# Spectral Efficiency and Energy Efficiency of Distributed Space-Time Relaying models

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***Abstract*—Cooperative relay techniques are exploited to reduce the transmission energy consumption which is very important for average and long range transmission in wireless sensor networks (WSNs). In this paper, the system having a two-antenna source, two one-antenna relays and a one-antenna destination is considered. Using distributed space-time code at relays, MIMO simple cooperative relay model (MSCR) and MIMO full cooperative relay model (MFCR) are proposed in comparison with MIMO normal cooperative relay model (MNCR) where the relays forward signals consecutively to destination. The outage probability analysis derives that all the models have the diversity order of 4. However, the analytic and simulation results show that MFCR has better performance than MNCR, whereas MSCR provides better spectral efficiency than MNCR. Moreover, the energy efficiency of these models is also considered by using a realistic power consumption model where the parameters are extracted from the characteristics of CC2420, a wireless sensor transceiver widely used and commercially available. For each transmission ranges, the optimal cooperative scheme in terms of energy efficiency is provided by simulation results.**

## I. INTRODUCTION

Recently, space-time diversity Multi-Input Multi-Output (MIMO) systems, especially distributed space-time coded (DSTC) systems, have attracted many researchers because they need less transmission energy for the same Bit Error Ratio (BER). It is shown in [1], [2], [3] that a DSTC scheme using different nodes to build a virtual transmit array can be very effective to induce a useful diversity gain. Besides, relay transmission has been identified as one of the core technologies that could enable robust and high-reliable information transfer over challenging wireless environment. In [4], cooperative relaying is thoroughly considered in terms of outage probabilities in the region of high Signal to Noise Ratio (SNR). The outage probability analysis is extended for multi-node amplify and forward relay networks in [5]. In [6], the performance of all possible diversity combining schemes at the relays and at destination is compared in a two-relay model. While in [1]-[6], all terminals have only one antenna, the MIMO relay channel in which the terminals have multi-antenna is considered in [7], [8]. In [7], using beam forming technique and Amplify and Forward (AF) relaying, a system having a two-antenna source, two one-antenna relays and one-antenna destination is proposed. In [8], the performance analysis of a multi-antenna MIMO relay channel is derived.

The present paper extends the system of [7] by using the DSTC at the relays and taking the direct transmission from soure to destination into account to improve the performance significantly. The transmission protocol of relays, non-regenerative DSTC or Alamouti Amplify and Forward (AAF), is considered in MIMO full cooperative relay model (MFCR) and MIMO simple cooperative relay model (MSCR), while MIMO normal cooperative relay model (MNCR) uses AF protocol [4]. The difference between MSCR and MFCR is that in MFCR there is a data exchange between the two relays. We derive that MFCR, MSCR and MNCR have the diversity order of 4 instead of 2 in comparison with the model in [7]. However, despite having the same diversity order, MSCR has the best spectral efficiency and MFCR has the best Bit Error Rate (BER) performance. The energy efficiency of the models is evaluated in a realistic power consumption model using a real wireless transceiver, the CC2420 from T.I.

The remainder of this paper is organized as follows. In Section II, the protocols of MFCR, MSCR and MNCR are thoroughly described. Then the analysis and the simulation of outage probability for these models are considered in Section III. Section IV presents the BER performance of these models. In Section V, the energy consumption analysis is briefly presented and the energy efficiency performance is also simulated.

In the following, lower case and uppercase bold letters stand for vectors and matrices, respectively. $a^*$ denotes the conjugate of $a$, $\boldsymbol{a}^T$ denotes the transpose of $\boldsymbol{a}$ and $\boldsymbol{A}^H$ denotes the Hermitian transpose of $\boldsymbol{A}$.

## II. SYSTEM MODEL

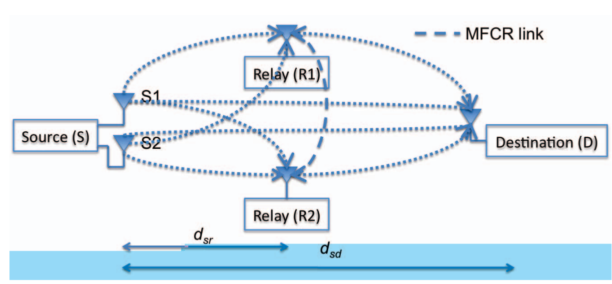


Fig. 1. Cooperative Model

For the transmission protocol at the relays, we can consider either MNCR, MSCR or MFCR (Fig. 1). While MNCR uses conventional AF protocol to forward the signals from relays to destination, MSCR and MFCR uses AAF protocol to forward the signals from relays to destination. The difference between MSCR and MFCR is that in MFCR there is a data exchange between two relays before forwarding the signals to destination. The transmission process of these communication models can be divided into the following steps.

**Step 1**:

The two-antenna source ($S1$, $S2$) transmits simultaneously the Alamouti coded signal $\boldsymbol{X} = \begin{bmatrix} s[2k] & s[2k+1] \\ -s^*[2k+1] & s^*[2k] \end{bmatrix}$ to the two relays ($R1$, $R2$) and to the destination ($D$) (where $s[2k]$ and $s[2k+1]$ are two consecutive signals at the source). The received signals at two relays and at destination are $\boldsymbol{y_{sr_1}}$, $\boldsymbol{y_{sr_2}}$, $\boldsymbol{y_{sd}}$ respectively:

$$\boldsymbol{y_{ij}} = \sqrt{P_s}\boldsymbol{X}\boldsymbol{h_{ij}} + \boldsymbol{n_{ij}} \quad i \in \{s\}, j \in \{r_1, r_2, d\} \tag{1}$$

where $\boldsymbol{h_{ij}} = \begin{bmatrix} h_{ij}[2k] & h_{ij}[2k+1] \end{bmatrix}^T$ are the Rayleigh channel coefficient vectors, $\boldsymbol{y_{ij}} = \begin{bmatrix} y_{ij}[2k] & y_{ij}[2k+1] \end{bmatrix}^T$, $\boldsymbol{n_{ij}} = \begin{bmatrix} n_{ij}[2k] & n_{ij}[2k+1] \end{bmatrix}^T$ are the AWGN noise vectors and $P_s$ is the transmitted source power.

**Step 2**:

For MNCR, the two relays use AF protocol to forward the signals consecutively to destination. The received data at destination from the relays is given by

$$y_{ji}[m] = \sqrt{P_r}h_{ji}[m]r_j[m] + n_{ji}[m] \tag{2}$$

where $j \in \{r_1, r_2\}, i \in \{d\}, m \in \{2k, 2k+1\}$, $P_r$ is the transmitted power of relays. The forwarded signal at relay, $r_j[m]$, can be expressed as

$$\boldsymbol{r_j} = (\boldsymbol{H_{ij}^H}\boldsymbol{\tilde{y}_{ij}})/\sqrt{P_s}(\boldsymbol{H_{ij}^H}\boldsymbol{H_{ij}}) \quad j \in \{r_1, r_2\}, i \in \{s\} \tag{3}$$

with $\boldsymbol{H_{ij}} = \begin{bmatrix} h_{ij}[2k] & h_{ij}[2k+1] \\ h_{ij}^*[2k+1] & -h_{ij}^*[2k] \end{bmatrix}$, $\boldsymbol{r_j} = \begin{bmatrix} r_j[2k] & r_j[2k+1] \end{bmatrix}^T$ and $\boldsymbol{\tilde{y}_{ij}} = \begin{bmatrix} y_{ij}[2k] & y_{ij}^*[2k+1] \end{bmatrix}^T$.

For MSCR, the two relays use the AAF protocol to transmit simultaneously the Alamouti re-encoded signals $\boldsymbol{R} = \begin{bmatrix} r_{r_1}[2k] & r_{r_2}[2k+1] \\ -r_{r_1}^*[2k+1] & r_{r_2}^*[2k] \end{bmatrix}$ to the receiver, where the forwarded signals at relay $r_j(m)$, $j \in \{r_1, r_2\}$ are found by (3). The received signal at the destination is

$$\boldsymbol{y_{rd}} = \sqrt{P_r}\boldsymbol{R}\boldsymbol{h_{rd}} + \boldsymbol{n_{rd}}, \tag{4}$$

where $\boldsymbol{h_{rd}} = \begin{bmatrix} h_{rd}[2k] & h_{rd}[2k+1] \end{bmatrix}^T$ is the Rayleigh channel coefficient vector of the relay-destination link, $\boldsymbol{y_{rd}} = \begin{bmatrix} y_{rd}[2k] & y_{rd}[2k+1] \end{bmatrix}^T$, and $\boldsymbol{n_{rd}} = \begin{bmatrix} n_{rd}[2k] & n_{rd}[2k+1] \end{bmatrix}^T$ is the AWGN noise vector of the relay-destination link.

For MFCR, before forwarding the signals to destination, the two relays exchange their data ($\boldsymbol{y_{sr_1}}$ and $\boldsymbol{y_{sr_2}}$) with each other to get the reception diversity. In this work, we assume that there is no errors in the data exchange between two relays. Because of the data exchange between the two relays, the forwarded signals at two relays are the same, $\boldsymbol{r_{r1}} = \boldsymbol{r_{r2}}$. The forwarded signal at each relay can be represented by

$$\boldsymbol{r_{r1}} = \boldsymbol{r_{r2}} = \boldsymbol{r} = \frac{(\boldsymbol{H_{sr_1}^H}\boldsymbol{\tilde{y}_{sr_1}} + \boldsymbol{H_{sr_2}^H}\boldsymbol{\tilde{y}_{sr_2}})}{\sqrt{P_s}(\boldsymbol{H_{sr_1}^H}\boldsymbol{H_{sr_1}} + \boldsymbol{H_{sr_2}^H}\boldsymbol{H_{sr_2}})} \tag{5}$$

where $\boldsymbol{H_{ij}} = \begin{bmatrix} h_{ij}[2k] & h_{ij}[2k+1] \\ h_{ij}^*[2k+1] & -h_{ij}^*[2k] \end{bmatrix}$, $\boldsymbol{r} = \begin{bmatrix} r[2k] & r[2k+1] \end{bmatrix}^T$, $\boldsymbol{r_j} = \begin{bmatrix} r_j[2k] & r_j[2k+1] \end{bmatrix}^T$, and $\boldsymbol{\tilde{y}_{ij}} = \begin{bmatrix} y_{ij}[2k] & y_{ij}^*[2k+1] \end{bmatrix}^T$ with $j \in \{r_1, r_2\}, i \in \{s\}$. The received signal at the destination is represented by (4) with the Alamouti re-encoded signals $\boldsymbol{R} = \begin{bmatrix} r[2k] & r[2k+1] \\ -r^*[2k+1] & r^*[2k] \end{bmatrix}$

**Step 3**:

At the destination, all the received signals are combined together to take advantage of spatial diversity and the maximal ratio combining technique is used to decode the signals.

We assume that the communication is performed over flat Rayleigh fading channel. The channel coefficients remain the same for two consecutive time intervals. Statistically, we model $h_{ij}[m]$ with $i \in \{s, r_1, r_2\}$ and $j \in \{r_1, r_2, d\}$ as zero mean, independent, complex Gaussian random variables with variances $\sigma_{ij}^2$. Similarly, we model $n_{ij}[m]$ as zero mean mutually independent complex Gaussian random variable with variance $N_0$. The protocols of these models are summarized in the following tables, Tab. I for MNCR, Tab. II for MSCR and Tab. III for MFCR. Note that, the white cells represent the transmission phases of the terminals, the light gray cells represent the reception phases of the terminals and the bold gray cells represent the sleep phases of the terminals.

| **Time Slot** | **S1** | **S2** | **R1** | **R2** | **D** |
|---|---|---|---|---|---|
| $2k$ | $s(2k)$ | $s(2k+1)$ | $y_{sr_1}(2k)$ | $y_{sr_2}(2k)$ | $y_{sd}(2k)$ |
| $2k+1$ | $-s^*(2k+1)$ | $s^*(2k)$ | $y_{sr_1}(2k+1)$ | $y_{sr_2}(2k+1)$ | $y_{sd}(2k+1)$ |
| $2k+2$ | | | $r_{r_1}(2k)$ | | $y_{r_1d}(2k)$ |
| $2k+3$ | | | $r_{r_1}(2k+1)$ | | $y_{r_1d}(2k+1)$ |
| $2k+4$ | | | | $r_{r_2}(2k)$ | $y_{r_2d}(2k)$ |
| $2k+5$ | | | | $r_{r_2}(2k+1)$ | $y_{r_2d}(2k+1)$ |

TABLE I
PROTOCOL OF THE MIMO NORMAL COOPERATIVE RELAY MODEL

| **Time slot** | **S1** | **S2** | **R1** | **R2** | **D** |
|---|---|---|---|---|---|
| $2k$ | $s(2k)$ | $s(2k+1)$ | $y_{sr_1}(2k)$ | $y_{sr_2}(2k)$ | $y_{sd}(2k)$ |
| $2k+1$ | $-s^*(2k+1)$ | $s^*(2k)$ | $y_{sr_1}(2k+1)$ | $y_{sr_2}(2k+1)$ | $y_{sd}(2k+1)$ |
| $2k+2$ | | | $r_{r_1}(2k)$ | $r_{r_2}(2k+1)$ | $y_{rd}(2k)$ |
| $2k+3$ | | | $-r_{r_1}^*(2k+1)$ | $r_{r_2}^*(k)$ | $y_{rd}(2k+1)$ |

TABLE II
PROTOCOL OF THE MIMO SIMPLE COOPERATIVE RELAY MODEL

| **Time Slot** | **S1** | **S2** | **R1** | **R2** | **D** |
|---|---|---|---|---|---|
| $2k$ | $s(2k)$ | $s(2k+1)$ | $y_{sr_1}(2k)$ | $y_{sr_2}(2k)$ | $y_{sd}(2k)$ |
| $2k+1$ | $-s^*(2k+1)$ | $s^*(2k)$ | $y_{sr_1}(2k+1)$ | $y_{sr_2}(2k+1)$ | $y_{sd}(2k+1)$ |
| $2k+2$ | | | $y_{sr_1}(2k)$ | $y_{sr_1}(2k)$ | |
| $2k+3$ | | | $y_{sr_1}(2k+1)$ | $y_{sr_1}(2k+1)$ | |
| $2k+4$ | | | $y_{sr_2}(2k)$ | $y_{sr_2}(2k)$ | |
| $2k+5$ | | | $y_{sr_2}(2k+1)$ | $y_{sr_2}(2k+1)$ | |
| $2k+6$ | | | $r(2k)$ | $r(2k+1)$ | $y_{rd}(2k)$ |
| $2k+7$ | | | $-r^*(2k+1)$ | $r^*(2k)$ | $y_{rd}(2k+1)$ |

TABLE III
PROTOCOL OF THE MIMO FULL COOPERATIVE RELAY MODEL

## III. OUTAGE ANALYSIS

In this section, we characterize the performance of the models in Section II in terms of outage probability in the high SNR region. Let $P_s = P_r = P$ and define the Signal to Noise Ratio $SNR = P/N_0$, we can determine the outage probability of the models based on the $SNR$ parameter. Note that, for Rayleigh fading, $|h_{ij}|^2$ is exponentially distributed with parameter $\sigma_{ij}^{-2}$. Its probability density function is given by

$$p_x(x) = \frac{1}{\sigma_{ij}^2}e^{-\frac{1}{\sigma_{ij}^2}x}, \quad i \in \{s, r_1, r_2\}, j \in \{r_1, r_2, d\}. \tag{6}$$

In this work, we assume that relay 1 and relay 2 have the same relative distance to source and destination, so we can note $\sigma_{sr} = \sigma_{sr_1} = \sigma_{sr_2}$ and $\sigma_{rd} = \sigma_{r_1d} = \sigma_{r_2d}$. In addition, the probability density function of random variable $||\boldsymbol{h_{ij}}||^2 = |h_{ij}(2k)|^2 + |h_{ij}(2k+1)|^2$ is given by

$$p_x(x) = \left(\frac{1}{\sigma_{ij}^2}\right)^2 xe^{-\frac{1}{\sigma_{ij}^2}x}, \quad i \in \{s, r_1, r_2\}, j \in \{r_1, r_2, d\}. \tag{7}$$

All the outage probability approximations in the following parts are based on Appendix I and II of [4].

### A. MIMO Normal Cooperative Relay model (MNCR)

For MNCR, the maximum average mutual information between source and destination for random signals generated i.i.d circularly symmetric, complex Gaussian at the source and two relays can be shown to be

$$I_{MNCR} = \frac{1}{3}\log\Big(1 + SNR||\boldsymbol{h_{sd}}||^2 + f(SNR||\boldsymbol{h_{sr_1}}||^2, SNR|h_{r_1d}|^2) + f(SNR||\boldsymbol{h_{sr_2}}||^2, SNR|h_{r_2d}|^2)\Big) \quad (8)$$

The function of the fading coefficients $f(.)$ is defined in [4]. The outage probability of MNCR for spectral efficiency $R$ is defined as

$$Pr[I_{MNCR} < R] = Pr\Big[||\boldsymbol{h_{sd}}||^2 + \frac{1}{SNR}f(SNR||\boldsymbol{h_{sr_1}}||^2, SNR|h_{r_1d}|^2) + \frac{1}{SNR}f(SNR||\boldsymbol{h_{sr_2}}||^2, SNR|h_{r_2d}|^2) < \frac{2^{3R}-1}{SNR}\Big] \quad (9)$$

Using the approximation in [6, eq. (16), (17)], the lower bound and upper bound of the outage probability of MNCR can be derived as

$$\frac{1}{48}\frac{1}{\sigma_{rd}^4\sigma_{sd}^4}\Big(\frac{2^{3R}-1}{SNR}\Big)^4 \le Pr[I_{MNCR} < R] \le \frac{1}{12}\frac{1}{\sigma_{rd}^4\sigma_{sd}^4}\Big(\frac{2^{3R}-1}{SNR}\Big)^4 \quad (10)$$

### B. MIMO Simple Cooperative Relay model (MSCR)

The maximum average mutual information between source and destination in MSCR for random signals generated i.i.d circularly symmetric, complex Gaussian at the source and two relays can be shown to be

$$I_{MSCR} = \frac{1}{2}\log\Big(1 + SNR||\boldsymbol{h_{sd}}||^2 + f(SNR||\boldsymbol{h_{sr}}||^2, SNR||\boldsymbol{h_{rd}}||^2\Big) \quad (11)$$

where $||\boldsymbol{h_{sr}}||^2 = max(||\boldsymbol{h_{sr1}}||^2, ||\boldsymbol{h_{sr2}}||^2)$. Without the loss of generality, we assume that $||\boldsymbol{h_{sr}}||^2 = ||\boldsymbol{h_{sr1}}||^2$.

So, the outage probability of MSCR for the spectral efficiency $R$ is

$$Pr[I_{MSCR} < R] = Pr\Big[||\boldsymbol{h_{sd}}||^2 + \frac{1}{SNR}f(SNR||\boldsymbol{h_{sr}}||^2, SNR||\boldsymbol{h_{rd}}||^2) < \frac{2^{2R}-1}{SNR}\Big] \quad (12)$$

The outage probability of MSCR can be approximated in high SNR region by

$$Pr[I_{MSCR} < R] \sim \frac{1}{4!}\frac{\sigma_{sr}^4+\sigma_{rd}^4}{\sigma_{sr}^4\sigma_{rd}^4}\frac{1}{\sigma_{sd}^4}\Big(\frac{2^{2R}-1}{SNR}\Big)^4 \quad (13)$$

### C. MIMO Full Cooperative Relay Model (MFCR)

For MFCR, the maximum average mutual information between source and destination for random signals generated i.i.d circularly symmetric, complex Gaussian at the source and two relays can be shown to be

$$I_{MFCR} = \frac{1}{4}\log\Big(1 + SNR||\boldsymbol{h_{sd}}||^2 + f\big(SNR||\boldsymbol{H_{sr}}||^2, SNR||\boldsymbol{h_{rd}}||^2\big)\Big) \quad (14)$$

where $||\boldsymbol{H_{sr}}||^2 = ||\boldsymbol{h_{sr1}}||^2 + ||\boldsymbol{h_{sr2}}||^2$ because in MFCR there is a data exchange between two relays.

The outage event for spectral efficiency $R$ is given by $I_{MFCR} < R$ and is equivalent to the event

$$SNR||\boldsymbol{h_{sd}}||^2 + f(SNR||\boldsymbol{H_{sr}}||^2, SNR||\boldsymbol{h_{rd}}||^2) < 2^{4R} - 1 \quad (15)$$

With the attention that the probability density function of random variable $||\boldsymbol{H_{sr}}||^2$ is $p_x(x) = \Big(\frac{1}{\sigma_{sr}^2}\Big)^4 x^3 e^{-\frac{1}{\sigma_{sr}^2}x}$, the outage probability of MFCR can be derived as

$$Pr[I_{MFCR} < R] \sim \frac{1}{4!}\frac{1}{\sigma_{rd}^4\sigma_{sd}^4}\Big(\frac{2^{4R}-1}{SNR}\Big)^4 \quad (16)$$

### D. Simulation of outage probability

Fig. 2 shows the outage probability of MNCR, MSCR and MFCR versus the rate-normalized $SNR_{norm}$ [4] in small, fixed $R$ regime ($R = 1$) for statistically symmetric networks, i.e. $\sigma_{ij}^2 = 1$. Solid curves correspond to high-SNR approximations obtained from the previous subsections. Dashed curves correspond to the simulations obtained via Monte Carlo method. From Fig. 2, the obtained outage probability approximations for MSCR and MFCR match with the simulations at high SNR, while for MNCR the simulation results is in the middle of the lower bound and the upper bound approximations. Furthermore, despite having the same diversity order of 4, MSCR is the model which has the best outage probability. Moreover, in comparison with the system [5] denoted by Karim06 (1-3-1) which uses 1 source, 3 relays and 1 destination, MNCR, MSCR and MFCR all have better outage probability.

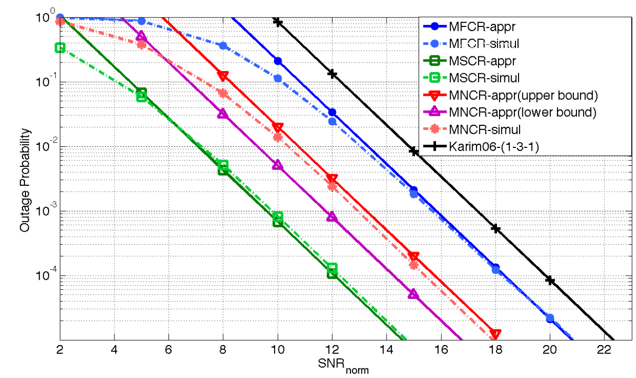


Fig. 2. Outage probability versus $SNR_{norm}$, small, fixed $R$ regime, for statistically symmetric networks, i.e. $\sigma_{ij}^2 = 1$

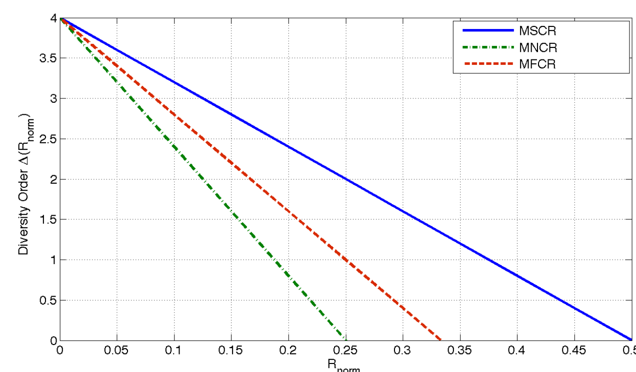


Fig. 3. Diversity order $\Delta(R_{norm})$ versus $R_{norm}$.

The tradeoff between the diversity order, $\Delta(R_{norm})$ [4] and normalized spectral efficiency $R_{norm}$ [4] at high SNR region is shown in Fig. 3. At the same $\Delta(R_{norm})$, the MSCR has a larger normalized spectral efficiency than MNCR and MFCR. However, we will see in the following section that without taking bandwidth into account, the BER performance of MFCR is better than that of MNCR and MSCR.

## IV. BER Simulation

In this section, the performance of MNCR, MSCR and MFCR is simulated in terms of BER using BPSK modulation. Using a common model for path-loss, we set $\sigma_{ij}^2 \propto d_{ij}^{-\alpha}$ where $d_{ij}$ is the distance between terminal $i$ and $j$, and $\alpha$ is the path-loss exponent. In our work, $\alpha = 2$ is used. Counting for the effects of geometry, the performance of the models is simulated depending on the relative distance of relays $r$ which is defined by the ratio of the source-relay distance $d_{sr}$ and the source-destination distance $d_{sd}$.

### A. MNCR vs MSCR

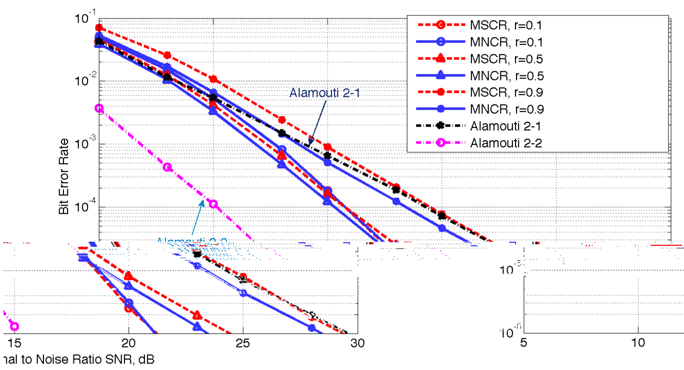


Fig. 4. BER of MNCR and MSCR at some values of $r$

BER of MNCR and MSCR is shown in Fig. 4. The performance of MNCR is lightly better than that of MSCR. However, from Fig. 3, the spectral efficiency of MSCR is better than that of MNCR. Therefore, MSCR is a better choice than MNCR for networks that require high spectral efficiency or low latency. Furthermore, when $r$ is high (i.e. the relays near the destination) the performance of MSCR is not better than that of Alamouti 2-1 scheme (using two-antenna source and one-antenna destination). Fortunately, the outage probability analysis in Section III makes sure that MSCR still have the diversity order of 4 when SNR is high. However, MNCR and MSCR are both worse than Alamouti 2-2 scheme (using two-antenna source and two-antenna destination).

### B. MSCR vs MFCR

Fig. 5 shows the performances of MFCR and MSCR using AAF protocol at $r$ equal to 0.1, 0.5 and 0.9. The performance of the MFCR is always better than that of the MSCR. Moreover, the larger $r$ is, the better the performance of MFCR is. This simulation result matches with (16) when $\sigma_{rd}$ is larger (i.e. the relays near the destination), the outage probability of MFCR is smaller. However, when $r$ is small ($r = 0.1$) the performances of MSCR and MFCR are the same. Due to the best performance, MFCR is the most suitable model to apply in WSNs, where the energy constraint is more important than the bit rate constraint. On the other hand, in Fig. 5, we can realize that the 3dB reduction of power in the best case of MFCR in comparison with Alamouti 2-2 scheme can be explained that the power of each constellation in MFCR is normalized to be 1/4 while in Alamouti 2-2 scheme the power of each constellation is only halved.

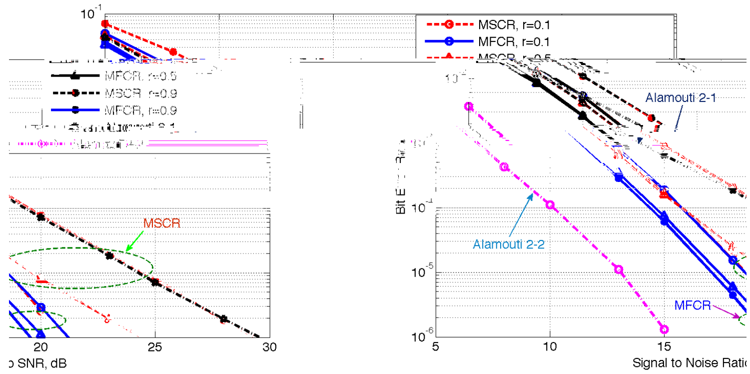


Fig. 5. BER of MFCR and MSCR at some values of $r$

## V. Energy Efficiency Analysis

To evaluate the energy efficiency performance of these models, instead of using the typical energy model in [9], the present paper applies a realistic power consumption model [10] which uses a wireless transceiver, CC2420 for a precise power consumption estimation.

The total power consumption for transmitting and for receiving, denoted by $P_T$ and $P_R$ are

$$P_T(d_{sd}) = P_{TB} + P_{TRF} + P_A(d_{sd}) = P_{T0} + P_A(d_{sd}) \quad (17)$$

$$P_R = P_{RB} + P_{RRF} + P_L = P_{R0} \quad (18)$$

where $P_{TB}/P_{RB}$ is power consumption (mW) in baseband digital signal processing circuit for transmitting/receiving, $P_{TRF}/P_{RRF}$ is power consumption (mW) in front-end circuit for transmitting/receiving, $P_A$ is power consumption (mW) of the power amplifier, $P_L$ is the power consumption (mW) of low noise amplifier and $d_{sd}$ is the transmission distance. Since $P_{TB}$ and $P_{TRF}$ do not depend on the transmission range, the two components can be modeled as a constant, $P_{T0}$ . Similarly, since $P_{RB}$, $P_{RRF}$ and $P_L$ do not depend on the transmission range, the power consumption of the receiving circuit can also be considered as a constant, $P_{R0}$.

In general, the power consumption of the power amplifier, $P_A(d_{sd})$ depends on the desired transmit power $P_{Tx}^{desired}(d_{sd})$ and the drain efficiency $\eta$

$$P_A(d_{sd}) = \frac{P_{Tx}^{desired}(d_{sd})}{\eta} \quad (19)$$

On the other hand, $P_{Tx}^{desired}$ can be derived as a function of the desired receive power $P_{Rx}^{desired}$ at the destination.

$$P_{Tx}^{desired}(d_{sd}) = P_{Rx}^{desired} \times \frac{(4\pi d_{sd})^2 L}{G_t G_r \lambda^2} \quad (20)$$

where $G_t$ and $G_r$ are the transmitter and receiver antenna gain, $L$ is the system loss factor not related to propagation, $\lambda$ is the carrier wavelength and $P_{Rx}^{desired}$ is the desired receive power at destination.

$P_{Rx}^{desired}$ can be referred as [11]

$$P_{Rx}^{desired} = N_0 SNR(1+\alpha) N_f R_b \quad (21)$$

with $\alpha$ the roll-off factor, $N_f$ the noise figure and $R_b$ the transmit bit rate.

The energy consumption per bit can be derived as

$$E^b = (P_T(d_{sd}) + P_R)/R_b \tag{22}$$

In a CC2420 chip, the maximum transmit power, $P_{Tx}^{max}$, is $0dBm$ and the sensitivity of receiver low noise amplifier is $-95dBm$. Therefore, in a real communication, the following conditions must be satisfied

$$P_{Tx}^{desired} \leq P_{Tx}^{max}(0dBm) \tag{23}$$

$$P_{Rx}^{desired} \geq P_{Rx}^{min}(-95dBm) \tag{24}$$

Fig. 6 shows the total energy consumption per bit using the realistic power consumption model at $r = 0.5$. In this work, $\alpha = 0.25$, $L = 1$, $N_f = 10dB$, $N_0/2 = -174dBm/Hz$ are used and the other parameters are extracted from the characteristics of CC2420 chip [12]. For the fair comparison, the energy consumption of the models is all calculated at $BER = 10^{-5}$. Applying the characteristics of the CC2420 wireless transceiver, we see that each model has a maximum application distance. While Alamouti 2-1 is the most energy efficient model for $d_{sd} < 122m$, for a transmission with $122m < d_{sd} < 205m$, MSCR is the suitable model to economize the energy consumption and so on for the other cases.

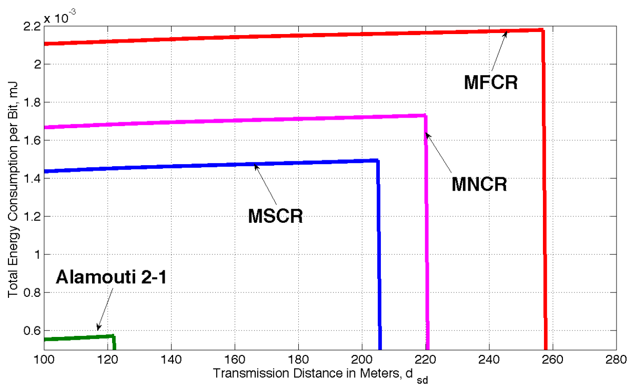


Fig. 6. Total energy consumption per bit with the transmit power lower than 0dBm, and the receive power larger than -95dBm (BER= $10^{-5}$, $r = 0.5$)

Fig. 7 shows the best cooperative strategy of the system in Fig. 1 at $BER = 10^{-5}$ to minimize the energy comsumption. Each colored area represents the model which gives us the minimum energy consumption at a given $d_{sd}$, fixed $r$. The white is the out of range area in which using CC2420, with MNCR, MSCR and MFCR it is impossible to get the desired reliable transmission ($BER = 10^{-5}$). Fig. 7 is very useful for real applications. Given a system as the one of Fig. 1, when $r$ and $d_{sd}$ are set and at desired $BER = 10^{-5}$, we can choose the suitable model to optimize the energy consumption for the system.

## VI. Conclusion

In this paper, the MSCR and MFCR techniques are shown to have more advantages than the MNCR technique. Although MSCR, MFCR and MNCR all have the diversity order of 4, MSCR brings us the best performance in terms of spectral efficiency while MFCR brings us the best performance in terms of BER or energy efficiency. The outage probability

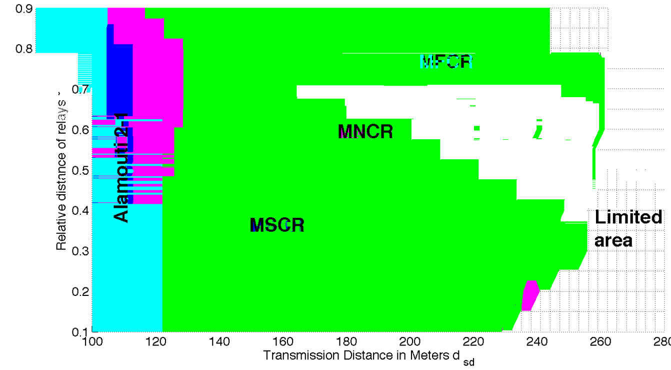


Fig. 7. The best cooperative strategy at BER= $10^{-5}$ to minimize the energy consumption.

analysis of MNCR, MSCR and MFCR is totally suitable with the simulation results. Using a realistic power consumption for a real wireless transceiver, CC2420, we show a precise energy consumption estimation for MNCR, MSCR and MFCR. Each model has a maximum application transmission distance which is determined based on $r$ and desired $BER$. The optimal energy efficient model selection is also shown as an example of how to choose the best model to optimize the energy consumption.

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