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ENERGY EFFICIENCY OF DECODE-AND-FORWARD RELAYING CONSIDERING CIRCUIT POWER

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ABSTRACT

Today Energy efficiency (EE) is taking a more significant role in the design of modern communication systems. One of the most crucial trade offs in the green communication frame work is the trade off between EE and Spectral Efficiency (SE). Relaying is expected to introduce an improvement on the EE; in addition, consideration of the circuit power in Power Consumption Model (PCM), as a practical concern, changes the traditional relation between EE and SE. In this paper, two transmitters as sources and one relay node working in Decode-and-Forward (DF) scheme are assumed and the circuit power of each node, as a constant, is taken into account besides the transmission power in the PCM. The best EE for a given SE is found by optimizing transmission time and transmission power of nodes. Our system can work in two strategies of DF relaying (with and without considering direct link) and direct transmission. Simulation results show in which SE, the EE of DF relaying strategy outperforms the direct transmission. Also, it is investigated that how different circuit power considerations can affect the EE-SE trade off in different strategies.

INTRODUCTION

Green communication has become very important and attractive for wireless system architects in the recent years. One of the most important trade-offs of this topic is SE versus EE trade-off (Chen *et al*., 2011). Spectral efficiency is the system throughput per unit of bandwidth while EE is defined as transmitted information bits per unit of energy. In (Chen*et al*., 2011) it is shown that if just the transmission energy is considered in the definition of EE, it will be a monotonic decreasing function of SE. However, if the device or circuit energy is also considered in the definition of EE, the relation of EE and SE will change to a cap shape. In other words, having a more practical view by considering the circuit power of each node in a SE-EE trade–off, we could define a point where SE is none zero and EE is maximized.

In (Li *et al*., 2011) the authors introduce the basic concepts of energy efficient communication and summarize advanced techniques to improve the energy efficiency of the systems. The first technique that has been investigated is orthogonal frequency division multiple access (OFDMA). It is shown that in contrast to the rate adaptation (RA) and margin adaptation (MA), which are not energy efficient methods, OFDMA can provide energy efficient communication under an optimized resource allocation scheme. The second technique is multiple input multiple output (MIMO) whose energy efficiency is still unknown under practical conditions but it is nominated as a good candidate. Then, the authors introduce several scenarios for the relay transmission and propose the relay as a useful device for improving the energy efficiency of communication systems.

In (Feng *et al*., 2013) authors introduce some current projects to improve the energy efficiency of communication systems including: Green Radio(Grant, 2009,Han *et al*., 2009), EARTH(Gruber *et al*., 2009), OPERA-Net(Esnault, 2009). Then, they summarize some EE metrics, energy consumption models, some energy efficient radio resource management techniques, and some energy efficient network strategies including relay and cooperative communication.

In (Chen*et al*., 2011, Li *et al*., 2011, Feng*et al*., 2013, Hasan,Boostanimehr and Bhargava, 2011) the relay is conceived as a candidate for improving the energy efficiency in communication networks when the circuit power is also considered in PCM. But a tangible proof or graph is not provided to conclude whether it is really good to use the cooperative communication or not. In this paper, we compare DF relaying and direct transmission to find which strategy is more energy efficient when the practical concerns such as circuit power of the device are considered.

Relay is known as a device that helps to the coverage of the network and also provides cooperative diversity. Cooperative diversity brings the benefits of MIMO without the use of multiple antennas in the transmitter or receiver (Laneman, Tse and Wornell, 2004). One of the open issues in SE-EE trade-off is, whether relaying can be helpful or not (Li *et al*., 2011).

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In (Sun and Yang, 2012), the EE of Amplify-and-Forward (AF) relaying has been studied. While, in this paper DF relaying is analyzed to find which strategy (DF relaying or direct transmission) is more energy efficient. Analogous to Sun and Yang, we consider the circuit energy of nodes for both transmitter and receiver and also an idle mode is considered. The circuitry energy in transmitting and receiving modes are equal and much higher than that of idle mode. Assume that the system is delay constraint meaning it should transmit *B* bits in a block duration of *T*. It may use a shorter duration for transmission (and reception) and for the rest of the block duration, the system stays in idle mode to start a new block. The goal is to minimize the energy consumption of the system. It seems to be helpful if the transmission time is decreased while the idle mode is increased. However, one should note that by reducing the transmission time the amount of required power to transmit *B* bits increases and it does not help the EE of the system. So, there should be an optimum time for transmission (and reception).

The rest of this paper is organized as follows. In sections 2 and 3, in addition to introducing system model, energy consumption (EC) of each strategy will be defined. In section 4, we will optimize EEs of each strategy. In section 5, we willshow the simulation results and the conclusion of this paper will be presented in section 6.

System Model

In this paper, a system is considered with three nodes, nodes ***A*** and***B*** as transceiver and node ***R*** as relay. Node ***A*** sends data to node ***B*** and node ***B*** sends data to node ***A***. Node ***R*** is a half-duplex relay node that helps the transfer of data between ***A*** and ***B*** in a DF cooperation scheme. Therefore, during each block duration of *T*, first node ***A*** sends bits as a packet of data to node ***B*** with the assistance of node ***R***, then node ***B*** sends data bits to node ***A*** through the relay node,***R***.

The channels between the nodes are assumed to be complex-valued, zero-mean Gaussian flat fading channels and the noise is zero-mean complex-valued additive white Gaussian noise (AWGN) with the power of N_0. Channel coefficients of $A \rightarrow B$, $A \rightarrow R$ and $R \rightarrow B$ links are indicated respectively by, h_{ab}, h_{ar}, h_{br}. Channel state information (CSI) is perfect and assumed to be available in each node. System has to transfer *B* bits in each direction ($A \rightarrow B$ and $B \rightarrow A$) during *T* seconds. But it does not have to use all the block duration. In other words, if transmission time is T_t, the system transmits in $2T_t$ Seconds and staysin idle mode (to start new block) in $T - 2T_t$ seconds. Therefore, each node has three modes: transmission mode, reception mode and idle modes.As mentioned before, the circuit power of devices (node ***A***, ***B*** and ***R***) should be considered in the PCM to make it more practical. Hence, there are two kinds of power:

1. Transmission power, P^T (which is well known and can be obtained by Shannon formula).
2. Circuit power, P^c.

In (Dohler and Li, 2010, Cui, Goldsmith and Bahai, 2004, Cui, Goldsmith and Bahai, 2005, Zhou *et al*., 2008, Miao*et al*., 2008,Miao, Himayat, and Li, 2010 ,Lim and Cimini, 2012) the PCMs include circuit power of nodes. And it is shown that the consideration of the circuit power of nodes in a network can change different performances (such as EE and best modulation scheme).According to (Cui, Goldsmith and Bahai, 2005), the circuit power consumption is mainly due to RF power circuit and it is independent of bit rate.Therefore, the circuit powers are constant. In each mode there is a unique circuit power P^c. Also, Sun and Yang (2012) assume that the circuit power of the transmission and reception modes are identical and much larger than that of idle mode ($P^{ct} = P^{cr} > P^{ci}$) and we use this assumption in our paper.

Energy Consumption Model (ECM)

In this section, two strategies of direct transmission and DF relaying ECM are introduced. We use the results of this section to maximize the EE in section 4.

Direct transmission

In direct transmission, there is no relay. First, node ***A*** transmits *B* bits to node ***B*** and then node ***B*** transmits *B* bits to node ***A***. Each node sends its data in T_D seconds. The system is delay constraint and has *T* seconds for transmitting *2B* data bits in both directions. But it can fulfill the transmitting process in $2T_D$ seconds and stay idle in the remaining time ($T - 2T_D$).

When the system is transmitting data in one direction transmitter consumes P^T Watts for transmission and P^{ct} Watts for circuit power, while receiver just requires P^{cr} Watts for its circuit power. When the system is in idle mode both nodes spend P^{ci} Watts for the circuit power.
So the ECM of the direct transmission mode is obtained as:

$$E_D = T_D(\frac{P_a^T}{£} + P_a^{ct} + P_b^{cr}) + T_D(\frac{P_b^T}{£} + P_b^{ct} + P_a^{cr}) + (T - 2T_D)(P_a^{ci} + P_b^{ci}), \quad (1)$$

where $£ \in (0,1]$ indicates the power amplifier efficiency.

We define: $P_D^{c1} = P_a^{ct} + P_b^{cr}$, $P_D^{c2} = P_b^{ct} + P_a^{cr}$ and $P_D^{ci} = P_a^{ci} + P_b^{ci}$ .Then, ECM can be obtained as:

$$E_D = T_D(\frac{P_a^T}{£} + P_D^{c1} - P_D^{ci}) + T_D(\frac{P_b^T}{£} + P_D^{c2} - P_D^{ci}) + TP_D^{ci}. \quad (2)$$

DF relaying transmission

In DF relaying scheme, we assume a two-hop connection through node ***R*** that is located in the middle of the distance between node ***A*** and node ***B***. It works in half-duplex mode and the cooperation scheme is decode-and-forward. Therefore, each node requires two hops in its transmission time T_O . First, node ***A*** sends its data to the relay (duration time for first hop is ${}^{T_O}\!/_2$ seconds). During the second hop, relay sends these bits with a different coding to node ***B***, and the duration time for the second hop is also ${}^{T_O}\!/_2$. Then node ***B*** starts to send its message for node ***A*** in two hops (again each hop has ${}^{T_O}\!/_2$ second duration). It should be clear that when one node is in its first transmission hop, relay is in receiving mode and destination node is in idle mode.

Then in the second hop of transmission, source node is in idle mode, relay is in transmitting mode and destination is in receiving mode. The ECM in one-way relaying could be obtained as follow:

$$E_O = \frac{T_O}{2}(\frac{P_a^T}{£} + P_a^{ct} + P_r^{cr} + P_b^{ci} + \frac{P_r^T}{£} + P_r^{ct} + P_b^{cr} + P_a^{ci}) + \frac{T_O}{2}(\frac{P_b^T}{£} + P_b^{ct} + P_r^{cr} + P_a^{ci} + \frac{P_r^T}{£} + P_r^{ct} + P_a^{cr} + P_b^{ci}) + (T - 2T_O)(P_a^{ci} + P_b^{ci} + P_r^{ci})$$

$$E_O = T_O(\frac{P_a^T + P_r^T}{2£} + P_O^{c1} - P_O^{ci}) + T_O(\frac{P_b^T + P_r^T}{2£} + P_O^{c2} - P_O^{ci}) + TP_O^{ci}, \quad (3)$$

where: $P_O^{c1} \equiv \frac{P_a^{ct} + P_r^{cr} + P_b^{ci} + P_r^{ct} + P_b^{cr} + P_a^{ci}}{2}$, $P_O^{c2} \equiv \frac{P_b^{ct} + P_r^{cr} + P_a^{ci} + P_r^{ct} + P_a^{cr} + P_b^{ci}}{2}$

$P_O^{ci} = P_a^{ci} + P_b^{ci} + P_r^{ci}$.

Optimization of Energy Efficiency

In this section the EE optimization of each strategy for a constant number of transmission bits is discussed. We will optimize EE for three strategies: direct transmission, DF relaying without the consideration of the direct link, and DF relaying with the consideration of the direct link. First let’s define EE. Energy efficiency is known as the capacity of a system per unit of power. In other words, energy efficiency in a system is the number of bits transmitted per unit of energy. In our system *2B* bits are transmitted in the block duration of *T* and since the energy consumption of each strategy is obtained in the above, hence, energy efficiency could be obtained as:

$$¦_{EE} = \frac{2B}{E}, \quad (4)$$

where *E* is energy consumption per block of each strategy.

Maximizing $¦_{EE}$ for a given *B* is equivalent to minimizing E in each strategy. In the above it was shown that E in each strategy depends on node powers. It is clear that for a given bandwidth and a given number of bits, the required power and time for transmission are inversely proportional. By optimizing the transmission time and power of nodes, E is minimized in each strategy, to maximize EE for a given number of bits. This will be the main approach of the proposed method as follows. In the first subsection we will optimize EE of the direct transmission, in the second and third subsections the EE of DF relaying without the consideration of the direct link and with considering direct link is optimized, respectively.

Direct transmission

To minimize E of the direct transmission, we consider thefollowing optimization problem:

$$\min_{T_t, P_a^T, P_b^T} \quad T_D(\frac{P_a^T}{£} + P_D^{c1} - P_D^{ci}) + T_D(\frac{P_b^T}{£} + P_D^{c2} - P_D^{ci}) + TP_D^{ci}$$

$$\boldsymbol{s.t} \qquad \boldsymbol{2T_D \leq T \ , P_a^T \leq P_{max}^T , P_b^T \leq P_{max}^T ,} \quad (5)$$

where $\boldsymbol{P_{max}^T}$ is the maximum available power in each node.It is constant and is the same for all nodes.

Assume direct transmissionwhere the system bandwidth is *W*, and *B* bits are transmitted in T_D seconds in each direction. According to the Shannon relation the capacity of system in each direction is obtained by:

$$\frac{B}{T_D} = W \ \log(1 + \frac{P_a^T |h_{ab}|^2}{N_0}). \quad (6)$$

$$\frac{B}{T_D} = W \ \log(1+\frac{P_b^T \left|h_{ab}\right|^2}{N_0}). \tag{7}$$

In this strategy transmission time and transmission power have simple relations and the optimization problem can be defined with respect to each of them. So the joint optimization problem (5) changes to:

$$\begin{gathered}\min_{T_D} \ T_D(\frac{N_0(2^{\frac{B}{WT_D}}-1)}{\pounds\left|h_{ab}\right|^2}+P_D^{c1}-P_D^{ci})+T_D(\frac{N_0(2^{\frac{B}{WT_D}}-1)}{\pounds\left|h_{ab}\right|^2}+P_D^{c2}-P_D^{ci})+TP_D^{ci} \\ \mathbf{s\,t} \qquad 2T_D \le T \ ,T_D > T_{D\min}, \end{gathered} \tag{8}$$

where $T_{D\min}$ is defined as minimum required time for the transmitter to send data when it consumes its maximum power, and it is obtained as:

$$T_{D\min} = \frac{B}{Wlog_2(1+\frac{P_{\max}^T \,|\, h_{ab} \,|^2}{N_0})}. \tag{9}$$

The objective function in (8) is a convex function of T_D and all of the constraints are also convex. Therefore, the problem leads to a convex optimization. According to (Boyd and Vandenberghe, 2004)by taking derivative of the objective function in (8) with respect to T_D and setting it to zero, the optimum T_D for minimizing E_D can be derived. According to the definition of the P_D^{c1} and P_D^{c2} , we know that they are equal and we have:

$$\frac{dE_D}{dt}=\frac{d}{dt}(T_D(\frac{N_0(2^{\frac{B}{WT_D}}-1)}{\pounds\left|h_{ab}\right|^2}+P_D^{c1}-P_D^{ci})+T_D(\frac{N_0(2^{\frac{B}{WT_D}}-1)}{\pounds\left|h_{ab}\right|^2}+P_D^{c2}-P_D^{ci})+TP_D^{ci})=0$$

$$[\frac{N_0(2^{\frac{2B}{WT_D}}-1)}{\pounds\left|h_{ab}\right|^2}+P_D^{c1}-P_D^{ci}]-\frac{N_0\ln 2}{\pounds\left|h_{ab}\right|^2}2^{\frac{2B}{WT_D}}\frac{2B}{WT_D}=0 \tag{10}$$

Now the optimum T_D can be found, but it does not have a closed form and a recursive method should be used to find it from (10).

If the optimum T_D is denoted by T_{Dopt} , then:

$$[\frac{N_0(2^{\frac{2B}{WT_{Dopt}}}-1)}{\pounds\left|h_{ab}\right|^2}+P_D^{c1}-P_D^{ci}]=[\frac{N_0(2^{\frac{2B}{WT_{Dopt}}}-1)}{\pounds\left|h_{ab}\right|^2}+P_D^{c2}-P_D^{ci}]=\frac{N_0\ln 2}{\pounds\left|h_{ab}\right|^2}2^{\frac{2B}{WT_{Dopt}}}\frac{2B}{WT_{Dopt}}. \tag{11}$$

And optimum energy efficiency is obtained as:

$$\text{¦}_{EEopt}^{D}=\frac{2B}{\frac{2BN_0(\ln 2)}{\pounds\left|h_{ab}\right|^2W}2^{\text{¦}_{SEopt}^{D}}+TP_D^{ci}}, \tag{12}$$

where $\eta_{SEopt}^{D} \equiv \frac{2B}{WT_{Dopt}}$.

DF relaying transmission

According to (3) the optimization problem for DF relaying scheme is defined as:

$$\begin{gathered}\min_{T_O,P_a^T,P_b^T,P_r^T} \ T_O(\frac{P_a^T+P_r^T}{2\pounds}+P_O^{c1}-P_O^{ci})+T_O(\frac{P_b^T+P_r^T}{2\pounds}+P_O^{c2}-P_O^{ci})+TP_O^{ci} \\ \mathbf{s\,t} \qquad 2T_O \le T \ ,P_a^T \le P_{max}^T,P_b^T \le P_{max}^T,P_r^T \le P_{max}^T. \end{gathered} \tag{13}$$

In this case, the joint optimization problem of EC should be modified to a simpler optimization problem that only has time as a variable. Therefore, transmission power should be expressed as a function of transmission time. For this propose, first, the transmission power is minimized and then it is derived as a function of time. However, since the cooperative scheme is decode-and- forward, the capacity (for one direction for example when node ***A*** is transmitting) is derived as (Cover and Thomas, 1991):

$$C = \frac{B}{T_O} = \frac{W}{2}\min\{\log_2(1+\frac{|h_{ar}|^2 P_a^T}{N_0}), \log_2(1+\frac{|h_{br}|^2 P_r^T}{N_0})\}. \tag{14}$$

Similar to(Sun and Yang, 2012), in this subsection we do not consider the direct link. The power transmission minimization problem is defined as:

$$\begin{aligned} &\min_{P_a^T, P_r^T} \quad P_a^T + P_r^T \\ &st \quad P_a^T \le P_{max}^T, P_r^T \le P_{max}^T, (14). \end{aligned} \tag{15}$$

This optimization problem can be solved in two different cases.

If $|h_{ar}|^2 P_a^T > |h_{br}|^2 P_r^T$:

In this case we can write P_r^T as a function of transmission time:

$$P_r^T = \frac{(2^{\frac{2B}{T_O W}} - 1)N_0}{|h_{br}|^2}. \tag{16}$$

Also (15) could be changed to:

$$\begin{aligned} &\min_{P_r^T} \quad P_r^T(1+\frac{|h_{br}|^2}{|h_{ar}|^2}) \\ &st \quad P_r^T \le P_{max}^T, (16). \end{aligned} \tag{17}$$

Since the objective function is linear in (17), the solution of (15) for this case can be derived as:

$$P_{aopt}^T + P_{ropt}^T = (2^{\frac{2B}{T_O W}} - 1)N_0(\frac{1}{|h_{br}|^2} + \frac{1}{|h_{ar}|^2}). \tag{18}$$

If $|h_{ar}|^2 P_a^T > |h_{br}|^2 P_r^T$:

Unlike the previous case, in this case, P_a^T determines the system capacity. Where:

$$P_a^T = \frac{(2^{\frac{2B}{T_O W}} - 1)N_0}{|h_{ar}|^2}. \tag{19}$$

And (15) can be derived as:

$$\begin{aligned} &\min_{P_r^T} \quad P_r^T(1+\frac{|h_{br}|^2}{|h_{ar}|^2}) \\ &st \quad P_r^T \le P_{max}^T, (19). \end{aligned} \tag{20}$$

It is interesting that the solution of (20) is exactly the same as the solution of (17). Hereby, both cases have equal answers for (16) and $T_{O1\min}$ (the minimum time required if transmitters use their maximum power) in this case is obtained as:

$$T_{O1\min} = \frac{2B}{W\ \min\{\log_2(1+\frac{P_{\max}^T |h_{ar}|^2}{N_0}), \log_2(1+\frac{P_{\max}^T |h_{br}|^2}{N_0})\}}. \tag{21}$$

When node ***B*** is in transmission mode and node ***A*** is in reception mode the problem is the same and it is similar to what derived before.

So, the joint optimization problem (13) can be simplified to a one variable optimization problem as:

$$\min_{T_O} \quad T_O\left(\frac{(2^{\frac{2B}{T_O W}}-1)N_0}{2\pounds\,|h_{eff}|^2}+P_O^{c1}-P_O^{ci}\right)+T_O\left(\frac{(2^{\frac{2B}{T_O W}}-1)N_0}{2\pounds\,|h_{eff}|^2}+P_O^{c2}-P_O^{ci}\right)+TP_O^{ci}$$

$$s.t \qquad 2T_O \le T \;, T_O \ge T_{O1\min}. \tag{22}$$

where $|h_{eff}|^2 \equiv \dfrac{1}{\dfrac{1}{|h_{br}|^2}+\dfrac{1}{|h_{ar}|^2}}$

The solution of (22) is the same as the solution of (8) and the optimum energy efficiency of the system could be obtained as:

$$\text{¦}_{EEopt}^{O}=\frac{2B}{\dfrac{2BN_0(\ln 2)}{\pounds\,|h_{eff}|^2 W}2^{\text{¦}_{SEopt}^{O}}+TP_O^{ci}}, \tag{23}$$

where $\eta_{SEopt}^{O} \equiv \dfrac{2B}{WT_{Oopt}}$ and T_{Oopt} is the optimum transmission time in DF relaying strategy without considering direct link.

DF relaying with direct link

In this subsection, the energy efficiency of DFrelaying is optimized with the assumption that there is also a direct link to help the transmission. Each node has two hops to transmit its data. The only difference between this scenario and the scenario without the direct link is that here at the first hop of transmission in each direction ($A \to B$ and $B \to A$) the transmitter sends its data to the relay node as well as to its destination. It is obvious that in this case, the capacity expression of each direction would change, however, the EC is similar to the case that the direct link is ignored. The capacity (for one direction for example when node ***A*** is transmitting) is derived as in (Cover and Thomas, 1991):

$$C=\frac{B}{T_O}=\frac{W}{2}\min\{\log_2(1+\frac{|h_{ar}|^2P_a^T}{N_0}),\log_2(1+\frac{|h_{br}|^2P_r^T}{N_0}+\frac{|h_{ab}|^2P_a^T}{N_0})\}. \tag{24}$$

Similar to the previous subsection we should minimize the summation of the transmission power first.

$$\min_{P_a^T,P_r^T} \quad P_a^T+P_r^T$$

$$s.t \qquad P_a^T \le P_{max}^T, P_r^T \le P_{max}^T, (24). \tag{25}$$

This problem can be solved in two different cases.

If $|h_{ar}|^2P_a^T > |h_{br}|^2P_r^T+|h_{ab}|^2P_a^T$:

The P_r^T can be driven as a function of transmission time:

$$P_r^T=(2^{\frac{2B}{T_O W}}-1)N_0\frac{|h_{ar}|^2-|h_{ab}|^2}{|h_{br}|^2|h_{ar}|^2}. \tag{26}$$

So (25) can change to:

$$\min_{P_r^T} \quad P_r^T\left(1+\frac{|h_{br}|^2}{|h_{ar}|^2-|h_{ab}|^2}\right)$$

$$s.t \qquad P_r^T \le P_{max}^T, (26). \tag{27}$$

Since the objective function in (27) is a linear function, the solution of (24) is derived as:

$$P_{aopt}^{T}+P_{ropt}^{T}=\frac{(2^{\frac{2B}{T_O W}}-1)N_0}{|h_{ar}|^2|h_{br}|^2}(|h_{ar}|^2+|h_{br}|^2-|h_{ab}|^2). \tag{28}$$

It is obvious that when the direct link is ignored ($h_{ab}=0$) (28) is equal to the (17).

If $|h_{ar}|^2 P_a^T < |h_{br}|^2 P_r^T + |h_{ab}|^2 P_a^T$:

Similar to the previous subsection now P_a^T determines the capacity expression and it is obtained as:

$$P_a^T=\frac{(2^{\frac{2B}{T_O W}}-1)N_0}{|h_{ar}|^2}. \tag{29}$$

And (26) changes to:

$$\begin{aligned}&\min_{P_a^T} && P_a^T\left(1+\frac{|h_{ar}|^2-|h_{ab}|^2}{|h_{br}|^2}\right)\\ &s\,t && P_a^T \le P_{max}^T, (29).\end{aligned} \tag{30}$$

The solution of the (30) is exactly equal to the solution of (28), so (29) is the solution for both cases. Also $T_{O2\min}$ (the minimum time required when transmitters use their maximum power) can be derived as:

$$T_{O2\min}=\frac{2B}{W\ \min\{\log_2(1+\frac{P_{\max}^T|h_{ar}|^2}{N_0}),\log_2(1+\frac{P_{\max}^T}{N_0}(|h_{br}|^2+|h_{ab}|^2)\}}. \tag{31}$$

We solve the problem for the ($A \to B$) direction. The problem for the opposite direction ($B \to A$) is solved similar to what we derived above. Therefore, the joint optimization problem of (13), when the direct link is also considered, is obtained as:

$$\begin{aligned}&\min_{T_O} && T_O\left(\frac{(2^{\frac{2B}{T_O W}}-1)N_0}{2\pounds\,|h_{effdirect}|^2}+P_O^{c1}-P_O^{ci}\right)+T_O\left(\frac{(2^{\frac{2B}{T_O W}}-1)N_0}{2\pounds\,|h_{effdirect}|^2}+P_O^{c2}-P_O^{ci}\right)+TP_O^{ci}\\ &s\,t && 2T_O \le T\ ,T_O \ge T_{O2\min}.\end{aligned} \tag{32}$$

where $|h_{effdirect}|^2 \equiv \dfrac{1}{\dfrac{|h_{ar}|^2+|h_{br}|^2-|h_{ab}|^2}{|h_{ar}|^2|h_{br}|^2}}$

Similar to the previous subsections, optimum energy efficiency is derived as:

$$\text{¦}_{EEopt}^{Odirect}=\frac{2B}{\frac{2BN_0(\ln 2)}{\pounds\,|h_{effdirect}|^2W}2^{\text{¦}_{SEopt}^{Odirect}}+TP_O^{ci}}, \tag{33}$$

where $\eta_{SEopt}^{Odirect}\equiv\dfrac{2B}{WT_{Odirectopt}}$ and T_{Odopt} is the optimum transmission time in DF relaying strategy with considering direct link.

Since we have not derived the close form expressions of the optimal transmission power and the optimal SEs, there is no close form for the optimal EE. We will use the simulations to compare the EEs of different strategies.

Simulations and Results

In this section, the effect of the circuit power on the relation between EE-SE is investigated. Also, we can find out how the optimal EE will change as a function of SE in each strategy and also achieve the strategy with the best energy efficiency for a given SE.

In the simulation, it is assumed that the channel gains between the nodes that have a Rayleigh distribution. The distance between sources is assumed to be 100(m) and the relay position to be in the middle of the two sources. The path loss attenuation of each channel is $30+10\log_{10}(distance^{\sim})dB$ and the path loss attenuation factor $\sim$ is assumed to be 3. Other parameters are: $W=10MHz$, $T=5ms$, $P^{T}_{\max}=40dBm$, $N_0=-94dBm$, $£=0.35$. The simulation parameters are similar to that of (Sun and Yang).

In Fig.1, for each node it is assumed that $P^{ct}=P^{cr}=100$ mw. According to the Fig. 1, it is obvious that in low spectral efficiencies, DF relying (with or without considering direct link) is more energy efficient, but for higher spectral efficiencies (more than 2.5 bits/s/Hz), direct transmission outperforms DF relaying. Consideration of the direct linkimproves the maximum available EE of the system, because the consideration of the direct link can improve the channel condition of DF relaying (it is obvious by comparing $|h_{eff}|$ and $|h_{effdirect}|$) and hence, it leads to a higher EE. Also, with respect to Fig. 1, it can be concluded that in very high spectral efficiencies (more than 6.5 bits/s/Hz), both strategies (DF relaying and direct transmission) converge to the same value.

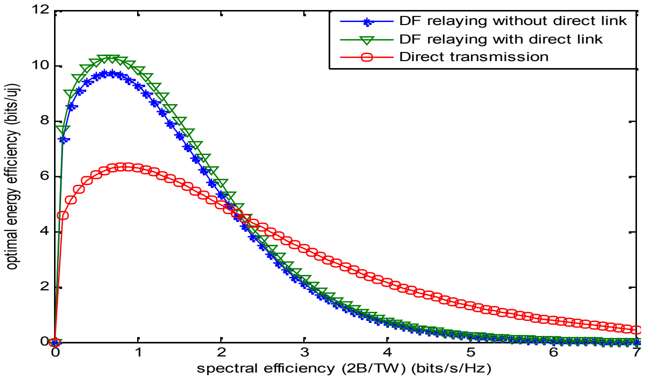

Fig. 1 The comparison of EE-SE with circuit power consideration in DF relaying strategies and direct transmission strategy.

In Fig.2, the effect of circuit power on energy efficiency of DF relaying transmission is presented. Obviously, without circuit power consideration in ECM, energy efficiency is a monotonic decreasing function of spectral efficiency. With circuit power consideration in ECM, the EE-SE curve becomes like a cap shape and can maximize energy efficiency in a point that has non-zero spectral efficiency. In low SEs, the circuit power of the devices has a significant role in comparison to the transmission power, so various amounts of circuit power change the optimum EE of the system. As it is represented in Fig.2, increase in the circuitry power leads to a decrease in the optimal EE. However, in high SEs, transmission power dominates the circuitry power and the optimal EE is independent of the consideration of circuit power in our ECM.

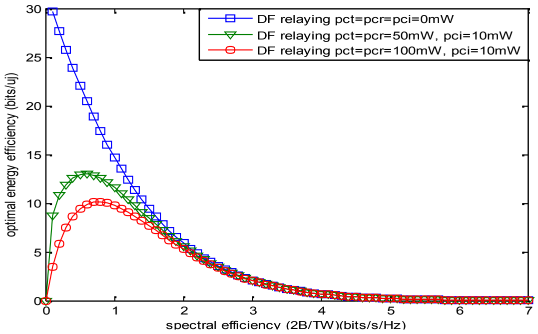

Fig. 2 The comparison of EE-SE with and without circuit power consideration in DFrelaying strategy (without direct link consideration).

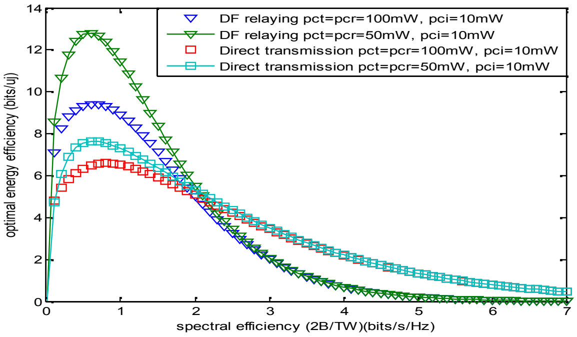

Fig. 3 The comparison of EE-SE with different circuit power for DF relaying (without direct link consideration) and direct transmission strategies.

In Fig. 3, the effect of circuit power on the energy efficiency of both strategies is shown. For each case (direct transmission and DF relaying) the optimum energy efficiency increases when the circuit power in the ECM decreases. The optimum energy efficiency in the direct transmission strategy has smaller changes under different amounts of circuit power. In DF relaying, however, more significant changes are observed when the circuitry power of device has changed by half. Again it is obvious that in the high SE region, the EE of both strategies do not depend on the power circuit of devices.

In Fig. 4, the outage probabilities of different strategies are compared. In some cases, the optimum system time needed to achieve the optimum energy efficiency, the solution of (9), (23) and (33), is more than the time slot T (even if the transmitters use their maximum available power). So we can conclude that in these cases outage has occurred. Obviously, the outage probability of both strategies increaseswith the increase in the spectral efficiency of the system. With respect to Fig. 4, it is concluded that for all spectral efficiencies the outage probability of DF relaying is more than that of direct transmission. Also, the maximum outage probability of the DF relaying does not exceed 0.14 and it is well accepted according to (Sun and Yang, 2012).

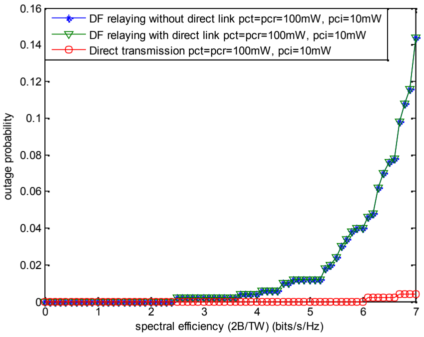

Fig. 4 The outage probability of different strategies.

CONCLUSIONS

In this paper, we analyzed the EE-SE trade off for three strategies including direct transmission and DF relaying (with and without the consideration of direct link). The system model is based on two data transmitters as sources and one relay node working in a decode-and-forward scheme. In addition to transmission power, circuit power of nodes in our power consumption model was considered. Our contribution is to optimize the EE of direct transmission and DF relaying (with and without the consideration of direct link) strategies. Then, the optimal EE is depicted for different SEs. Despite the traditional research, results that show exponential decrease of EE with increase in SE, by considering the circuit power. And the EE-SE relation will form a cap shape. In simulation results it is shown that, for most of the small SE values (under 2 bits/s/Hz), the EE of both DF relaying strategies outperformthat of direct transmission. However the EE of direct transmission is better than that of DF relaying for higher SEs. Furthermore, it is shown that the consideration of the direct link in DF relaying improves the EE of the system. It is concluded that by reducing the circuit power constants in the PCM, DF relaying and direct transmission would have better EE and the changes are more significant for DF relaying. Finally, it is demonstrated that direct transmission has better outage probability performance for different SEs.

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