Energy-Efficient Cooperative Beamforming based CMISO Transmission with Optimal Nodes Deployment in Wireless Sensor Networks

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Abstract

This paper analyzes the nodes deployment optimization problem in energy constrained wireless sensor networks, which multi-hop cooperative beamforming (CB) based cooperative-multi-input-single-output (CMISO) transmission is adopted to reduce the energy consumption. Firstly, we establish the energy consumption models for multi-hop SISO, multi-hop DSTBC based CMISO, multi-hop CB based CMISO transmissions under random nodes deployment. Then, we minimize the energy consumption by searching the optimal nodes deployment for the three transmissions. Furthermore, numerical results present the optimal nodes deployment parameters for the three transmissions. Energy consumption of the three transmissions are compared under optimal nodes deployment, which shows that CB based CMISO transmission consumes less energy than SISO and DSTBC based CMISO transmissions. Meanwhile, under optimal nodes deployment, the superiorities of CB based CMISO transmission over SISO and DSTBC based CMISO transmissions can be more obvious when path-loss-factor becomes low.

Keywords: Nodes deployment, Wireless sensor networks, Cooperative beamforming, CMISO

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1. Introduction

In wireless sensor networks (WSNs), nodes are deployed in monitored areas, physical data collected by the source node (SN) that needs to be transmitted to the destination node (DN) via single-hop transmission or multi-hop transmission. Under these circumstances, nodes deployment is an important factor affecting energy consumption between SN and DN in energy-constrained WSNs. However, replacing or recharging the batteries of the nodes is restricted after deployment. So, searching an optimal nodes deployment to minimize the energy consumption becomes a very important design consideration in WSNs [1, 2].

Various researches [3-7] have focused on nodes deployment optimization with different perspectives in recent years. In [3], the authors select optimal nodes to forward the data from SN to DN by a vector optimization. In [4], the authors have focused on solving energy-hole problem by deploying nodes to balance traffic load. In [5], the authors have presented the hybrid nodes placement method to select optimal position from candidate locations. Moreover, optimal nodes deployment with delay constrained and fault-tolerant are considered in [6] and [7], respectively. Although the above works [3-7] have already showed the energy efficiency improvement with nodes deployment optimization, the researches are based on single-input-single-output (SISO) transmission,the circuit energy consumption is not considered.

Recently, cooperative-multi-input-multi-output (CMIMO) techniques and its variations, e.g.cooperative-multi-input-single-output (CMISO) have been proved to reduce transmission energy consumption in WSNs [8]. Single-hop distributed-space-time-block-code (DSTBC) based CMIMO transmission is first proposed in [9].It shows that, with considering the circuit blocks energy consumption, DSTBC scheme can outperform SISO scheme in energy efficiency with long range transmission distance.CMIMO transmission based on vertical-bell-labs-layered-space-time (V-BLAST) architecture has been analyzed in [10], which does not require sensor cooperation in transmitter side. However, the number of transmit antennas must less than the receive antennas, which limits the adoption of the V-BLAST scheme. Energy efficiency of single-hop cooperative beamforming (CB) based CMISO transmission scheme has been investigated in [11], which shows that CB scheme has more superiority than DSTBC scheme in energy efficiency. In addition, multi-hop CMIMO (or its variations) transmission with topology control [12,13], optimal power allocation [14,15,16,17] ,channel reuse[18],transmission capacity[19] and data gathering [20] have been also investigated. The above works [9-20] have already showed the potential advantages of cooperative transmission in WSNs. However, the research on CMIMO (or its variations) transmission have mainly been restricted to show the energy-saving by optimizing the parameters with random nodes deployment, without considering optimizing the nodes deployment. To the best of our knowledge, we make the first attempt to investigate the problem of nodes deployment optimization combined with CMISO transmission for the goal of improving energy efficiency. This paper aims at source-destination transmission, we minimize the energy consumption by finding optimal nodes deployment for multi-hop SISO, multi-hop DSTBC based CMISO, multi-hop CB based CMISO transmissions.The superiority of nodes deployment by using CB based CMISO transmission is also provided.

The rest of this paper is organized as follows. In section 2, we present the energy consumption models for multi-hop SISO, multi-hop DSTBC based CMISO, multi-hop CB based CMISO transmissions under random nodes deployment. In section 3, energy consumption for the three transmissions are minimized by searching optimal nodes deployment. In section 4, numerical results show the optimal nodes deployment and the superiority of nodes deployment by using CB based CMISO transmission. Finally, section 5 summarizes the paper.

2. Energy Consumption Model

2.1 Multi-hop CB based CMISO Transmission

Nodes are deployed over a two-dimensional plane and equipped itself with single-antenna. SN S needs to transmit L bits data to DN D, the distance between S and D is d_{SD}. **Fig. 1** shows the system model.

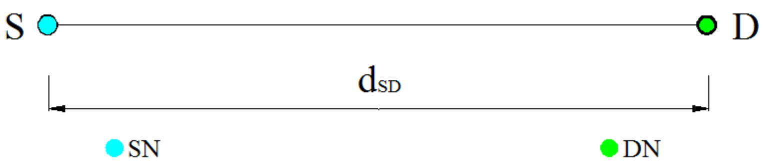

Fig. 1. System model

In order to realize the multi-hop CB based CMISO transmission, N_C+1 relay nodes (RNs) ($R_C(1),\cdots,R_C(i),\cdots,R_C(N_C+1)$) are deployed between the S and the D. In order to simplify the system model, we only consider one cooperative node (CN) in each hop. CN $C_C(1)$is deployed in the first hop, CN $C_C(i)$ ($2\leq i\leq N_C$) is deployed in the i hop, CN $C_C(N_C+1)$ is deployed in the last hop. For each hop in multi-hop CB based CMISO transmission, the RN (or S in the first hop) transmits the data to the CN, and the CN receives it. Then, the RN and their CN can cooperatively transmit the data to the RN in the next hop (or D in the last hop) using CB scheme. We assume that perfectly time synchronization between nodes and power control are enabled for nodes. In order to make our paper readable, main symbols are shown in **Table 1**.

Table 1. Main symbols

Symbols	Description
ξ	Peak-to-Average-Ratio (PAR)
η	Drain efficiency
B	System bandwidth
G_tG_r	Antenna gain
λ	Carrier wavelength
M_l	Link margin
N_f	Receiver noise figure
N_0	Thermal noise power-spectral-density (PSD)
k	Path-loss-factor
P_{DAC}	Power consumption of the digital-to-analog-converter (DAC)
P_{mix}	Power consumption of the mixer
P_{filt}	Power consumption of the active filters at the transmitter side
P_{syn}	Power consumption of the frequency synthesizer
P_{LNA}	Power consumption of the low-noise-amplifier (LNA)
P_{IFA}	Power consumption of the intermediate-frequency-amplifier (IFA)
P_{filr}	Power consumption of the active filters at the receiver side
P_{ADC}	Power consumption of the analog-to-digital-converter (ADC)

P_{CT}, P_{CR}	Power consumption of the transmitter side, receiver side
E_{total}^{S}, E_{total}^{D}, E_{total}^{C}	Total energy consumption of the SISO,DSTBC and CB transmissions
E_{local}^{S}, E_{local}^{D}, E_{local}^{C}	Local minimal energy consumption of the SISO,DSTBC and CB transmissions
E_{opt}^{S}, E_{opt}^{D}, E_{opt}^{C}	Global minimal energy consumption of the SISO,DSTBC and CB transmissions
$E_{btp}^{C}(i)$, $E_{btp,t}^{C}(i)$, $E_{btp,c}^{C}(i)$	Total, transmission and circuit energy consumption at the i hop in BTP of the CB transmission
$E_{ctp}^{C}(i)$, $E_{ctp,t}^{C}(i)$, $E_{ctp,c}^{C}(i)$	Total, transmission and circuit energy consumption at the i hop in CTP of the CB transmission
$E_{btp}^{D}(i)$, $E_{btp,t}^{D}(i)$, $E_{btp,c}^{D}(i)$	Total, transmission and circuit energy consumption at the i hop in BTP of the DSTBC transmission
$E_{ctp}^{D}(i)$, $E_{ctp,t}^{D}(i)$, $E_{ctp,c}^{D}(i)$	Total, transmission and circuit energy consumption at the i hop in CTP of the DSTBC transmission
$E^{S}(i)$, $E_{t}^{S}(i)$, $E_{c}^{S}(i)$	Total, transmission and circuit energy consumption at the i hop of the SISO transmission
$\overline{P}_{b,btp}$, $\overline{P}_{b,ctp}$	BER requirements of the BTP and CTP
$\overline{E}_{b,btp}^{C}$, $\overline{E}_{b,ctp}^{C}$	Required energy per bit in BTP and CTP of the CB transmission
$\overline{E}_{b,btp}^{D}$, $\overline{E}_{b,ctp}^{D}$	Required energy per bit in BTP and CTP of the DSTBC transmission

Fig. 2 shows the random nodes deployment model for multi-hop CB based CMISO transmission.

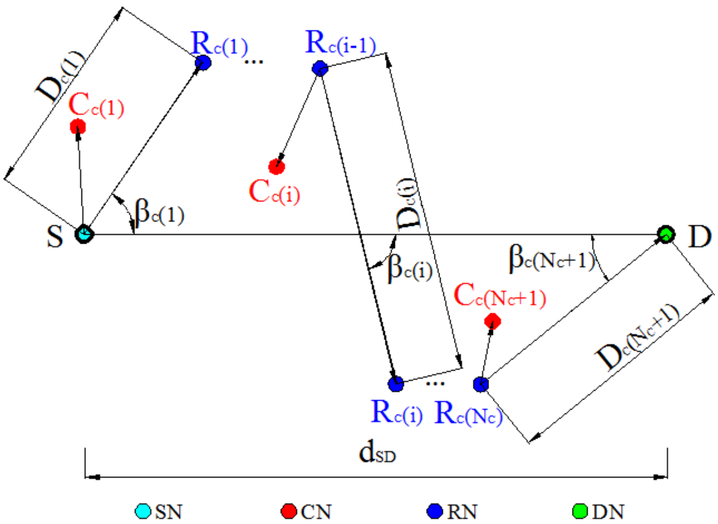

Fig. 2. Random nodes deployment model for multi-hop CB based CMISO transmission

The CNs deployment and RNs deployment can be represented by (1) and (2), respectively.

$$\begin{pmatrix} \left|\overrightarrow{SC_c(1)}\right| & \left\langle \overrightarrow{SR_c(1)}, \overrightarrow{SC_c(1)} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_c(i-1)C_c(i)}\right| & \left\langle \overrightarrow{R_c(i-1)R_c(i)}, \overrightarrow{R_c(i-1)C_c(i)} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_c(N_c)C_c(N_c+1)}\right| & \left\langle \overrightarrow{R_c(N_c)D}, \overrightarrow{R_c(N_c)C_c(N_c+1)} \right\rangle \end{pmatrix} = \begin{pmatrix} d_c(1) & \alpha_c(1) \\ \vdots & \vdots \\ d_c(i) & \alpha_c(i) \\ \vdots & \vdots \\ d_c(N_c+1) & \alpha_c(N_c+1) \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} \left|\overrightarrow{SR_C(1)}\right| & \left\langle \overrightarrow{SR_C(1)}, \overrightarrow{SD} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_C(i-1)R_C(i)}\right| & \left\langle \overrightarrow{R_C(i-1)R_C(i)}, \overrightarrow{SD} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_C(N_C)D}\right| & \left\langle \overrightarrow{R_C(N_C)D}, \overrightarrow{SD} \right\rangle \end{pmatrix} = \begin{pmatrix} D_C(1) & \beta_C(1) \\ \vdots & \vdots \\ D_C(i) & \beta_C(i) \\ \vdots & \vdots \\ D_C(N_C+1) & \beta_C(N_C+1) \end{pmatrix} \tag{2}$$

where, $\left|\overrightarrow{SC_C(1)}\right|$ is the size of vector $\overrightarrow{SC_C(1)}$, represents the distance between S and $C_C(1)$. $\left\langle \overrightarrow{SR_C(1)}, \overrightarrow{SC_C(1)} \right\rangle$ is angle between $\overrightarrow{SR_C(1)}$ and $\overrightarrow{SC_C(1)}$.

The multi-hop CB based CMISO transmission scheme in each hop is consists of two phases, broadcast transmission phase (BTP) and cooperative transmission phase (CTP). In BTP, the RN (or S in the first hop) transmits the data to the CN, and the CN receives it. In CTP, the RN and the CN can cooperatively transmit the data to the RN in the next hop using CB scheme (or D in the last hop). We assume the system with a flat rayleigh fading with k law-path-loss. BPSK modulation is used for data transmission. The same energy consumption model is adopted as that in [9,11,21]. For CB based CMISO transmission, the energy consumption at the i hop $E^C(i)$is given by

$$\begin{aligned} E^C(i) &= E^C_{btp}(i) + E^C_{ctp}(i) \\ &= \left(E^C_{btp,t}(i) + E^C_{btp,c}(i)\right) + \left(E^C_{ctp,t}(i) + E^C_{ctp,c}(i)\right) \\ &= \left(LG\overline{E}^C_{b,btp}(d_C(i))^k + \frac{L(P_{CT}+P_{CR})}{R_b}\right) + \left(LG\overline{E}^C_{b,ctp}\frac{((D_C(i))^k + (D^*_C(i))^k)}{2} + \frac{L(2P_{CT}+P_{CR})}{R_b}\right) \end{aligned} \tag{3}$$

where $G = \frac{\xi}{\eta}\frac{(4\pi)^2}{G_t G_r \lambda^2} M_l N_f$

$$D^*_C(i) = \sqrt{(D_C(i))^2 + (d_C(i))^2 - 2D_C(i)d_C(i)\cos(\alpha_C(i))}$$

$$\overline{E}^C_{b,btp} = \frac{N_0}{\left(1-2\overline{P}_{b,btp}\right)^{-2} - 1}$$

$$\overline{E}^C_{b,ctp} = \frac{N_0}{\left(1-2\sqrt{\frac{\overline{P}_{b,ctp}}{3}}\right)^{-2} - 1}$$

To simplify the analysis, digital signal processing blocks (source coding, pulse-shaping, and digital modulation, and soon) are omitted in our system model. We assume that the system is uncoded, without error correction code (ECC) blocks. P_{CT} and P_{CR} can be represented as[9,21]

$$P_{CT} = P_{DAC} + P_{mix} + P_{fift} + P_{syn} \tag{4}$$

$$P_{CR} = P_{LNA} + P_{mix} + P_{IFA} + P_{fifr} + P_{ADC} + P_{syn} \tag{5}$$

The specific description of these above symbols are given in **Table 1**.

The total energy consumption E^C_{total} is the sum of energy consumption per hop,which is given by

$$E^C_{total} = \sum_{i=1}^{N_C+1} E^C(i) = = \sum_{i=1}^{N_C+1}\left\{E^C_{btp}(i) + E^C_{ctp}(i)\right\} \tag{6}$$

2.2 Multi-hop STBC based CMISO Transmission

In order to realize the multi-hop DSTBC based CMISO transmission, N_D RNs ($R_D(1),\ldots,R_D(i),\ldots,R_D(N_D)$) are deployed between the S and the D, N_D+1 CNs

($C_D(1),\ldots,C_D(i),\ldots,C_D(N_D+1)$) are deployed the each hop. **Fig. 3** shows the random nodes deployment model for multi-hop DSTBC based CMISO transmission.

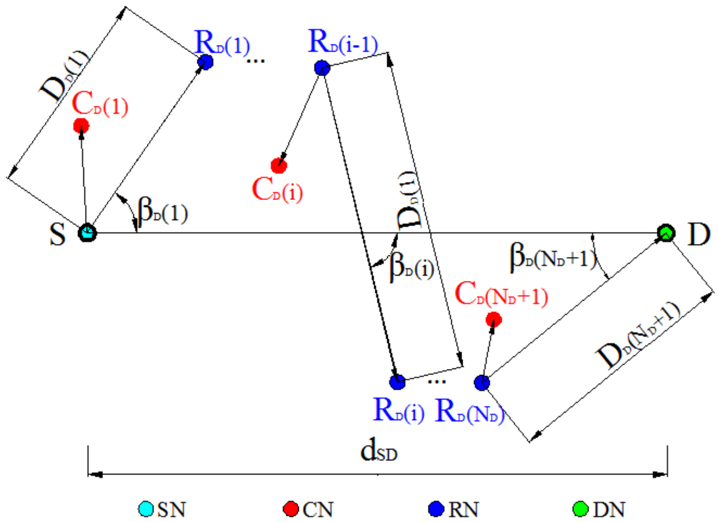

Fig. 3. Random nodes deployment model for multi-hop DSTBC based CMISO transmission

The CNs deployment and RNs deployment can be represented by (7) and (8), respectively.

$$\begin{pmatrix} \left|\overrightarrow{SC_D(1)}\right| & \left\langle \overrightarrow{SR_D(1)}, \overrightarrow{SC_D(1)} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_D(i-1)C_D(i)}\right| & \left\langle \overrightarrow{R_D(i-1)R_D(i)}, \overrightarrow{R_D(i-1)C_D(i)} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_D(N_D)C_D(N_D+1)}\right| & \left\langle \overrightarrow{R_D(N_D)D}, \overrightarrow{R_D(N_D)C_D(N_D+1)} \right\rangle \end{pmatrix} = \begin{pmatrix} d_D(1) & \alpha_D(1) \\ \vdots & \vdots \\ d_D(i) & \alpha_D(i) \\ \vdots & \vdots \\ d_D(N_D+1) & \alpha_D(N_D+1) \end{pmatrix} \tag{7}$$

$$\begin{pmatrix} \left|\overrightarrow{SR_D(1)}\right| & \left\langle \overrightarrow{SR_D(1)}, \overrightarrow{SD} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_D(i-1)R_D(i)}\right| & \left\langle \overrightarrow{R_D(i-1)R_D(i)}, \overrightarrow{SD} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_D(N_D)D}\right| & \left\langle \overrightarrow{R_D(N_D)D}, \overrightarrow{SD} \right\rangle \end{pmatrix} = \begin{pmatrix} D_D(1) & \beta_D(1) \\ \vdots & \vdots \\ D_C(i) & \beta_D(i) \\ \vdots & \vdots \\ D_D(N_D+1) & \beta_D(N_D+1) \end{pmatrix} \tag{8}$$

Similar to multi-hop CB based CMISO transmission ,the multi-hop DSTBC based CMISO transmission scheme in each hop is also consists of BTP and CTP. In BTP, the RN (or S in the first hop) transmits the data to the CN, and the CN receives it. In CTP, the RN and the CN can cooperatively transmit the data to the RN in the next hop using DSTBC scheme (or D in the last hop).We know that, the fundamental difference between multi-hop DSTBC based CMISO transmission and multi-hop CB based CMISO transmission is the CTP. The total energy consumption E_{total}^D is given by

$$\begin{aligned} E_{total}^D &= \sum_{i=1}^{N_D+1} E^D(i) = \sum_{i=1}^{N_D+1} \left\{ E_{btp}^D(i) + E_{ctp}^D(i) \right\} \\ &= \sum_{i=1}^{N_D+1} \left(E_{btp,t}^D(i) + E_{btp,c}^D(i) \right) + \sum_{i=1}^{N_D+1} \left(E_{ctp,t}^D(i) + E_{ctp,c}^D(i) \right) \\ &= \sum_{i=1}^{N_D+1} \left(LG\overline{E}_{b,btp}^D (d_D(i))^k + \frac{L(P_{CT}+P_{CR})}{R_b} \right) + \sum_{i=1}^{N_D+1} \left(LG\overline{E}_{b,ctp}^D \frac{((D_D(i))^k + (D_D^*(i))^k)}{2} + \frac{L(2P_{CT}+P_{CR})}{R_b} \right) \end{aligned} \tag{9}$$

where $D_D^*(i) = \sqrt{(D_D(i))^2 + (d_D(i))^2 - 2D_D(i)d_D(i)\cos(\alpha_D(i))}$

$$\overline{E}_{b,btp}^D = \frac{N_0}{\left(1-2\overline{P}_{b,btp}\right)^{-2} - 1}$$

$$\overline{E}_{b,ctp}^D = \frac{2N_0}{\left(1-2\sqrt{\frac{\overline{P}_{b,ctp}}{3}}\right)^{-2} - 1}$$

The specific description of these above symbols are aslo given in **Table 1**.

2.3 Multi-hop SISO Transmission

In order to realize the conventional multi-hop SISO transmission, N_S RNs ($R_S(1)$,…,$R_S(i)$,…, $R_S(N_S)$) are deployed between the S and the D. For multi-hop SISO transmission, S transmits the data to D by using multi-hop SISO transmission with the help of RNs. **Fig. 4** shows the system model.

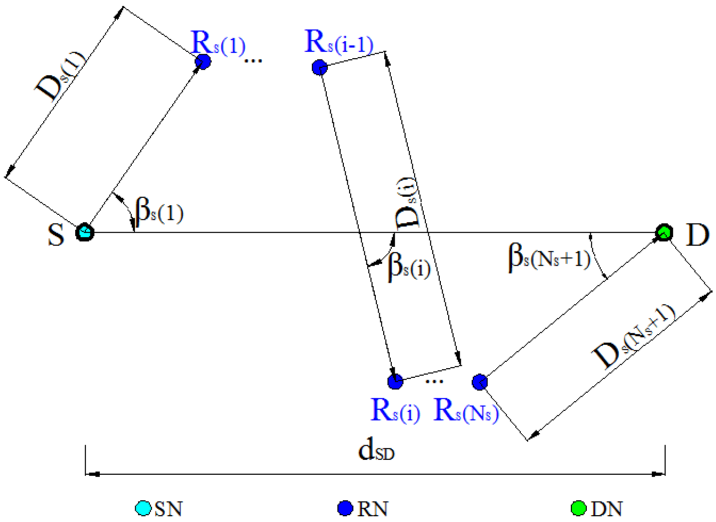

Fig. 4. Random nodes deployment model for multi-hop SISO transmission

The random RNs deployment in multi-hop SISO scheme can be represented by (10).

$$\begin{pmatrix} \left|\overrightarrow{SR_S(1)}\right| & \left\langle \overrightarrow{SR_S(1)}, \overrightarrow{SD} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_S(i-1)R_S(i)}\right| & \left\langle \overrightarrow{R_S(i-1)R_S(i)}, \overrightarrow{SD} \right\rangle \\ \vdots & \vdots \\ \left|\overrightarrow{R_S(N_S)D}\right| & \left\langle \overrightarrow{R_S(N_S)D}, \overrightarrow{SD} \right\rangle \end{pmatrix} = \begin{pmatrix} D_S(1) & \beta_S(1) \\ \vdots & \vdots \\ D_S(i) & \beta_S(i) \\ \vdots & \vdots \\ D_S(N_S+1) & \beta_S(N_S+1) \end{pmatrix} \tag{10}$$

The total energy consumption in multi-hop SISO transmission E_{total}^S ,which is given by

$$\begin{aligned} E_{total}^S &= \sum_{i=1}^{N_S+1} E^S(i) = \sum_{i=1}^{N_S+1} \left\{ E_t^S(i) + E_c^S(i) \right\} \\ &= \sum_{i=1}^{N_S+1} \left\{ LG\overline{E}_{b,siso}^S (D_S(i))^k + \frac{L(P_{CT}+P_{CR})}{R_b} \right\} \end{aligned} \tag{11}$$

where, $\bar{E}_{b,siso}^{S}$ is the required energy consumption per bit in SISO transmission[9].The specific description of these above symbols are aslo given in **Table 1**.

3. Nodes Deployment Optimization

3.1 Nodes deployment optimization for Multi-hop CB based CMISO Transmission

In this section, optimal nodes deployment for CB based CMISO Transmission is presented to minimize E_{total}^{C} . From equations (1)-(6), E_{total}^{C} is a function of N_C, $D_C(i)_{(i=1,2,\cdots,N_C+1)}$, $\beta_C(i)_{(i=1,2,\cdots,N_C+1)}$, $d_C(i)_{(i=1,2,\cdots,N_C+1)}$, $\alpha_C(i)_{(i=1,2,\cdots,N_C+1)}$.
The optimization problem is characterized as:

$$\begin{aligned}
&\min_{N_C, D_C(i), \beta_C(i), d_C(i), \alpha_C(i), i=1,2,\ldots,N_C+1} E_{total}^{C} = \sum_{i=1}^{N_C+1}\left(LG\bar{E}_{b,btp}^{C}(d_C(i))^k + LG\bar{E}_{b,ctp}^{C}\frac{((D_C(i))^k+(D_C^*(i))^k)}{2} + \frac{L(3P_{CT}+2P_{CR})}{R_b} \right) \\
&Subject\ to: N_C \geq 0, N_C\ is\ a\ integer \\
&\qquad D_C(i) > 0, i=1,2,\cdots,N_C+1 \\
&\qquad 0° \leq \beta_C(i) \leq 90°, i=1,2,\ldots,N_C+1 \\
&\qquad d_C(i) > 0, i=1,2,\cdots,N_C+1 \\
&\qquad 0° \leq \alpha_C(i) \leq 90°, i=1,2,\ldots,N_C+1 \\
&\qquad \sum_{i=1}^{N_C+1} D_C(i)\cos(\beta_C(i)) = d_{SD}
\end{aligned} \tag{12}$$

$4N_C$+5 variables need to be optimized in (12), two-steps optimization to solve the problem. In the first step, optimizing the CNs deployment parameters ($\alpha_C(i)_{(i=1,2,\cdots,N_C+1)}$, $d_C(i)_{(i=1,2,\cdots,N_C+1)}$) under a given RNs deployment (N_C,$D_C(i)_{(i=1,2,\cdots,N_C+1)}$,$\beta_C(i)_{(i=1,2,\cdots,N_C+1)}$). In the second step, optimizing RNs deployment (N_C,$D_C(i)_{(i=1,2,\cdots,N_C+1)}$,$\beta_C(i)_{(i=1,2,\cdots,N_C+1)}$).

Step1: Optimizing the CNs deployment parameters $\alpha_C(i)_{(i=1,2,\cdots,N_C+1)}$,$d_C(i)_{(i=1,2,\cdots,N_C+1)}$,for a given RNs deployment, which can be solved by Proposition 1.

Proposition 1: For a given RNs deployment(N_C,$D_C(i)_{(i=1,2,\cdots,N_C+1)}$,$\beta_C(i)_{(i=1,2,\cdots,N_C+1)}$),if optimal CNs deployment are $d_C(i)_{(i=1,2,\cdots,N_C+1)} = T_C D_C(i)$, $T_C = \frac{1}{1+\sqrt[k-1]{\frac{2\bar{E}_{b,btp}^{C}}{\bar{E}_{b,ctp}^{C}}}}$, $\alpha_C(i)_{(i=1,2,\cdots,N_C+1)} = 0°$ the minimum energy consumption can be achieved.

Proof: Taking the partial derivative of E_{total}^{C} to $d_C(i)$ and $\alpha_C(i)$, respectively. We can obtain that

For i=1,2,…,N_C+1

$$\begin{cases}
\frac{\partial E_{total}^{C}}{\partial d_C(i)} = \frac{\partial E^{C}(i)}{\partial d_C(i)} = GL\bar{E}_{b,btp}^{C}k(d_C(i))^{k-1} + \frac{GL\bar{E}_{b,ctp}^{C}k(D_C^*(i))^{k-1}}{2}\frac{\partial D_C^*(i)}{\partial d_C(i)} \\
\frac{\partial E_{total}^{C}}{\partial \alpha_C(i)} = \frac{\partial E^{C}(i)}{\partial \alpha_C(i)} = \frac{GL\bar{E}_{b,ctp}^{C}k(D_C^*(i))^{k-1}}{2}\frac{\partial D_C^*(i)}{\partial \alpha_C(i)}
\end{cases} \tag{13}$$

We get $T_C = \frac{1}{1+\sqrt[k-1]{\frac{2\overline{E}^C_{b,btp}}{\overline{E}^C_{b,ctp}}}}$, $\left.\frac{\partial E^C_{total}}{\partial d_C(i)}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} = 0$, $\left.\frac{\partial E^C_{total}}{\partial \alpha_C(i)}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} = 0$,

$\left.\frac{\partial^2 E^C_{total}}{\partial d_C(i)^2}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} > 0$, $\left.\frac{\partial^2 E^C_{total}}{\partial d_C(i)\partial \alpha_C(i)}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} = 0$, $\left.\frac{\partial^2 E^C_{total}}{\partial \alpha_C(i)^2}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} > 0$

$\left.\frac{\partial^2 E^C_{total}}{\partial d_C(i)^2}\frac{\partial^2 E^C_{total}}{\partial \alpha_C(i)^2} - \frac{\partial^2 E^C_{total}}{\partial d_C(i)\partial \alpha_C(i)}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} > 0$.

As we can be seen from the proof that $d_C(i)_{(i=1,2,\cdots,N_C+1)} = T_C D_C(i)$, $T_C = \frac{1}{1+\sqrt[k-1]{\frac{2\overline{E}^C_{b,btp}}{\overline{E}^C_{b,ctp}}}}$, $\alpha_C(i)_{(i=1,2,\cdots,N_C+1)} = 0^\circ$ are enough to achieve the minimum energy consumption.

Step2: Based on Proposition 1, we know that, for a given RNs deployment, the corresponding optimal CNs deployment can be solved. Setting CNs deployment parameters achieve the optimal value .Thus, the optimization problem in (12) is reduced to

$$\begin{aligned}&\min_{N_C, D_C(i), \beta_C(i), i=1,2,\ldots,N_C+1} \left.E^C_{total}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} = \sum_{i=1}^{N_C+1}\left(LG\overline{E}^C_{b,btp}(T_C D_C(i))^k + LG\overline{E}^C_{b,ctp}\frac{(D_C(i))^k + (D_C(i)-T_C D_C(i))^k}{2} + \frac{L(3P_{CT}+2P_{CR})}{R_b}\right)\\ &\textit{Subject to}: N_C \ge 0, N_C \textit{ is a integer}\\ &\qquad D_C(i) > 0, i=1,2,\cdots,N_C+1\\ &\qquad 0^\circ \le \beta_C(i) \le 90^\circ, i=1,2,\ldots,N_C+1\\ &\qquad \sum_{i=1}^{N_C+1} D_C(i)\cos(\beta_C(i)) = d_{SD}\end{aligned} \tag{14}$$

Then, $2N_C+1$ variables need to be optimized in (14). Firstly, optimizing the RNs deployment $D_C(i)_{(i=1,2,\cdots,N_C+1)}$,$\beta_C(i)_{(i=1,2,\cdots,N_C+1)}$,for a given N_C, the optimization problem can be solved by Proposition 2.Then, optimizing N_C to further reduce the energy consumption.

Proposition 2: For a given N_C, if $D_C(i)_{(i=1,2,\cdots,N_C+1)} = \frac{d_{SD}}{N_C+1}$,$\beta_C(i)_{(i=1,2,\cdots,N_C+1)} = 0^\circ$, the local minimum energy consumption E^C_{local} can be achieved.

Proof: We set

$$F = \left.E^C_{total}\right|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}} + \omega\left(\sum_{i=1}^{N_C+1} D_C(i)\cos(\beta_C(i)) - d_{SD}\right) \tag{15}$$

where, $\omega \neq 0$ is Lagrange multiplier, $D_C(i) \neq 0$.

Based on Lagrange multipliers, we get

$$\begin{cases}\frac{\partial F}{\partial D_C(i)} = 0, i=1,2,\cdots,N_C+1\\ \frac{\partial F}{\partial \beta_C(i)} = 0, i=1,2,\cdots,N_C+1\\ \frac{\partial F}{\partial \omega} = 0\end{cases} \tag{16}$$

Then, we obtain

$$\begin{cases} \dfrac{\partial E_{total}^{C}\Big|_{\substack{d_C(i)=T_C D_C(i)\\ \alpha_C(i)=0^\circ}}}{\partial D_C(i)} = -\omega\cos(\beta_C(i)), i=1,2,\cdots,N_C+1 \\ \omega D_C(i)\sin(\beta_C(i)) = 0, i=1,2,\cdots,N_C+1 \\ \sum_{i=1}^{N_C+1} D_C(i)\cos(\beta_C(i)) = d_{SD} \end{cases} \tag{17}$$

It can be found that $D_C(i)_{(i=1,2,\cdots,N_C+1)} = \frac{d_{SD}}{N_C+1}$,$\beta_C(i)_{(i=1,2,\cdots,N_C+1)} = 0°$, are sufficient for achieving the local minimum energy consumption, which is given by

$$\begin{aligned} E_{local}^{C} &= E_{local,t}^{C} + E_{local,c}^{C} \\ &= GL(N_C+1)\left(\frac{d_{SD}}{N_C+1}\right)^k \left(\overline{E}_{b,btp}^{C} T_C^k + \frac{\overline{E}_{b,ctp}^{C}}{2}\left(1+(1-T_C)^k\right) \right) + \frac{((3N_C+3)P_{CT} + (2N_C+2)P_{CR})L}{R_b} \end{aligned} \tag{18}$$

We can find in formula (18) ,$E_{local,t}^{C}$ is a decreasing function of N_C, $E_{local,c}^{C}$ is a increasing function of N_C. In general, there exists an optimal N_C to further reduce the E_{local}^{C}.

As $k>1$,setting $\frac{\partial E_{local}^{C}}{\partial N_C}=0$

We have

$$N_{C,opt} = \sqrt[k]{\frac{(3P_{CT}+2P_{CR})}{GR_b(k-1)\left(\overline{E}_{b,btp}^{C} T_C^k + \frac{\overline{E}_{b,ctp}^{C}}{2}\left(1+(1-T_C)^k\right)\right) d_{SD}{}^{k}}} - 1 \tag{19}$$

As the $N_{C,opt}$ (the optimal N_C) is a positive integer, which can be elected as either [$N_{C,opt}$] or [$N_{C,opt}$] +1(defined by the minimum E_{local}^{C} and [.] represents floor). Then, the optimal RNs deployment and CNs deployment can be obtained by Proposition 2 and Proposition 1.

3.2 Nodes deployment optimization for Multi-hop DSTBC based CMISO Transmission

From equations (7)-(9), E_{total}^{D} is a function of N_D , $D_D(i)_{(i=1,2,\cdots,N_D+1)}$, $\beta_D(i)_{(i=1,2,\cdots,N_D+1)}$, $d_D(i)_{(i=1,2,\cdots,N_D+1)}$, $\alpha_D(i)_{(i=1,2,\cdots,N_D+1)}$ .The optimization problem is characterized as:

$$\begin{aligned} &\min_{N_D, D_D(i), \alpha_D(i), d_D(i), \beta_D(i), i=1,2,\ldots,N_D+1} E_{total}^{D} = \sum_{i=1}^{N_D+1}\left(LG\overline{E}_{b,btp}^{D}(d_D(i))^k + LG\overline{E}_{b,ctp}^{D}\frac{((D_D(i))^k + (D_D^*(i))^k)}{2} + \frac{L(3P_{CT}+2P_{CR})}{R_b} \right) \\ &\textit{Subject to}: N_D \ge 0, N_D \textit{ is a integer} \\ &\quad D_D(i) > 0, i=1,2,\cdots,N_D+1 \\ &\quad 0° \le \beta_D(i) \le 90°, i=1,2,\ldots,N_D+1 \\ &\quad d_D(i) > 0, i=1,2,\cdots,N_D+1 \\ &\quad 0° \le \alpha_D(i) \le 90°, i=1,2,\ldots,N_D+1 \\ &\quad \sum_{i=1}^{N_D+1} D_D(i)\cos(\beta_D(i)) = d_{SD} \end{aligned} \tag{20}$$

Similar to nodes deployment optimization results in the above section, for a given N_D ,if $d_D(i)_{(i=1,2,\cdots,N_D+1)} = T_D D_D(i)$, $T_D = \frac{1}{1+\sqrt[k-1]{\frac{2\bar{E}^D_{b,btp}}{\bar{E}^D_{b,ctp}}}}$, $D_D(i)_{(i=1,2,\cdots,N_D+1)} = \frac{d_{SD}}{N_D+1}$,$\alpha_D(i)_{(i=1,2,\cdots,N_D+1)} = 0°$,$\beta_D(i)_{(i=1,2,\cdots,N_D+1)} = 0°$the local minimal energy consumption can be achieved,which is given by

$$\begin{aligned} E^D_{local} &= E^D_{local,t} + E^D_{local,c} \\ &= GL(N_D+1)(\frac{d_{SD}}{N_D+1})^k\left(\bar{E}^D_{b,btp}T^k_D + \frac{\bar{E}^D_{b,ctp}}{2}\left(1+(1-T_D)^k\right)\right) + \frac{((3N_D+3)P_{CT}+(2N_D+2)P_{CR})L}{R_b} \end{aligned} \tag{21}$$

Similarly ,we can find in formula (21) , $E^D_{local,t}$ is a decreasing function of N_D, $E^D_{local,c}$is a increasing function of N_D. In general, there exists an optimal N_D to further reduce the E^D_{local}.

As $k > 1$,setting $\frac{\partial E^D_{local}}{\partial N_D} = 0$

We have

$$N_{D,opt} = \text{-}\sqrt[k]{\frac{(3P_{CT}+2P_{CR})}{GR_b(k-1)\left(\bar{E}^D_{b,btp}T^k_D + \frac{\bar{E}^D_{b,ctp}}{2}\left(1+(1-T_D)^k\right)\right)d_{SD}{}^k}} - 1 \tag{22}$$

As the $N_{D,opt}$ (the optimal N_D) is a integer, which can be elected as either [$N_{D,opt}$] or [$N_{D,opt}$] +1(defined by the minimum E^D_{local} and [.] represents floor). Then, the optimal RNs deployment and CNs deployment can be obtained.

3.3 Nodes deployment optimization for Multi-hop SISO Transmission

From equations (10)-(11), E^S_{total} is a function of N_S,$D_S(i)_{(i=1,2,\cdots,N_S+1)}$,$\beta_S(i)_{(i=1,2,\cdots,N_S+1)}$.The optimization problem is characterized as:

$$\begin{aligned} &\min_{N_S, D_S(i), \beta_S(i), i=1,2,\ldots,N_S+1} E^S_{total} = \sum_{i=1}^{N_S+1}\left(LG\bar{E}^S_{b,SISO}(d_S(i))^k + \frac{L(P_{CT}+P_{CR})}{R_b}\right) \\ &Subject\ to: N_S \geq 0, N_S\ is\ a\ integer \\ &\quad D_S(i) > 0, i = 1,2,\cdots,N_S+1 \\ &\quad 0° \leq \beta_S(i) \leq 90°, i = 1,2,\ldots,N_S+1 \\ &\quad \sum_{i=1}^{N_S+1} D_S(i)\cos(\beta_S(i)) = d_{SD} \end{aligned} \tag{23}$$

Similarly ,for a given N_S, if $D_S(i)_{(i=1,2,\cdots,N_S+1)} = \frac{d_{SD}}{N_S+1}\ and\ \beta_S(i)_{(i=1,2,\cdots,N_S+1)} = 0°$,the local minimal energy consumption E^S_{local}can be achieved,which is given by

$$\begin{aligned} E^S_{local} &= E^S_{local,t} + E^S_{local,c} \\ &= (N_S+1)LG\bar{E}^S_{b,SISO}(\frac{d_{SD}}{N_S+1})^k + (N_S+1)\frac{L(P_{CT}+P_{CR})}{R_b} \end{aligned} \tag{24}$$

We can find in formula (24) ,$E_{local,t}^{S}$ is a decreasing function of N_S, $E_{local,c}^{S}$ is a increasing function of N_S. In general, there exists an optimal N_S to further reduce the E_{local}^{S}.

As $k>1$,setting $\frac{\partial E_{local}^{S}}{\partial N_S}=0$

We have

$$N_{S,opt}=\sqrt[k]{\frac{(P_{CT}+P_{CR})}{GR_b(k-1)\left(\bar{E}_{b,siso}^{S}\right)d_{SD}{}^{k}}}-1 \tag{25}$$

As the $N_{S,opt}$ (the optimal N_S) is a integer, which can be elected as either $[N_{S,opt}]$ or $[N_{S,opt}]+1$(defined by the minimum E_{local}^{S} and [.] represents floor). Then, the optimal RNs deployment can be obtained.

4. Numerical results

We use Matlab 2013a to do numerical results. The system parameters are shown in **Table 2**.

Table 2. System parameters

$\xi=1(BPSK)$	$\eta=0.35$	$L=100$	$B=1/T_s=10KHz$
$G_tG_r=5dBi$	$f_c=2.5GHz$	$\lambda=0.12m$	$M_l=40dB$
$N_f=10dB$	$N_0/2=-174dBm/Hz$	$\bar{P}_{b,btp}=10^{-3}$	$\bar{P}_{b,ctp}=10^{-3}$
$P_{DAC}=15.4mw$	$P_{mix}=30.3mw$	$P_{fifr}=2.5mw$	$P_{fift}=2.5mw$
$P_{syn}=50mw$	$P_{LNA}=20mw$	$P_{IFA}=3mw$	$P_{ADC}=6.70mw$

Fig. 5 shows the local minimum energy consumption E_{local}^{S},E_{local}^{D},E_{local}^{C} under different the number of RNs N_S, N_D and N_C with d_{SD}=100m,k=4.0,respectively.Transmission and circuit energy consumption are also included. It shows that the optimal N_S, optimal N_D and optimal N_C can be determined to further reduce the local minimum energy consumption for three transmissions.The reason is that the transmission energy consumption decreases with the number of RNs, circuit energy consumption linearly increases with the number of RNs, there exists an optimal number of RNs to minimize total energy consumption. For SISO transmission, the optimal N_S is 9 ,the global minimum energy consumption is 2.7470×10^{-2}J and the corresponding optimal nodes deployment ($N_{S,opt}$, $D_{S,opt}(i)$(i=1,2,…, $N_{S,opt}$ +1), $\beta_{S,opt}(i)$ (i=1,2,…, $N_{S,opt}$+1) are 9,10m,0°, respectively. For DSTBC based CMISO transmission, the optimal N_D is 2 ,the global minimum energy consumption is 2.4769×10^{-2}J and the corresponding optimal nodes deployment ($N_{D,opt}$, $D_{D,opt}(i)$ (i=1,2,…, $N_{D,opt}$+1) ,$\beta_{D,opt}(i)$ (i=1,2,…, $N_{D,opt}$ +1) , $d_{D,opt}(i)$ (i=1,2,…, $N_{D,opt}$+1)) ,$\alpha_{D,opt}(i)$ (i=1,2,…, $N_{D,opt}$ +1) are 2,33.33m, 0°,9.03m, 0°,respectively.For CB based CMISO transmission, the optimal N_S is 2 ,the global minimum energy consumption is 2.0403×10^{-2}J and the corresponding optimal nodes deployment ($N_{C,opt}$, $D_{C,opt}(i)$ (i=1,2,…, $N_{C,opt}$+1) ,$\alpha_{C,opt}$ (i) (i=1,2,…, $N_{C,opt}$+1) , $d_{C,opt}$ (i) (i=1,2,…, $N_{C,opt}$+1) ,$\beta_{C,opt}$ (i) (i=1,2,…, $N_{C,opt}$ +1)) are 2,33.33m, 0°,7.61m, 0°, respectively.

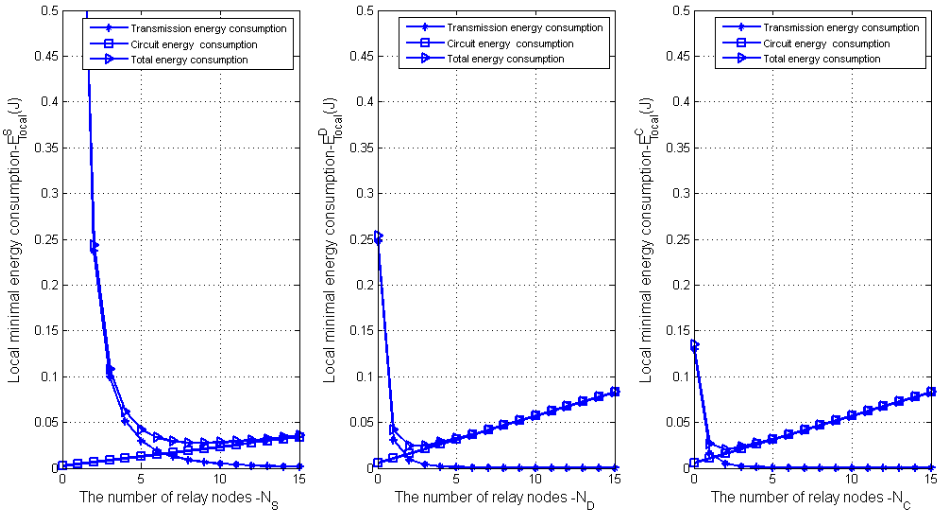

Fig. 5. Local minimal energy consumption over the number of RNs with d_{SD}=100m, k=4.0

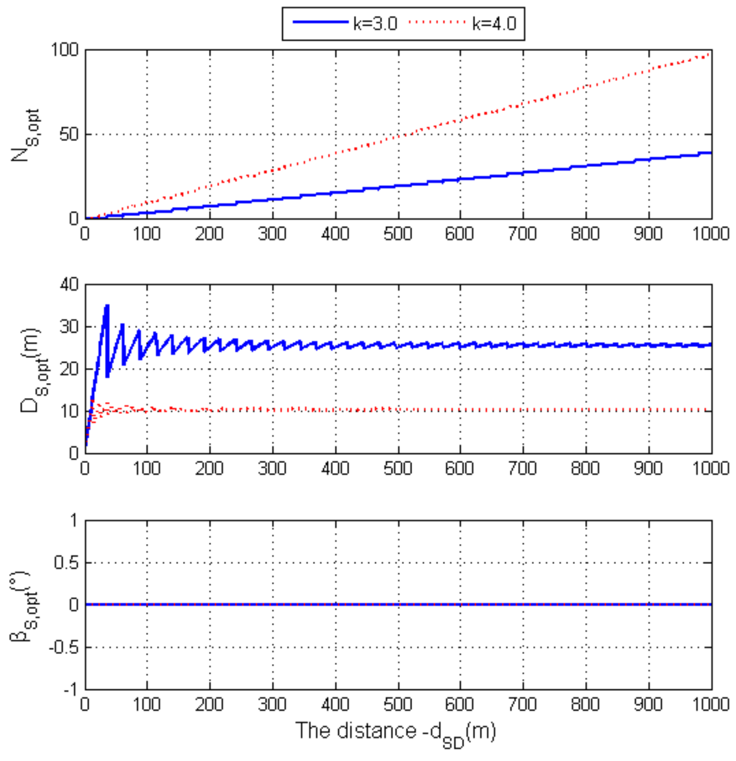

Fig. 6. Optimal nodes deployment parameters for SISO transmission

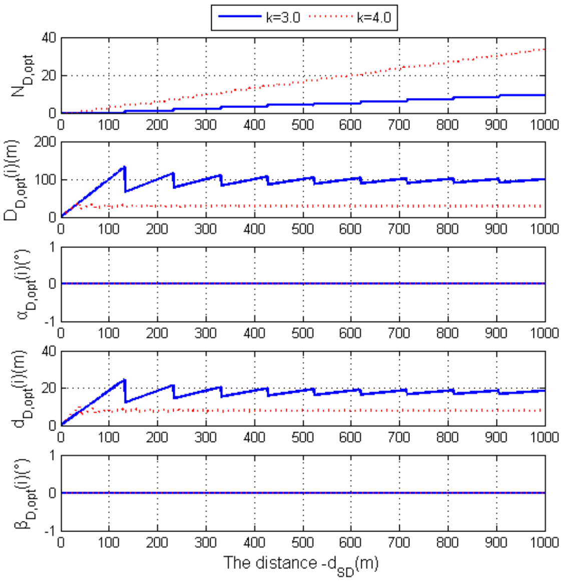

Fig. 7. Optimal nodes deployment parameters for DSTBC based CMISO transmission

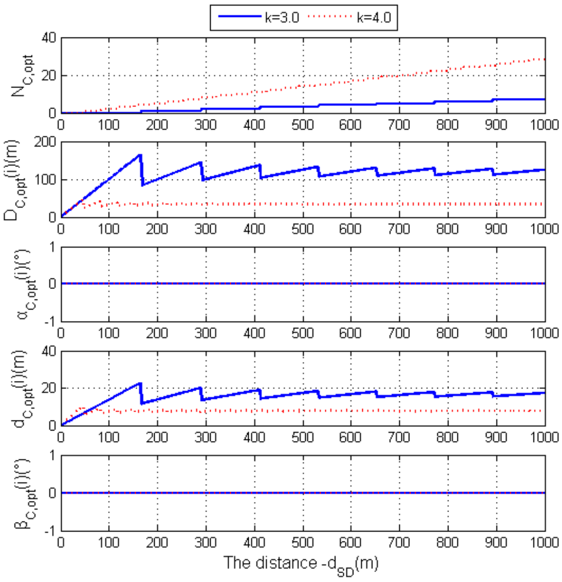

Fig. 8. Optimal nodes deployment parameters for SISO transmission

Fig. 6, Fig. 7 and **Fig. 8** show the optimal nodes deployment for SISO ,DSTBC based CMISO and CB based CMISO transmissions, respectively. The $\beta_{S,opt}(i)$, $\beta_{D,opt}(i)$, $\beta_{C,opt}(i)$, $\alpha_{D,opt}(i)$ and $\alpha_{C,opt}(i)$ are equal to 0°, which means all nodes are optimal deployed on the straight line connecting S and D. Meanwhile ,each component of the $D_{S,opt}(i)$, $D_{D,opt}(i)$, $d_{D,opt}(i)$,$D_{C,opt}(i)$, $d_{C,opt}(i)$ are equal, which means the optimal nodes are homogeneous deployed in each hop for three transmissions.It can be also observed that, a larger $N_{S,opt}$, $N_{D,opt}$, $N_{C,opt}$ are selected for a lager path-loss-factor k.The reason is that, as k increases, the transmission energy consumption sharply increases for both three transmissions, a larger $N_{S,opt}$, $N_{D,opt}$, $N_{C,opt}$ are preferred to reduce deployment hop distance $D_{S,opt}(i)$, $D_{D,opt}(i)$ and $D_{C,opt}(i)$, respectively. It results in a significant reduction in the transmission energy consumption and total transmission energy consumption, in spite of small increases in circuit energy consumption. The same reason can explain that, a larger $N_{S,opt}$, $N_{D,opt}$, $N_{C,opt}$ are selected for a lager d_{SD}.

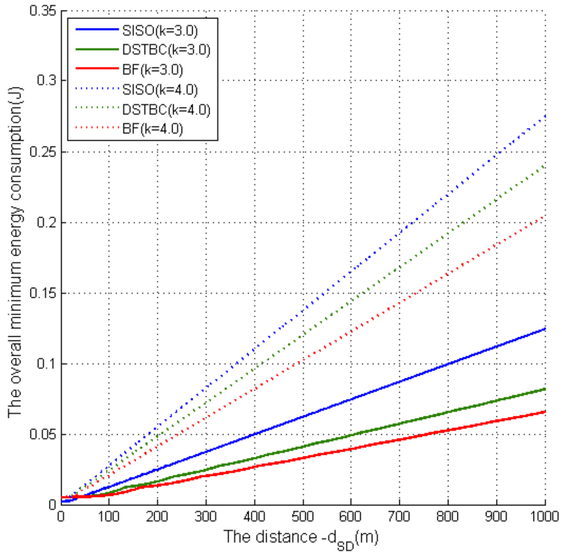

Fig. 9. Global minimal energy consumption for SISO, DSTBC based CMISO and CB based CMISO transmissions

Table 3. Energy efficiency of CB based CMISO transmission vs SISO transmission

Energyefficiency $E_{CB\text{-}SISO}$	d_{SD}=100m	d_{SD}=200m	d_{SD}=500m	d_{SD}=1000m
k=3.0	45.86%	45.86%	47.3%	47.3%
k=4.0	25.73%	25.73%	25.67%	25.67%

Table 4. Energy efficiency of CB based CMISO transmission vs DSTBC based CMISO transmission

Energyefficiency $E_{CB\text{-}DSTBC}$	d_{SD}=100m	d_{SD}=200m	d_{SD}=500m	d_{SD}=1000m
k=3.0	17.59%	17.59%	19.75%	19.75%
k=4.0	17.25%	14.87%	14.89%	14.89%

Fig. 9 shows the global minimum energy consumption E_{opt}^S,E_{opt}^D,E_{opt}^C under optimal nodes deployment. **Table 3** shows energy efficiency of CB based CMISO transmission vs SISO transmission, the energy efficiency is defined as $E_{CB-SISO} = \frac{E_{opt}^S - E_{opt}^C}{E_{opt}^S} \times 100\%$.**Table 4** shows energy efficiency of CB based CMISO transmission vs DSTBC based CMISO transmission, the energy efficiency is defined as $E_{CB-DSTBC} = \frac{E_{opt}^D - E_{opt}^C}{E_{opt}^D} \times 100\%$.It is shown that, for k =3.0, if d_{SD} less than 42.2m and 40.8m, SISO transmission consumes less energy than DSTBC based CMISO and CB based CMISO transmissions,respectively. The reason is that cooperative transmission deploys CN that will cause the extra broadcast and cooperative energy consumption. As d_{SD} increases, transmission energy consumption dominates in total energy consumption, DSTBC based CMISO and CB based CMISO transmissions have higher energy efficiency in comparison with SISO. For d_{SD}=200m, 34.29%,45.86% energy can be saved by using the DSTBC based CMISO and CB based CMISO transmissions in comparison with SISO transmission. However, the superiority of DSTBC based CMISO and CB based

CMISO transmissions over SISO transmission could not be more obvious for a farther d_{SD}.The reason is that, deployment hop distances $D_{S,opt}(i)$, $D_{D,opt}(i)$ and $D_{C,opt}(i)$ do not change with the increase of d_{SD}, energy consumption per hop and energy consumption per unit transmission distance have not changed. It can be clearly seen that CB based CMISO transmission consumes less energy than DSTBC based CMISO transmission.The reason is that $\bar{E}_{b,ctp}^{C}$ is half of $\bar{E}_{b,ctp}^{D}$ .It can be also observed that, as k decreases, energy consumption for the three transmissions are decreases. However, for d_{SD}=200m, as k decreases from 4.0 to 3.0,$E_{CB\text{-}SISO}$ increases from 25.73% to 45.86% by using CB based CMISO transmission in comparison with SISO transmission, $E_{CB\text{-}DSTBC}$ increases from 14.87% to 17.59% by using CB based CMISO transmission in comparison with DSTBC based CMISO transmission . The reason is that, a smaller $N_{S,opt}$, $N_{D,opt}$, $N_{C,opt}$ are preferred to increase deployment hop distance $D_{S,opt}(i)$, $D_{D,opt}(i)$ and $D_{C,opt}(i)$, respectively. As k decreases, $D_{C,opt}(i)$ increases faster than $D_{D,opt}(i)$ and $D_{S,opt}(i)$,transmission energy consumption dominates in total enengy consumption ,which result in more energy efficiency by using CB transmission.

5. Conclusions

In summary, this paper has solved the optimization problem of nodes deployment by using multi-hop CB based CMISO transmission to improve the energy efficiency. In order to reduce the energy consumption,the nodes deployment for multi-hop SISO, multi-hop DSTBC based CMISO, multi-hop CB based CMISO transmissions are optimized.Numerical results show that, under optimal nodes deployment,CB based CMISO transmission can save 45.86% and 17.59% energy than SISO and DSTBC based CMISO transmissions. Simultaneously,as the path-loss-factor becomes low,the superiority can be more obvious. Here, we only consider multi-hop CB based CMISO transmission in this paper, multi-hop CB based CMIMO transmission can be analyzed in our future research.

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