communication performance and extend the transmission distances among nanosensors within nanonetworks. The combination of energy harvesting and a relaying protocol provides an emerging solution **not only** to overcome the aforementioned energy issues but also enhance the system performance. Therefore, in this paper, simultaneous wireless information and power transfer nanonetworks in the Terahertz (THz) Band (0.1-10 THz) is proposed. An amplify and forward (AF) relaying nanonetwork in **this** band is investigated, where the relay harvests energy from the received THz signal **which is then consumed** to forward the information to the destination. Performance based on both time-switching and power-splitting protocols is analyzed. The numerical results show the optimal power-splitting ratio and time switching ratio that achieves the maximum throughput at the destination as well as the impact of transmission distance on system performance. It is seen that the power-splitting protocol gives greater throughput than that of the time-switching protocol.

Key Words: Nanosensor, Nanonetworks, THz, Energy Harvesting, amplify and forward (AF), Time-Switching, Power-Splitting, Throughput.

1. Introduction

Nanotechnology has introduced a variety of novel devices and thus opened the door to reshape the conventional communication paradigm. Nano-sized sensors are expected to drive the evolution of many areas of information and communication technology. The interconnection of massive nanosensor numbers requires a communication network, i.e. a nanonetwork; the so-called Internet of Nano-Things (IoNT) [1], [2]. In this paradigm, many nanosensors with fundamental sensing and communication capabilities are attached to objects or distributed in the environment for information acquisition and exchange. Due to the size limitations of nanosensors, the potential of **each individual device** is limited. **Communications** among them will vastly increase their capabilities so as to execute **many** more complex missions [3]. To date, there are **two main** paradigms of communication at the nanoscale [4] i.e. molecular communication, and electromagnetic (EM) communication in the THz band. Here, the focus is on communication among nanosensors in the THz band to establish nanonetworks that can be applied in, for example, healthcare and environmental monitoring [3]. For healthcare monitoring, a therapeutic nanosensor network can be developed which is applicable either inside or off the body [5], [6]. The high path loss of the THz channel communication means that the transmission distance and performance within nanonetworks are limited. **Although the schemes are challenging, the achieved data rates and transmission distances are still promising for short-range communications among nanosensors such as those implanted or worn by humans** [7]**.**

A relaying protocol is a promising way to improve the communication performance and to extend transmission distances [8]. Furthermore, the performance of THz communication within the IoNT is limited by the energy loss and the storage capacity of nano batteries [9], [10]. Harvesting energy from the ambient environment provides a promising approach to enhance the lifetime and performance of energy constrained THz communication nanonetworks [8]. Traditional energy harvesting mechanisms such as solar energy are not available in nanonetworks as the efficiency of solar cells is quite low given the size limitations [10]. Therefore, novel energy harvesting mechanisms need to be developed. **Recently, energy harvesting schemes for nanonetworks have been proposed [9]–[12]. Limited by the size of powering units within nanonetworks, these works are mostly based on nanowires which satisfy the size limitation when providing the required energy. Alternatively,** harvesting energy from ambient EM waves has **become** more and more attractive over the last decade [13]. **Furthermore, energy harvesting using THz electronics (i.e. rectennas) has been widely studied and form a promising solution to powering nanonetworks.** In the THz band, some new nano-rectennas have been proposed and manufactured [14], [15] opening the door to energy harvesting based on EM in nanonetworks. Moreover, since EM signals carry not only information but also energy, this inspires a way to collect energy and accomplish information processing from ambient EM signals simultaneously [16]–[19]. In tradition EM communications, the simultaneous wireless information and power transfer system (SWIPT) has been investigated with the idea of transmitting power and information simultaneously being first proposed by Varshney [17] who also proposed a capacity-energy tradeoff function to analyse the fundamental performance of SWIPT. In [19], SWIPT via a frequency selective channel was analyzed which gives the idea of transmitting power and information simultaneously in the THz band. This provides an exciting approach to overcoming the above obstacle of energy constrained nanoscale communication networks.

To date, there **has been** no research in wireless energy harvesting and information transfer for nanonetworks in the THz band. Motivated by this, we develop in this paper an AF relaying simultaneous wireless Information and power transfer scheme for such networks. The scenario is that an AF relay harvests EM energy from the received THz signal transmitted by a source node and then consumes the harvested energy to amplify and forward the signal to the destination node [20]. Here, both time-switching and power-splitting protocols are adopted [21]. In the former, the received signal at the relay is first used for energy harvesting for some time, and then used for information transmission in the remaining time. In the latter, the signal is divided into two portions, one for energy harvesting and the other one for information processing. **The word 'simultaneously' in SWIPT implies that the system completes the two tasks of 'receiving energy' and 'receiving information' within a unit time over a single noisy channel. For the time switching protocol, the unit time is divided into two parts, one of which is used for receiving energy and the other for receiving information. The key point of the use of the term '*simultaneous*' here is that the same channel and the same signal can be used in part for transporting energy and in part for transmitting information.**The objective of the study here is to find the optimal time switching fraction and power splitting ratio that achieve the maximal throughput at the destination. In the paper, we investigate both the instantaneous and the time-delayed throughputs.

The rest of the paper is comprised of four sections. In section 2, the propagation model in the THz band is presented. The following section 3, investigates the time switching and power splitting AF relaying protocols in detail. Section 4 shows the numerical results and the analysis of the obtained results. Lastly, section 5 concludes the paper.

2. THz Band Propagation Model

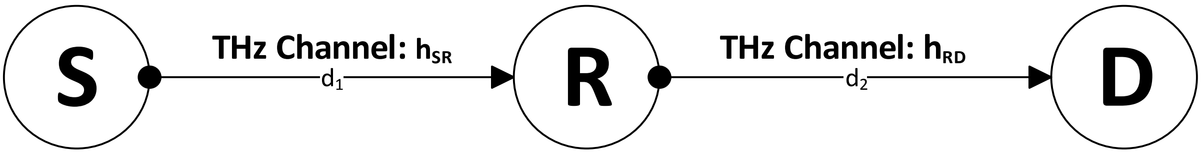

Fig. 1 AF relaying model in the THz band at the nanoscale

For communication in nanonetworks, the propagation of EM waves is determined by the THz channel characteristics. The main peculiarity of the THz band is the impact of molecular absorption on the EM wave's propagation [22], [23], which causes molecular absorption loss. When the propagation frequency of the wave comes close to the resonant frequency of internal molecular vibration, this absorption occurs. The vibration of a molecule absorbs the energy of the EM wave and converts it to kinetic energy [23]. Therefore, the frequency response of the THz band channel is [23],:

$$H_c(f,d) = PL_{spread}(f,d)PL_{abs}(f,d) \tag{1}$$

where PL_{spread} stands for the free space spreading loss due to the EM wave expansion when it propagates through the channel and PL_{abs} refers to the molecular absorption loss. The spreading loss is given by:

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

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

The molecular absorption loss is determined by the transmittance of the medium τ which is given by:

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

where $k(f)$ is the overall absorption coefficient of the medium and is given by:

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

where p and p_0 stand for the pressure of the system and the reference pressure respectively, while T_{STP} refers to the standard temperature, Q^q is the molecules volume density (molecules m^{-3}) of gas q and σ^q is the absorption cross-section ($\text{m}^2\ (\text{molecule})^{-1}$). More details of these terms are given by Jornet and Akyildiz in [23].

Therefore, by applying the inverse Fourier transformation to the channel frequency response $H_c\left(f,d\right)$, the impulse response can be obtained as [24]:

$$h_c\left(t,d\right) = \mathrm{F}^{-1}\left\{H_c\left(f,d\right)\right\} \tag{5}$$

For the system, the impulse repose is given as [24]:

$$h = h_a^{Tx} * h_c * h_a^{Rx} \tag{6}$$

where h_a^{Tx} and h_a^{Rx} are the impulse responses of transmission and reception antennas, respectively.

In the THz band at the nanoscale, the major noise power at the receiver is contributed by molecular absorption noise, given by [23]:

$$n_{abs}(f,d) = k_B T_{STP}\left(1-e^{-k(f)d}\right) \tag{7}$$

It is assumed that the source to relay link and the relay to destination link contain noise sources which are independent of each other. As water vapor in the air majorly contributes to the total absorption [23], in this paper, the system is assumed to be operated in air with 0.1% water vapor content.

3. System Model

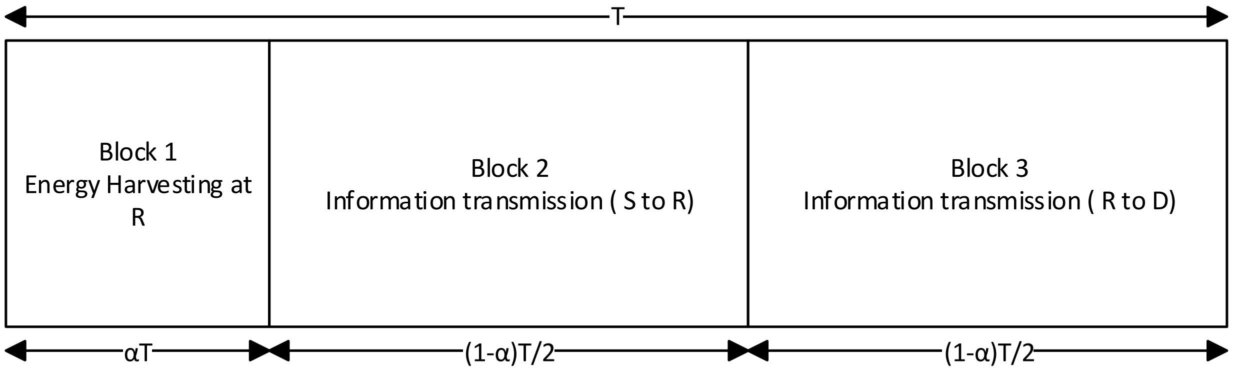

Fig. 2 Time-switching protocol

The relay-assisted wireless link in the THz band with information and power transfer simultaneously is illustrated in Fig.1. Thus in this paper, a three node AF relaying system is studied, where the source node (**S**) transmits information to the destination node (**D**) with the assistance of the relay (**R**). As the direct link between **S** and **D** could be out of the THz signal coverage and there might be obstacles between the **S** and **D**, we assume that the direct link does not exist. It is also assumed that all the nodes are equipped with a single antenna and are half-duplex. Moreover, the relay is assumed to be energy constrained where it consumes the harvested energy from the source signal to forward the received information to the destination. Both time switching (shown in Fig. 2) and power switching (shown later in Fig. 3) schemes are considered and the total communication time is assumed to be T. Following previous research [25], [26], **for the purpose of simplicity, we assume that the destination knows the THz channel state information perfectly in line with previous works in this field;** it can estimate the THz channel concurrently with the information transmission. **The power required for signal processing is assumed to be negligible in comparison with the power used for signal transmission** [20], [27]. Differential binary phase shift keying (BPSK) is applied as the channel access scheme [28], [29].

3.1 Time switching

In the time switching protocol shown in Fig. 2, T is the total communication time from source to destination, α is a fraction of the total time, i.e. αT which is used for **R** harvest energy from source. The remaining time is used for information transfer, which is divided in half, $(1-\alpha)T/2$ for information transmission from source to relay and $(1-\alpha)T/2$ for information transmission from relay to destination. Therefore, the received signal at **R** (during Block 1 and Block 2) is given by [30]:

$$y_R = \sqrt{P_s} h_{S,R} x_s + n_R \tag{8}$$

where P_s is the transmitted power from **S**, h is the THz channel gain in (6), hence $h_{\mathrm{S,R}}$ represents the channel gain of the source to relay link, x_s is the normalized transmitted signal of the source; n_R refers to the overall noise at the relay. Note that the overall noise introduced by the relay's receiver is comprised of the channel noise, the system electronic noise and the antenna noise. According to [23] and [31], the second two noise sources are ultralow for nanomaterials, therefore for graphene-based nanonetworks in the THz band, we only consider the noise contributed by the THz channel, i.e. n_R is the overall molecular absorption noise given in (7). For noise introduced by the receiver at the destination is considered to be the same.

The harvested energy at the relay from the source can be obtained using (8),

$$E_h = \eta P_s \left| h_{S,R} \right|^2 \alpha T \tag{9}$$

where $0 < \eta < 1$ is the THz wave to energy conversion efficiency factor.

During the next step, the received signal (Block 2) at the relay y_R is amplified and forwarded to the destination, and this process consumes the harvested energy from the source (Block 1), i.e. E_h, therefore the received signal at the destination is expressed as:

$$y_D = \sqrt{P_r} h_{R,D} \beta y_R + n_D \tag{10}$$

where $h_{R,D}$ is the THz channel gain of the relay to destination link, n_D represents the overall noise at the destination, P_r is the transmission power of the relay, which can be obtained as:

$$P_r = \frac{E_h}{(1-\alpha)\frac{T}{2}} = \frac{2\alpha}{1-\alpha}\eta P_s \left|h_{S,R}\right|^2 \tag{11}$$

β is the amplification gain of the relay, which is taken to be [30]:

$$\beta = \sqrt{\frac{1}{P_s\left|h_{S,R}\right|^2 + N_{0R}}} \tag{12}$$

Here, substituting (12) into (10), we obtain,

$$\begin{aligned} y_D &= h_{R,D}\sqrt{P_r}\sqrt{\frac{1}{P_s\left|h_{S,R}\right|^2 + N_{0R}}}\, y_R + n_D \\ &= \frac{\sqrt{P_r}\, h_{R,D}}{\sqrt{P_s\left|h_{S,R}\right|^2 + N_{0R}}}\, y_R + n_D \end{aligned} \tag{13}$$

Substituting (8) into (13), the received signal is:

$$\begin{aligned} y_D &= \frac{\sqrt{P_r}\, h_{R,D}}{\sqrt{P_s\left|h_{S,R}\right|^2 + N_{0R}}}\left(\sqrt{P_s}\, h_{S,R} x_s + n_R\right) + n_D \\ &= \frac{\sqrt{P_r P_s}\, h_{S,R} h_{R,D} x_s}{\sqrt{P_s\left|h_{S,R}\right|^2 + N_{0R}}} + \frac{\sqrt{P_r}\, h_{R,D} n_R}{\sqrt{P_s\left|h_{S,R}\right|^2 + N_{0R}}} + n_D \end{aligned} \tag{14}$$

Then, substituting (9) into (14), we get

$$y_D = \underbrace{\frac{\sqrt{2\alpha\eta\left|h_{S,R}\right|^2} P_s h_{S,R} h_{R,D} x_s}{\sqrt{(1-\alpha)}\sqrt{P_s\left|h_{S,R}\right|^2 + N_{0R}}}}_{signal} + \underbrace{\frac{\sqrt{2\alpha\eta\left|h_{S,R}\right|^2}\, P_s h_{R,D} n_R}{\sqrt{(1-\alpha)}\sqrt{P_s\left|h_{S,R}\right|^2 + N_{0R}}} + n_D}_{noise} \tag{15}$$

Therefore, the instantaneous Signal to noise ratio (SNR) at the destination for the entire THz band is given by:

$$
\begin{aligned}
\gamma &= \frac{\mathrm{E}\left\{\left| signal\ part\ in\ (15)\right|^2\right\}}{\mathrm{E}\left\{\left| noise\ part\ in\ (15)\right|^2\right\}} \\
&= \frac{\dfrac{2\alpha\eta P_s^2 \left|h_{S,R}\right|^4 \left|h_{R,D}\right|^2}{(1-\alpha)P_s \left|h_{S,R}\right|^2 + N_{0R}}}{\dfrac{2\alpha\eta P_s \left|h_{S,R}\right|^2 \left|h_{R,D}\right|^2 N_{0R}}{(1-\alpha)P_s \left|h_{S,R}\right|^2 + N_{0R}} + N_{0D}} \\
&= \frac{2\alpha\eta P_s^2 \left|h_{S,R}\right|^4 \left|h_{R,D}\right|^2}{2\alpha\eta P_s \left|h_{S,R}\right|^2 \left|h_{R,D}\right|^2 N_{0R} + (1-\alpha)P_s \left|h_{S,R}\right|^2 N_{0D} + N_{0R}N_{0D}} \\
&= \frac{\dfrac{P_s \left|h_{S,R}\right|^2}{N_{0R}} \eta \dfrac{2\alpha}{1-\alpha} \dfrac{P_s \left|h_{S,R}\right|^2 \left|h_{R,D}\right|^2}{N_{0D}}}{\eta \dfrac{2\alpha}{1-\alpha} \dfrac{P_s \left|h_{S,R}\right|^2 \left|h_{R,D}\right|^2}{N_{0D}} + \dfrac{P_s \left|h_{S,R}\right|^2}{N_{0R}} + 1/(1-\alpha)} \\
&= \frac{\gamma_{S,R}\gamma_{R,D}}{\gamma_{R,D} + \gamma_{S,R} + 1/(1-\alpha)}
\end{aligned}
\tag{16}
$$

where $\mathrm{E}\{\cdot\}$ refers to the expectation operator; N_{0R} and N_{0D} are the noise powers at the receivers of the relay and the destination respectively.

• Throughput Analysis

The following section analyses the instantaneous throughout and the delay-limited throughput performance of the AF relaying nanonetworks with THz energy harvesting and the optimal time switching factor and power splitting ratio are investigated.

According to the THz channel model given previously, the band is frequency-selective and the molecular absorption noise is non-white. Thus, the entire THz band is divided into a number of narrow enough sub-bands with center frequency f_i $(i = 1,2,3 \ldots M)$ and $\Delta f = f_{i+1} - f_i$ is the corresponding sub-bandwidth. Therefore, these sub-bands behave as frequency non-selective and the noise can be considered as white [23]. The SNR for each sub-band at the destination is obtained by rewriting (16) as:

$$
\begin{aligned}
\gamma(f_i) &= \frac{2\alpha\eta P_{s(i)}^2 \left|h_{S,R}(f_i)\right|^4 \left|h_{R,D}(f_i)\right|^2}{2\alpha\eta P_{s(i)} \left|h_{S,R}(f_i)\right|^2 \left|h_{R,D}(f_i)\right|^2 \sigma_R^2 + (1-\alpha) P_{s(i)} \left|h_{S,R}(f_i)\right|^2 \sigma_D^2 + \sigma_R^2 \sigma_D^2} \\
&= \frac{\dfrac{P_{s(i)} \left|h_{S,R}(f_i)\right|^2}{\sigma_R^2} \dfrac{2\alpha\eta}{(1-\alpha)} \dfrac{P_{s(i)} \left|h_{S,R}(f_i)\right|^2 \left|h_{R,D}(f_i)\right|^2}{\sigma_D^2}}{\dfrac{2\alpha\eta}{(1-\alpha)} \dfrac{P_{s(i)} \left|h_{S,R}(f_i)\right|^2 \left|h_{R,D}(f_i)\right|^2}{\sigma_D^2} + \dfrac{P_{s(i)} \left|h_{S,R}(f_i)\right|^2}{\sigma_R^2} + \dfrac{1}{(1-\alpha)}} \\
&= \frac{\gamma_{S,R}(f_i)\gamma_{R,D}(f_i)}{\gamma_{R,D}(f_i) + \gamma_{S,R}(f_i) + 1/(1-\alpha)}
\end{aligned}
\tag{17}
$$

where $P_{s(i)}$ is the transmitted power at the source within the i_{th} sub-band , for the entire band we have $\sum_i^I P_{s(i)} = P_s$, $h_{S,R}\left(f_i\right)$ and $h_{R,D}\left(f_i\right)$ are the i_{th} sub-channel gain within the source to relay link and the relay to destination link, respectively which can be calculated from (6) using the center frequency f_i and a fixed distance d, σ_R^2 and σ_D^2 are the variance of the overall additive white Gaussian noise (AWGN) in the i_{th} sub-band at the relay and the destination respectively. In addition, $h(f_i)$ is dominated by f_i and d .

Based on (17), the resulting instantaneous throughput at the destination can be obtained by summing the throughput of each sub-band [17]:

$$
\mathrm{R}_I = \frac{(1-\alpha)}{2} \times \sum_i^M \log_2\left(1 + \gamma\left(f_i\right)\right) \tag{18}
$$

From (18) we can get the optimal α when achieving the maximum instantaneous throughput.

The outage probability is the probability of SNR going below a fixed threshold γ_{th} or a fixed transmission rate $R_{th} = \log_2\left(1 + \gamma_{th}\right)$, which is expressed as:

$$
p_{out} = \mathrm{pr}\left\{\gamma \le \gamma_{th}\right\} \tag{19}
$$

For nanonetworks in the THz band, the entire band is divided into many sub-bands, so that each sub-band is flat. The outage probability is, therefore, the product of the outage probability of each sub-band. Recalling (16), we can rewrite (19) for the entire THz band as [27],

$$
\begin{aligned}
p_{out} &= \frac{1}{M} \sum_i^M \mathrm{pr}\left\{\gamma\left(f_i\right) \le \gamma_{th}\right\} \\
&= \frac{1}{M} \sum_i^M \mathrm{pr}\left\{\frac{\gamma_{S,R}(f_i)\gamma_{R,D}(f_i)}{\gamma_{R,D}(f_i) + \gamma_{S,R}(f_i) + 1/(1-\alpha)} \le \gamma_{th}\right\}
\end{aligned}
\tag{20}
$$

Therefore, the throughput of delay-limited transmission within the nanonetwork is given as [21], [32]:

$$\mathrm{R}_{DL} = \left(1-p_{out}\right)R_{th}\frac{\left(1-\alpha\right)T/2}{T} = \frac{R_{th}\left(1-\alpha\right)\left(1-p_{out}\right)}{2} \tag{21}$$

3.2 Power Splitting

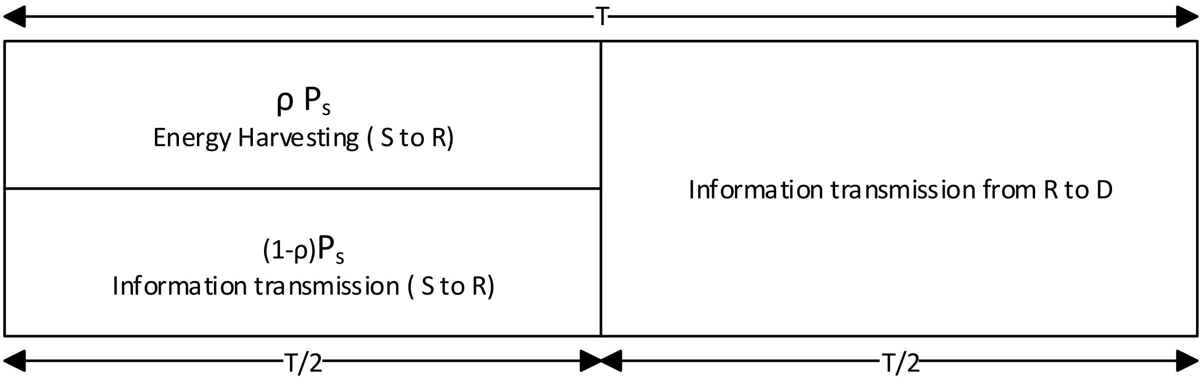

Fig. 3 Power-splitting protocol

The process of the power-splitting model is illustrated in Fig. 3, the first half of the block time is used for energy harvesting and information transmission from source to relay, while during the other half of the time, information transmission is conducted from relay to destination. The parameter $\rho, (0 < \rho < 1)$ is the power fraction factor of the signal, i.e. ρP_S is allocated for energy harvesting and the left part $(1-\rho)P_S$ is used for information transmission. As **in** the time-switching model, we assume **that** all the harvested energy at the relay is used for information transmission from the relay to the destination. The objective of this study is to find the optimal ρ that achieves the maximum throughout at destination.

The power of the received signal at relay is split into two portions, i.e. one portion of the signal $\sqrt{\rho}y_R$ is transmitted for energy harvesting, and hence the harvested energy at the relay is expressed as:

$$E_h = \eta\rho P_s \left|h_{S,R}\right|^2 \left(\frac{T}{2}\right) \tag{22}$$

The other portion of the signal $\sqrt{1-\rho}y_R$ is sent to the information receiver for information transmission, the received signal at the relay is therefore given by:

$$y_R = \sqrt{\left(1-\rho\right)P_s}\,h_{S,R}x_s + n_R \tag{23}$$

where the parameters are those defined in (8). As in time switching, the channel noise dominates and so we consider the noise contributed by the THz channel alone, i.e. n_R only. The relay amplification factor for the power-splitting model is given by [30]:

$$\beta = \sqrt{\frac{1}{(1-\rho)P_s\left|h_{S,R}\right|^2 + N_{0R}}} \tag{24}$$

Here we modeled the noise at the receivers n_R and n_D as independent AWGN sources with variances N_{0R} and N_{0D}, respectively. By substituting (24) into (10), the received signal at the destination for the power-splitting model is given as:

$$\begin{aligned} y_D &= h_{R,D}\sqrt{P_r}\left(\sqrt{(1-\rho)P_s}h_{S,R}x_s + n_R\right)y_R + n_D \\ &= \frac{\sqrt{P_r}h_{R,D}}{\sqrt{(1-\rho)P_s\left|h_{S,R}\right|^2 + N_{0R}}}y_R + n_D \end{aligned} \tag{25}$$

Then substituting (24) into (25), y_D is now,

$$\begin{aligned} y_D &= \frac{\sqrt{P_r}h_{R,D}}{\sqrt{(1-\rho)P_s\left|h_{S,R}\right|^2 + N_{0R}}}\left(\sqrt{(1-\rho)P_s}h_{S,R}x_s + n_R\right) + n_D \\ &= \frac{\sqrt{(1-\rho)P_r P_s}h_{S,R}h_{R,D}x_s}{\sqrt{(1-\rho)P_s\left|h_{S,R}\right|^2 + N_{0R}}} + \frac{\sqrt{P_r}h_{R,D}n_R}{\sqrt{(1-\rho)P_s\left|h_{S,R}\right|^2 + N_{0R}}} + n_D \end{aligned} \tag{26}$$

The transmitted power of the relay for power-splitting protocol is given as,

$$P_r = {E_h}\big/{(T/2)} = \eta\rho P_s\left|h_{S,R}\right|^2 \tag{27}$$

Now, using (22) and substituting (27) into (26),

$$y_D = \underbrace{\frac{\sqrt{\rho(1-\rho)\eta\left|h_{S,R}\right|^2 P_s}h_{S,R}h_{R,D}}{\sqrt{P_s\left|h_{S,R}\right|^2(1-\rho) + N_{0R}}}x_s}_{signal} + \underbrace{\frac{\sqrt{\rho\eta\left|h_{S,R}\right|^2 P_s}h_{R,D}n_R}{\sqrt{P_s\left|h_{S,R}\right|^2(1-\rho) + N_{0R}}} + n_D}_{noise} \tag{28}$$

The SNR of the system is therefore obtained using (28) as,

$$\begin{aligned}\gamma &= \frac{\mathrm{E}\left\{\left|signal\ part\ in\ (28)\right|^2\right\}}{\mathrm{E}\left\{\left|noise\ part\ in\ (28)\right|^2\right\}} \\ &= \frac{\eta(1-\rho)\rho P_s^2\left|h_{S,R}\right|^4\left|h_{R,D}\right|^2}{\eta\rho P_s\left|h_{S,R}\right|^2\left|h_{R,D}\right|^2 N_{0R}+(1-\rho)P_s\left|h_{S,R}\right|^2 N_{0D}+N_{0R}N_{0D}} \\ &= \frac{(1-\rho)\dfrac{P_s\left|h_{S,R}\right|^2}{N_{0R}}\rho\eta\dfrac{P_s\left|h_{S,R}\right|^2\left|h_{R,D}\right|^2}{N_{0D}}}{\rho\eta\dfrac{P_s\left|h_{S,R}\right|^2\left|h_{R,D}\right|^2}{N_{0D}}+(1-\rho)\dfrac{P_s\left|h_{S,R}\right|^2}{N_{0R}}+1} \\ &= \frac{\gamma_{S,R}\gamma_{R,D}}{\gamma_{R,D}+\gamma_{S,R}+1}\end{aligned} \quad . \qquad (29)$$

For nanonetworks in the THz band, we divide the entire channel into a number of sufficiently narrow sub-bands in the say was as for the time-switching protocol. The SNR for power splitting protocol in each sub-band is expressed via:

$$\begin{aligned}\gamma(f_i) &= \frac{(1-\rho)\rho\eta P_{s(i)}^2\left|h_{S,R}(f_i)\right|^4\left|h_{R,D}(f_i)\right|^2}{\eta\rho P_{s(i)}\left|h_{S,R}(f_i)\right|^2\left|h_{R,D}(f_i)\right|^2\sigma_R^2+(1-\rho)P_{s(i)}\left|h_{S,R}(f_i)\right|^2\sigma_D^2+\sigma_R^2\sigma_D^2} \\ &= \frac{(1-\rho)\dfrac{P_{s(i)}\left|h_{S,R}(f_i)\right|^2}{\sigma_R^2}\rho\eta\dfrac{P_{s(i)s}\left|h_{S,R}(f_i)\right|^2\left|h_{R,D}(f_i)\right|^2}{\sigma_D^2}}{\rho\eta\dfrac{P_{s(i)s}\left|h_{S,R}(f_i)\right|^2\left|h_{R,D}(f_i)\right|^2}{\sigma_D^2}+(1-\rho)\dfrac{P_{s(i)s}\left|h_{S,R}\right|(f_i)^2}{\sigma_R^2}+1} \\ &= \frac{\gamma_{S,R}(f_i)\gamma_{R,D}(f_i)}{\gamma_{R,D}(f_i)+\gamma_{S,R}(f_i)+1}\end{aligned} \qquad (30)$$

σ_R^2 and σ_D^2 are the variances of the overall AWGN in the i_{th} sub-band at the relay and the destination, respectively.

- ### Throughput Analysis

The following part is to determine the throughput at the destination of the power-splitting protocol, given the SNR at the destination in (30), using (17), we obtain the outage probability for power splitting protocol as:

$$\begin{aligned}p_{out} &= \frac{1}{M}\sum_i^M \mathrm{pr}\left\{\gamma(f_i)\le\gamma_{th}\right\} \\ &= \frac{1}{M}\sum_i^M \mathrm{pr}\left\{\frac{\gamma_{S,R}(f_i)\gamma_{R,D}(f_i)}{\gamma_{R,D}(f_i)+\gamma_{S,R}(f_i)+1}\le\gamma_{th}\right\}\end{aligned} \qquad (31)$$

Also , the power splitting throughput at the destination is:

$$\mathrm{R}_I = \frac{1}{2}\sum_{i}^{M}\log_2\left(1+\gamma\left(f_i\right)\right) \tag{32}$$

Given the fixed transmission rate, the delay-limited throughput at the destination is:

$$\mathrm{R}_{DL} = \left(1-p_{out}\right)R_{th}\frac{T/2}{T} = \frac{R_{th}\left(1-p_{out}\right)}{2} \tag{33}$$

4. Numerical Results

In this section, numerical results will be presented to validate the analysis expressed previously. For the purpose of simplicity, the frequency band used for calculation ranges from 0.5 to 1.5 THz and Δf is fixed at 0.01 THz. The distances of S to R and R to D are set to be 10 mm. The threshold transmission rate is set as $R_{th} = \log_2\left(1+\gamma_{th}\right) = 5\ \mathrm{bps\ Hz^{-1}}$ the threshold SNR is therefore $\gamma_{th} = 2^{R_{th}} - 1 = 31$. We set the energy harvesting efficiency as $\eta = 0.5$ and the THz signal power to 1dBm.

Again for simplicity, we assume **that** the distances between source to relay and relay to destination are the same and are both represented by d. Firstly, we analysis the effect of α and ρ at a fixed distance i.e. d=10mm as shown in Fig. 4 and Fig. 5. **For the time-switching protocol in Fig. 4**, the delay-limited throughput at the destination rises with α until it **approaches** the optimal value and the throughput reaches its maximum and then decreases more gently with the increase in α. According to the result obtained, the optimal value of α for our system is around 0.35. The reasons are, on **the** one hand when α is smaller than its optimal value, this implies that less energy is harvested at the relay, the SNR at the relay to destination link **is** getting worse which dominates the overall SNR at the destination (refer to (16)). On the other hand, when α is larger than its optimal value, there is less information transmitted and more time is spent on energy harvesting and more signal has been wasted. As a result, the throughput at the destination getting smaller as the factor $(1-\alpha)/2$ in (16) gets smaller; the trend **in the** instantaneous throughput of the system is similar.

For the power splitting protocol, as shown in Fig. 5, the delay-limited throughput at the destination grows gently with increasing ρ from zero to the optimal value (0.8 in our system); it then decreases quickly from the peak with further increases in ρ. The explanation for this trend is similar **to that** for the time switching protocol; when ρ is smaller than its optimal value, the relay harvests less energy from the received signal. Consequently, the transmission power from **the** relay gets smaller and therefore the SNR at the relay to destination link gets worse which dominates the overall SNR at the destination (given by (29)) resulting in **increasing** outage probability as per (30). Furthermore, when ρ is larger than its optimal value, the relay harvests more than enough energy from the received signal with the increase of ρ, which **results** in reduced information transmission from S to R, i.e. the more power that used for energy harvesting the more signal that gets wasted. The smaller and smaller strength information signal is then amplified and forwarded by the relay via the noisy R to D link to the destination, the SNR at the destination becomes smaller and the outage probability gets larger. The trend for the instantaneous throughput of the system is similar.

Recalling (5), it can be seen that the THz channel gains will be affected by the transmission distance of the signal. Fig. 6 and Fig. 7 show the impact of distances on the system throughput at the destination. When the S to R and R to D distances increase from 0.1 mm to 1 mm, the effect on throughout at the destination is clear in the figures. As one might expect, for longer the distances the throughput is smaller. Moreover, for transmission distances smaller than a few millimeters, the power of the signal is much higher than the noise power at the receivers of R and D which provides a much higher achievable throughput at the destination. For larger transmission distances, the power of the received signals and the power of molecular absorption noise both decrease but the signal power decreases more drastically (with the noise power effectively being able to be treated as constant). According to the results shown in Fig.6 and Fig.7, we can see that suitable transmission distances for **nanonetworks** in the THz band fall in the range of a few millimeters. Moreover, based on all the results, the power-splitting protocol can provide more throughput than that of the time-switching protocol. However, the former brings more complexities of components which are a challenge for nanoscale communications systems.

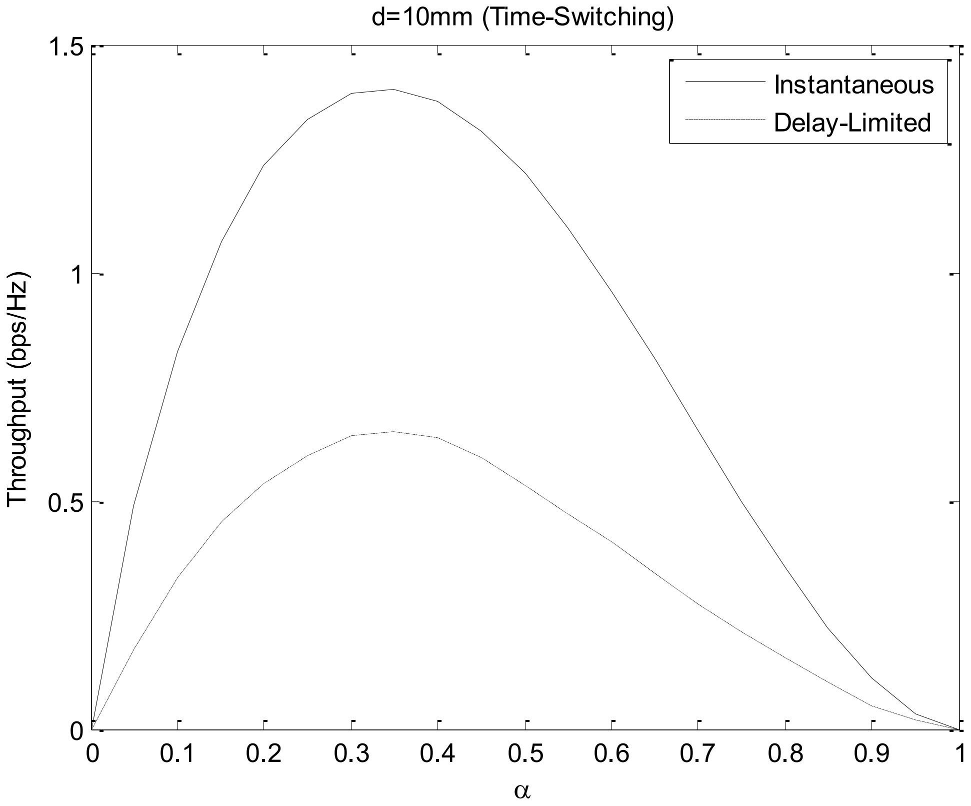

Fig. 4 Instantaneous and delay-limited throughput at the destination for time-switching protocol with the distance of 10 mm.

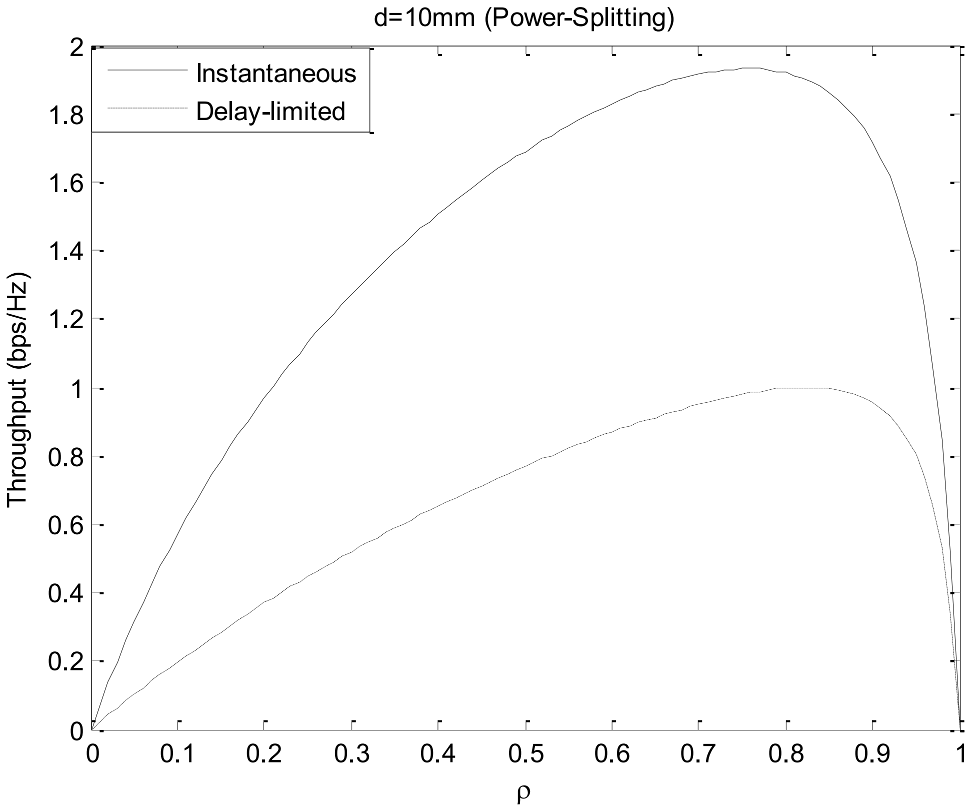

Fig. 5 Instantaneous and delay-limited throughput at the destination for power-splitting protocol with the distance of 10 mm

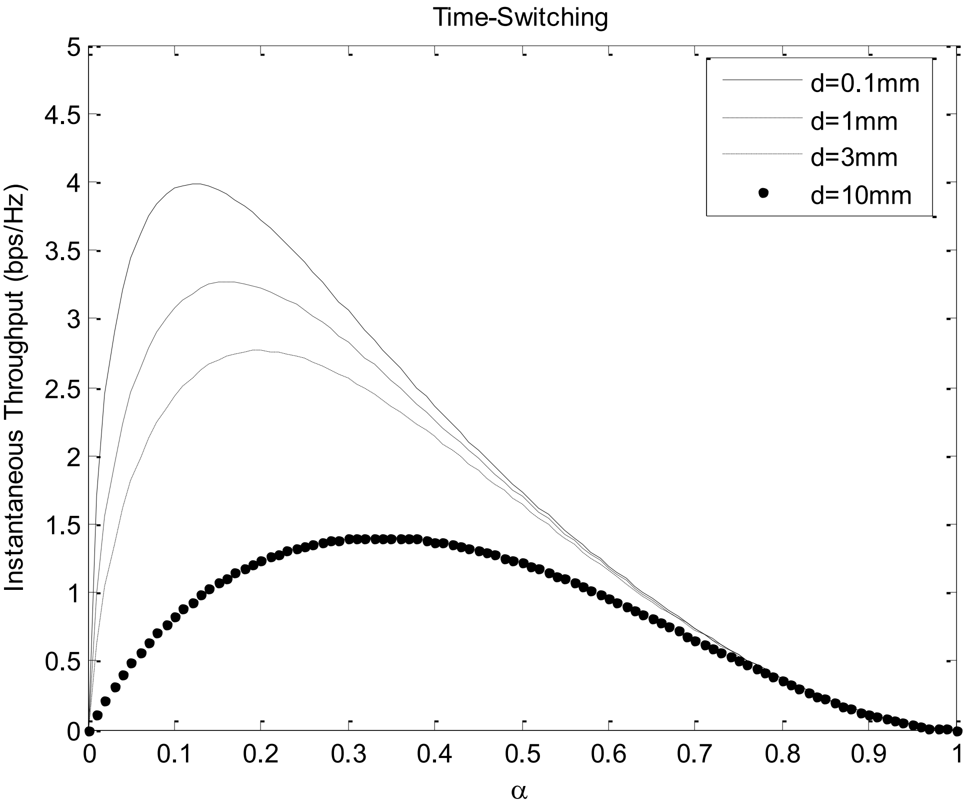

Fig. 6 The impact of transmission distances on throughout at the destination for time-switching protocol.

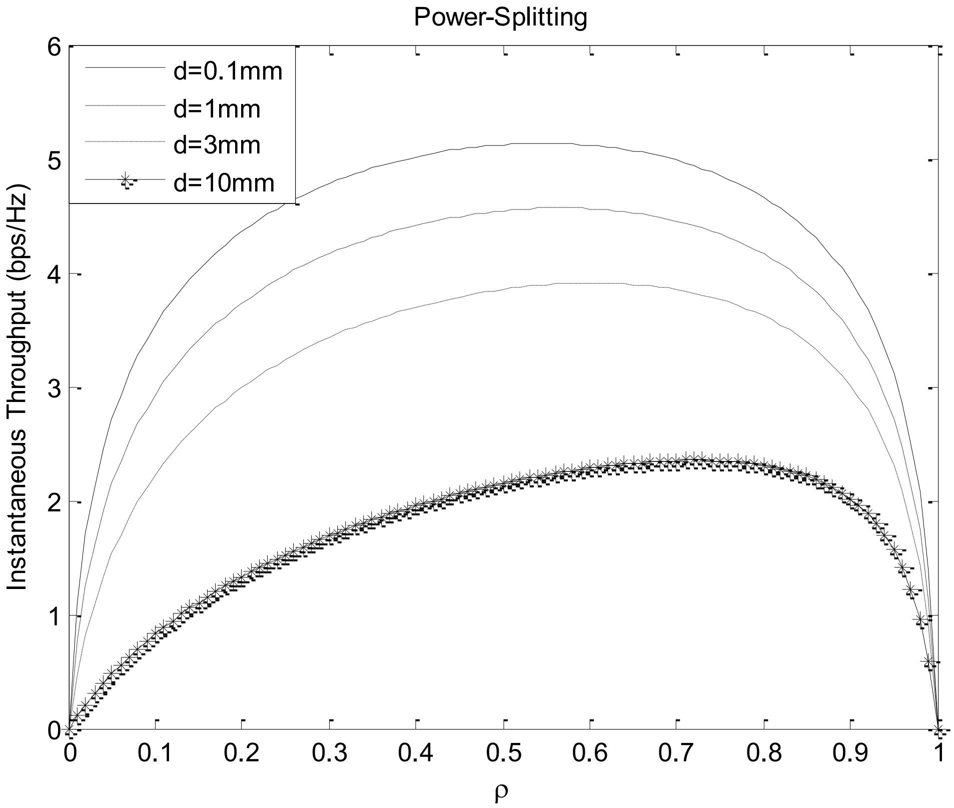

Fig. 7 the impact of transmission distances on throughout at the destination for the power-splitting protocol.

Conclusions

In this paper, simultaneous wireless information and power transfer for AF relaying nanonetworks in the THz band has been investigated. The AF harvests energy from the received signal and consumes **this** to amplify and forward the information to the destination. Both time switching and power splitting protocols have been studied. The entire THz band was divided into a number of narrow sub-bands for analysis. In order to determine the optimal time switching factor as well as the optimal power splitting ratio, we **derived** the instantaneous throughout and the delay-limited throughput at the destination to evaluate the performance of the variety of time factors and power ratios. The results have shown the optimal factors and power ratios for different transmission distances numerically. For time switching, the optimum time factor is approximately 0.35, whereas for power splitting the corresponding power ratio is 0.8. In the paper, we have assumed that the source to relay and relay to destination distance is equal; in future work, the impact of relay positions should be analyzed. Moreover, multi-relay schemes, full-duplex and relays equipped with two antennas are **also the subjects of ongoing research**.

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