Multi-hop Cooperative XIXO Transmission Scheme for Delay Tolerant Wireless Sensor Networks

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***Abstract*—Delay Tolerant Wireless Sensor Networks (DT-WSN) are sensor networks sparsely populated where connectivity between sensor nodes is intermittent. The energy consumption is critical to the performance of these networks, since nodes have to carry data for a long period of time due to opportunistic transmissions. This work presents a multi-hop cooperative multiple/single input multiple/single output (C-XIXO) transmission scheme for DT-WSN in order to achieve longer communication ranges and consequently reduce the message delivery time to the sink, maximizing the energy efficiency. Simulations results suggest that the proposed scheme provides higher message propagation speed and reduced energy consumption when compared with a state-of-the-art scheme for DT-WSN.**

I. Introduction

Delay Tolerant Wireless Sensor Networks (DT-WSN) are composed by wireless mobile nodes deployed in large areas in order to execute specific sensing applications and forward the collected data to a sink node, which stores and processes the received information [1]. Examples of DT-WSN applications are disaster areas monitoring, biodiversity mapping, military surveillance, health care and precision agriculture.

Due to the intermittent connectivity, sensor nodes must carry data for a long period of time and consequently spend a lot of energy. As nodes are powered by small batteries and replacement/recharging of a node is typically unfeasible [2], it is fundamental to develop energy saving schemes in order to maximize network lifetime. Cooperative multiple input multiple output (C-MIMO) is a technique where single antenna sensors are grouped in clusters to form virtual MIMO devices. This scheme usually extends the communication range of the nodes by exploring MIMO array gain, which reduces the energy consumption of the WSN [3]. Optionally a virtual cluster can communicate with a single node, constituting a multiple input single output (MISO) channel. Similarly, a single node can transmit to another one or to a virtual cluster, with single input single output (SISO) or single input multiple output (SIMO) configurations, respectively. When applied together, these techniques are generally known as XIXO, which stands for multiple/single input multiple/single output.

There is a significant amount of investigations in the field of cooperative MIMO. In [4] the authors explore the usage of the C-MIMO technique to minimize energy consumption used for long range communications in WSN. The use of cooperative MIMO techniques to support communications between static sensors in a sparse WSN is presented in [5]. In [6] it is presented an approach to use C-MIMO techniques for improving energy efficiency in WSN communications. A heterogeneous aware cooperative MIMO scheme is also proposed in [7] to optimize the network lifetime and save energy for WSN.

With respect to DT-WSN, in [1], a buffer management algorithm for estimate the quality of information of packets transmitted in the DT-WSN is proposed. In [8], the authors modeled and analyzed the behavior of the nodes in sparse wireless sensor nodes. The applicability of the bundle protocol for Delay Tolerant WSN through data elevators is shown in [9].

In this paper we propose a C-XIXO communication scheme for data transmission in DT-WSN. Messages can be forwarded by four ways: cooperatively between virtual MIMO clusters, between single nodes (SISO) or between a virtual cluster and a single node (MISO or SIMO). The proposed scheme is compared to the state-of-the art scheme for DT-WSN known as epidemic routing [10] via computational simulations. Simulation results show that the proposed scheme reduces both the message delivery time to the sink and the energy consumption of the network.

The rest of the paper is organized as follows. The multi-hop cooperative XIXO transmission scheme is composed by the C-XIXO transmission model and the energy consumption model, which are shown in Sections II and III, respectively. In Section IV we present the simulation results. Finally, Section V concludes the paper and suggests future works.

Notation: Uppercase and lowercase bold letters denote matrices and vectors, respectively. Lowercase italic letters denote scalars. The transpose is denoted by $\{.\}^\top$.

II. Multi-hop C-XIXO Transmission Model

This section presents the multi-hop cooperative XIXO transmission model. In a SISO configuration, a single node transmits data directly to another one. If the transmitted signal in the jth SISO hop is denoted by $s_t^j \in \mathbb{C}$, the received signal y_r^j at the receiver node can be expressed as

$$y_r^j = h_{r,t}^j s_t^j + n_r^j, \tag{1}$$

where n_r^j is the noise present at the receiver, and $h_{r,t}^j \in \mathbb{C}$ represents the complex impulse response of channel between transmitter and receiver nodes.

A virtual cluster consists of M connected nodes, of which $M-1$ are called *forwarder nodes* and the remaining node is the *cluster head* (CH). We assume that each CH stores the location (xy coordinates) of all nodes of the DT-WSN and synchronization is perfect, which is provided by a real-time location system. Let us consider the jth MIMO hop between transmitter and receiver clusters. The signal transmitted by the transmitter cluster can be expressed as vector $\mathbf{s^j_{m_t}} = [s^j_{1_t} \quad s^j_{2_t} \quad ... \quad s^j_{M_t}]^\top \in \mathbb{C}^{M\times1}$. The received signal at the receiver cluster is given by

$$\mathbf{y^j_{m_r}} = \mathbf{H^j_{m_r,m_t}} \mathbf{s^j_{m_t}} + \mathbf{n^j_{m_r}}, \tag{2}$$

where $\mathbf{H^j_{m_r,m_t}} \in \mathbb{C}^{M\times M}$ is the virtual MIMO channel matrix between clusters, and $\mathbf{n^j_{m_r}} = [n^j_{1_r} \quad n^j_{2_r} \quad ... \quad n^j_{M_r}]^\top \in \mathbb{C}^{M\times1}$ is the additive Gaussian noise vector at the receiver cluster in the jth hop.

Alternatively, a virtual cluster can forward data to a single node, constituting a MISO configuration. Let us consider the jth MISO hop between the transmitter cluster and the receiver node. If the signal transmitted by the cluster is $\mathbf{s^j_{m_t}} = [s^j_{1_t} \quad s^j_{2_t} \quad ... \quad s^j_{M_t}]^\top \in \mathbb{C}^{M\times1}$, the received signal at the single node in the jth hop can be modeled as

$$y^j_r = \mathbf{h^j_{r,m_t}} \mathbf{s^j_{m_t}} + n^j_r, \tag{3}$$

where $\mathbf{h^j_{r,m_t}} \in \mathbb{C}^{1\times M}$ is the MISO channel matrix between the cluster and the node, and $n^j_r \in \mathbb{C}$ is the noise present at the receiver node.

Finally, a cluster can receive data originated by a single node, in a SIMO configuration. Assuming that the signal transmitted by the single node is $s^j_t \in \mathbb{C}$, the received signal at the cluster in the jth SIMO hop is given by

$$\mathbf{y^j_{m_r}} = \mathbf{h^j_{m_r,t}} s^j_t + \mathbf{n^j_{m_r}}, \tag{4}$$

where $\mathbf{h^j_{m_r,t}} \in \mathbb{C}^{M\times1}$ is the SIMO channel matrix between the node and the cluster, and $\mathbf{n^j_{m_r}} = [n^j_{1_r} \quad n^j_{2_r} \quad ... \quad n^j_{M_r}]^\top \in \mathbb{C}^{M\times1}$ is the additive Gaussian noise vector at the receiver cluster in the jth hop.

Figure 1 shows an example of the multi-hop cooperative XIXO transmission scheme. Link 1 represents a SIMO transmission between a single node and the left cluster. Data is forwarded by the left cluster and follows links 2 to 6 until it reaches the destination (sink). Link 2 corresponds to a virtual MIMO channel between the left and the right clusters. Link 3 illustrates a MISO channel between the right cluster and a single node. Links 4 and 5 show two SISO channels between single nodes. Finally, link 6 corresponds to a SISO (or SIMO) channel between a single node and a sink equipped with 1 (or M) antenna(s).

III. Energy Consumption Model for the Proposed Multi-hop C-XIXO Transmission Scheme

We used the model proposed in [11] and [12] to derive the energy consumption model for the proposed multi-hop C-XIXO transmission scheme. Figure 2 illustrates the RF system block for transmitter and receiver. For simplicity, all RF circuit

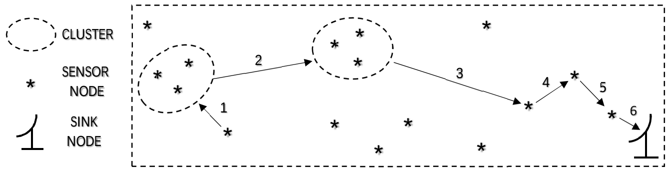

Fig. 1. Example of a multi-hop cooperative XIXO network

blocks inside the dotted rectangles at the top of the figure are represented by transmit/receive electronics blocks.

The circuit powers $P^{\mathrm{tx}}_{\mathrm{ckt}}$ and $P^{\mathrm{rx}}_{\mathrm{ckt}}$ at transmitter and receiver are treated as constants and consist of the power consumptions for all RF circuit blocks presented, respectively, in Figures 2(a) and 2(b), e.g., digital-to-analog and analog-to-digital converters (DAC/ADC), mixers, active filters, frequency synthesizers, low noise amplifier (LNA) and intermediate frequency amplifier (IFA).

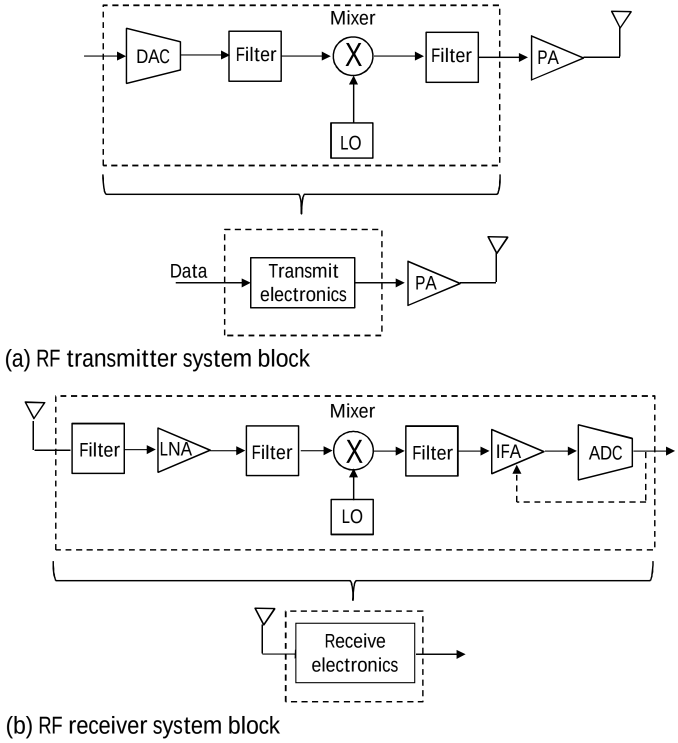

Fig. 2. RF system blocks used in the energy consumption model. (a) transmitter and (b) receiver.

The transmission power of the power amplifier $P^{\mathrm{tx}}_{\mathrm{PA}}$ can be expressed as

$$P^{\mathrm{tx}}_{\mathrm{PA}} = K E_{\mathrm{b}} R_{\mathrm{b}} N_{\mathrm{f}} d^\gamma, \tag{5}$$

where E_{b}, R_{b} and N_{f} are the required mean energy per bit at the receiver for an acceptable bit error rate, the bit rate and the receiver noise figure, respectively. The variables d, γ and K denote, respectively, the distance between transmitter and receiver, the path loss exponent, and a constant which depends on the transmitter/receiver antenna gain, link margin, carrier wavelength, drain efficiency of the power amplifier and peak-to-average ratio of the signal [12].

As described in [12], the energy dissipated by a single node for transmitting and receiving an L_1-bit message are, respectively, $E^{\rm tx} = (L_1/R_b)(P_{\rm PA}^{\rm tx} + P_{\rm ckt}^{\rm tx})$ and $E^{\rm rx} = (L_1/R_{\rm b})P_{\rm ckt}^{\rm rx}$. For all communications between nodes, we consider a Rayleigh fading channel combined with path loss radio propagation model. We assume free space model with γ = 2 for transmissions originated by a single node, i.e., SISO or SIMO configurations. Similarly, γ = 4 is adopted for long distance transmissions, i.e., MISO or MIMO configurations. In each SISO hop, the energy consumed by transmitter and receiver nodes is given by

$$\begin{aligned} E^{\rm siso} &= E^{\rm tx} + E^{\rm rx} \\ &= L_1 \left(\frac{P_{\rm PA}^{\rm tx} + P_{\rm ckt}^{\rm tx}}{R_{\rm b}} + \frac{P_{\rm ckt}^{\rm rx}}{R_{\rm b}} \right) \\ &= \frac{L_1}{R_{\rm b}} (K E_{\rm b} R_{\rm b} N_{\rm f} d^2 + P_{\rm ckt}^{\rm tx} + P_{\rm ckt}^{\rm rx}), \end{aligned} \tag{6}$$

where d is the distance between nodes.

Analogously, the energy consumed by a single node and a cluster with M members in each SIMO or MISO hop can be expressed as

$$\begin{aligned} E^{\rm simo} &= E^{\rm tx} + M E^{\rm rx} \\ &= \frac{L_1}{R_{\rm b}} (K E_{\rm b} R_{\rm b} N_{\rm f} d_{\rm tocl}^2 + P_{\rm ckt}^{\rm tx} + M P_{\rm ckt}^{\rm rx}), \end{aligned} \tag{7}$$

$$\begin{aligned} E^{\rm miso} &= M E^{\rm tx} + E^{\rm rx} \\ &= \frac{L_1}{R_{\rm b}} [M(K E_{\rm b} R_{\rm b} N_{\rm f} d_{\rm tocl}^4 + P_{\rm ckt}^{\rm tx}) + P_{\rm ckt}^{\rm rx})], \end{aligned} \tag{8}$$

where $d_{\rm tocl}$ is the distance from the single node to the cluster.

In a MIMO hop, the energy consumed by two clusters with M members each is given by

$$\begin{aligned} E^{\rm mimo} &= M(E^{\rm tx} + E^{\rm rx}) \\ &= \frac{L_1 M}{R_{\rm b}} (K E_{\rm b} R_{\rm b} N_{\rm f} d_{\rm inter}^4 + P_{\rm ckt}^{\rm tx} + P_{\rm ckt}^{\rm rx}), \end{aligned} \tag{9}$$

where $d_{\rm inter}$ is the intercluster distance.

Additionally, each cluster head dissipates energy receiving location data from the real-time location system (a packet of size L_2 bits) and transmitting the received data to the $M-1$ cluster members. We assume that the cluster head stores the received data from the location system and transmits it to the cluster members only after receiving the L_1-bit information packet. Since the cluster head is close to the cluster members, the energy dissipation for transmission follows a square law, i.e., γ = 2. Therefore, the energy consumption in the cluster head can be expressed as

$$\begin{aligned} E^{\rm CH} &= E^{\rm rx} + (M-1)E^{\rm tx} \\ &= \frac{L_2}{R_{\rm b}} [P_{\rm ckt}^{\rm rx} + (K E_{\rm b} R_{\rm b} N_{\rm f}) \sum_{\rm m=1}^{\rm M-1} d_{\rm m,toCH}^2 + \\ &\quad + (M-1) P_{\rm ckt}^{\rm tx}], \end{aligned} \tag{10}$$

where $d_{\rm m,toCH}$ is the distance between the mth cluster member and the cluster head.

Finally, nodes spend energy in moving. The energy consumed by each node due to movement is given by

$$E^{\rm mov} = l \cdot e^{\rm mov}, \tag{11}$$

where $e^{\rm mov}$ is the energy cost for a node to move one unit distance, and l is the total distance traveled by the single node [13].

Therefore, the total energy consumption in the C-XIXO transmission scheme is given by

$$\begin{aligned} E_{\rm total} = &\sum_{\rm k=1}^{\rm K_1} E_{\rm k}^{\rm siso} + \sum_{\rm k=1}^{\rm K_2} E_{\rm k}^{\rm simo} + \sum_{\rm k=1}^{\rm K_3} E_{\rm k}^{\rm miso} + \\ &+ \sum_{\rm k=1}^{\rm K_4} E_{\rm k}^{\rm mimo} + \sum_{\rm k=1}^{\rm K_3+K_4} E_{\rm k}^{\rm CH} + \sum_{\rm k=1}^{\rm N} E_{\rm k}^{\rm mov}, \end{aligned} \tag{12}$$

where $E_{\rm k}^{\rm siso}$, $E_{\rm k}^{\rm simo}$, $E_{\rm k}^{\rm miso}$, $E_{\rm k}^{\rm mimo}$, $E_{\rm k}^{\rm CH}$ and $E_{\rm k}^{\rm mov}$ are defined from (6) to (11), respectively. The variables K_1, K_2, K_3 and K_4 denote the total number of SISO, SIMO, MISO and MIMO hops, respectively, and N is the total number of nodes. The cluster head transmits location data to the cluster members immediately before all MISO and MIMO communications, i.e., whenever the cluster transmits information.

IV. Simulation Results

In this section, we present the performance of the proposed multi-hop cooperative XIXO scheme through numerical simulations. Bit error rate (BER) and energy consumption of nodes are used to evaluate the efficiency of C-XIXO communications. The MATLAB simulator was employed to simulate the scenarios described next.

15 mobile sensors with known Rayleigh fading channels are displaced in an area of $100 \times 100\ {\rm m}^2$ and they move according to the random waypoint mobility model at speeds between 1.0 and 2.0 m/s. Each node has a transmission range of 15 m and an initial energy of 2.0 J. The source node creates a message of 4000 bits and transmits a copy of that message to a receiver node if the latter did not receive the message before. Each virtual cluster has two sensor nodes. The remaining system parameters are adopted from [12]. The simulation is finished when data is delivered to the sink which is placed at a fixed position of the grid.

Due to node mobility and sparseness of the network, nodes in DT-WSN are intermittently connected, which increases message delivery time and energy consumption. Simple epidemic routing, i.e., flooding is typically applied in delay tolerant networks and wastes network resources, as bandwidth and node energy [10]. Here we compare the performance of our proposed multi-hop cooperative XIXO with the one of the epidemic routing, which is the state-of-the-art scheme for DT-WSN.

We use as metric the BER, which gives the amount of mistaken bits in a transmission. Figure 3 illustrates the results obtained for BER, considering a signal-to-noise ratio (SNR) ranging from -10 to 20 dB. According to Figure 3, multi-hop cooperative XIXO has BER lower than epidemic routing in all SNR range. For a BER of 4×10^{-3}, it is required a SNR of 15 dB for C-XIXO and 17 dB for epidemic case. Also in Figure 3, considering a SNR of 20 dB, it is obtained a BER of 5×10^{-4} for C-XIXO case and 1.5×10^{-3} for epidemic routing. To perform the data delivery to the sink, the epidemic case required 1594 s with 12 multi-hop SISO transmissions, increasing the noise level of the signal and consequently the BER, which provided a further degradation of the transmitted data. On the other hand, the C-XIXO case required 520 s by using four SISO and five 2×2 cooperative MIMO transmissions.

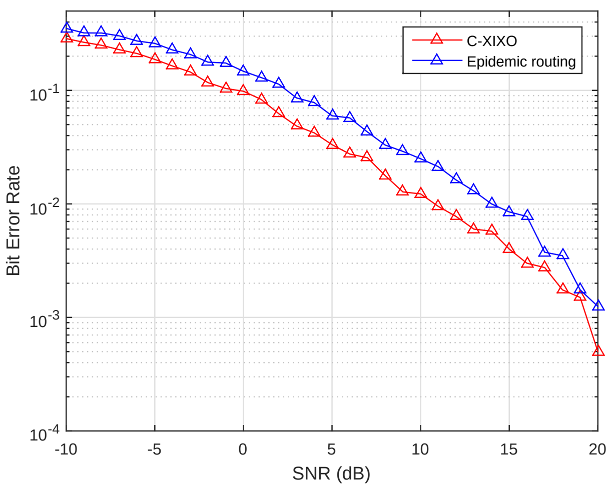

Fig. 3. Bit Error Rate for C-XIXO and epidemic routing.

Figure 4 shows the average residual energy per node for C-XIXO and epidemic cases. Note that, in the epidemic routing, the mean residual energy decreases linearly with time. However, the proposed multi-hop C-XIXO scheme drastically outperforms its state-of-the-art counterpart scheme. The average residual energy per node also presents a linear decreasing, but it shows two significant decays due to the long distance MIMO transmissions, as illustrated by dotted ellipses in the figure. In each MIMO transmission, two nodes transmit and two nodes receive data over long distances following a fourth power law, i.e., $\gamma = 4$, consuming a lot of energy which provided the abrupt drops in the curve. Both drops represent, respectively, three and two cooperative MIMO transmissions.

If we observe only the first 500 s of simulation, most of the time multi-hop cooperative XIXO presents higher energy consumption. However, if we consider the average residual energy per node in each curve at the instants of time where message is delivered to the sink, i.e., 520 s for C-XIXO and 1594 s for epidemic routing, multi-hop C-XIXO presents more energy efficiency than the epidemic routing scheme. The values of mean residual energy of each node for C-XIXO and epidemic cases when sink receives the data are 1.1509 J and 0.0574 J, respectively. Therefore, multi-hop C-XIXO has lower data delivery time which reduces the energy cost of the nodes displacement.

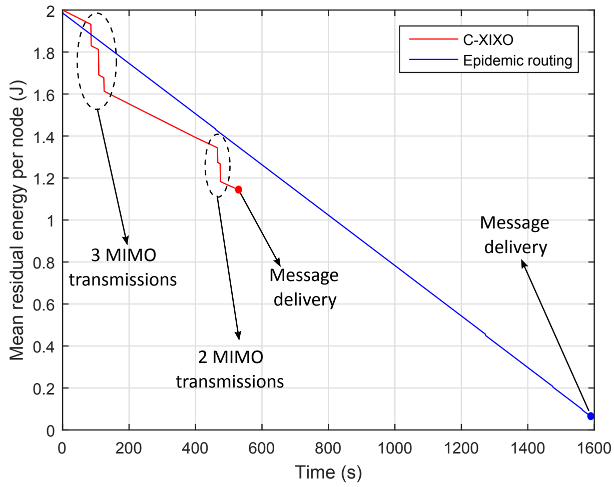

Fig. 4. Mean residual energy per node over time.

V. Conclusion and Future Work

This paper proposes a multi-hop cooperative XIXO transmission scheme for DT-WSN, which achieves longer communication ranges and improve energy consumption. The network performance is measured through bit error rate and mean residual energy per sensor node.

Due to the similarity of application scenarios, we compare the proposed multi-hop C-XIXO scheme with the epidemic routing case through simulations. Results show that the proposed scheme presents higher residual energy per node because data is delivered faster to the sink. According to our simulation results, the proposed multi-hop cooperative XIXO shows lower BER since it has less multi-hop transmissions, which reduces the signal noise level.

Future works include extending the proposed scheme to consider optimum adaptive MIMO selecting for data transmission, as well as to deal with different propagation models, e.g., Rice and Nakagami-m.

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