# Clustering for Cooperative MIMO Cognitive Radio Sensor Networks under Interference Constraints

Amr Y. Elnakeeb, Hany M. Elsayed and Mohamed M. Khairy
Electronics and Electrical Communications Department,
Faculty of Engineering, Cairo University, Egypt
{amr.y.elnakeeb,helsayed,mkhairy}@ieee.org

***Abstract*—CRSN (Cognitive Radio Sensor Networks) have recently gained huge interest as an area of research. Naturally, due to energy limitations in WSN (Wireless Sensor Networks), grouping sensor nodes into clusters has been widely adopted by the research community to overcome the issue of limited energy budget and generally achieve high energy efficiency as well as prolonging network lifetime in large-scale WSN environments. Combining clustering of WSN with MIMO (Multiple Input Multiple Output) is a promising technique used in literature of this research area leading to what is called cooperative MIMO clustered WSN. Compared with existing work, our contributions are: i) Extension of CR (Cognitive Radio) technique to cooperative MIMO clustered WSN in a spectrum sharing sense as well as demonstrating that SISO setting isn't always the best setting for transmission even at small distances. The shift to other settings is more favorable to guarantee not disturbing the primary user while transmitting on the same channel; and ii) Proposing a selection criterion for cooperative MIMO CRSN that chooses the minimum energy setting (SISO/SIMO/MISO/MIMO) to guarantee a proper communication for the secondary CR system under some interference constraint to the primary user as well as satisfying a specific BER requirement for CR secondary system.**

***Index Terms*—CRSN, Clustering, MIMO, sensor network.**

## I. Introduction

The effects of wireless spectrum scarcity will rise as mobile traffic and users increase. Spectrum shortage will result in a bottleneck for many users. To better utilize the spectrum, Joseph Mitolla introduced the concept of CR [1], [2]. CR is considered as a promising technology for efficient spectrum utilization in communication systems to solve such a problem. CR targets maximizing throughput in the secondary network while keeping interference below certain threshold in the PU network. In [3], the authors introduced the fact that CR has two operational modes. The first one is overlay or Opportunistic Spectrum Access (OSA), which enables the communicating secondary users to exploit, in a dynamic manner, the spectrum bands that are not utilized by the primary users licensed to operate over such bands. The other operational mode is underlay or Spectrum Sharing (SS), which enables CR users to communicate at the same time with PUs provided that CR users don't exceed tolerable values for power and interference. Our work is based on the latter operational mode, and for such scenario, the CR usually deals with a tradeoff between maximizing its own throughput and maintaining sufficient thresholds for interference on PU.

Over the past years, WSN have gained attention due to their impact in military and industrial applications. It is well known that such networks are energy limited due to the difficulty of replacing or recharging wireless sensor nodes [4]. One of effective and mostly used solutions to solve energy limitation problem is clustering of sensor networks; that is the network is divided into some portions each having a leader, called the Cluster Head (CH). All nodes within one cluster send their data to their CH and the latter, in turn, aggregates and forwards this data either to the BS (Base Station) directly in one hop or to another CH in a multi-hop basis [5]. The incorporation of CR in WSN was investigated in [6]. Such systems are called CRSN. The authors in [6] discussed this integration and how incorporation of CR capabilities with WSN limitations can be accomplished.

MIMO technology has attracted huge attention in wireless communications track, because it either reduces transmission power required for the same throughput; through spatial diversity or it offers significant increase in throughput without additional increase in transmission power. In WSN, the node is usually limited in size, thus it is infeasible to superimpose multiple antennas in such systems. The solution to this obstacle was investigated in [7]–[9] by allowing nodes to cooperate, and hence a virtual antenna array can be formed to achieve spatial diversity although each node has only one antenna. Such criterion is so called cooperative techniques or cooperative MIMO (CMIMO). In [8], [9], the work is based on how to integrate CMIMO with WSN. This issue has been investigated well and studying which transmission mode that should be used to minimize energy consumption in a multi hop system was subject of these papers. A huge effort has been exerted to study energy efficiency in cooperative communication in WSN [9]–[12]. In [9], energy issues were investigated and authors deduced that cooperative communication reduces total energy consumption even if cooperation overhead is considered. They extended the work in [10] by combining a cross-layer design framework to improve overall energy efficiency and reduce network delay. In addition, the authors in [11] extended the work for fixed and variable rates. The authors in [12] proposed a cooperative transmission scheme based on distributed space-time block coding where sensors that can correctly decode received packets only participate in the cooperative transmission and they used a more realistic analysis; that is they used packet

CROWNCOM 2014, June 02-04, Oulu, Finland

DOI 10.4108/icst.crowncom.2014.255377

error rate rather than symbol error rate.

Combining CR, in a spectrum sharing sense, with CMIMO WSN is the essence of this paper. That is; the CMIMO wireless sensor nodes are considered as the secondary system that shares the same channel with the primary user as long as it doesn't exceed a predefined threshold for interference to the primary user. Demonstrating that SISO setting isn't the best setting for transmission even at small distances is one of the distinctions of our work. Also, we propose a selection criterion for the transmission mode for CMIMO CRSN which satisfies a specific BER for the CR secondary system while not interfering on the PU system and minimizes energy consumption in the secondary network. The rest of this paper is organized as follows. Section II presents background. The integration of CR with CMIMO WSN for single hop system is investigated in Section III, where the system model is presented with its assumptions. Proposed criterion for transmission mode selection and thorough simulation results are given in Section IV. Finally, Section V concludes the paper.

## II. Background

In [9], the total power consumption consists of two components: power consumption of amplifiers $P_{PA}$ which depends on transmission power $P_t$ with the relation

$$P_{PA} = (1+\alpha)P_t \tag{1}$$

where $\alpha = \frac{\xi}{\eta} - 1$ with $\eta$ the drain efficiency of the power amplifier and $\xi$ the peak-to-average power ratio(PAPR), which depends on the modulation scheme and the associated constellation size. Transmission power $P_t$ is given by the link-budget relationship when the channel experiences a square-law path loss

$$P_t = \overline{E_b} \times \frac{R_b (4\pi d)^2}{G_t G_r \lambda^2} M_l N_f \tag{2}$$

where $\overline{E_b}$ is the required energy per bit for a given BER requirement, $R_b$ is the bit rate of the RF system, $d$ is the transmitting distance. $G_t$ and $G_r$ are the antenna gain of the transmitter and the receiver respectively, $\lambda$ is the carrier wavelength, $M_l$ is the link margin compensating the hardware process variations and other additive background noise or interference, $N_f$ is the receiver noise figure defined as $N_f = \frac{N_r}{N_0}$ with $N_0$ the single-sided thermal noise power spectral density (PSD) at room temperature and $N_r$ is the PSD of the total effective noise at the receiver input. The other term, $P_c$, in the total power consumption is the circuit power which is given by

$$\begin{aligned} P_c = {} & M_t(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} \\ & + M_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}) \end{aligned} \tag{3}$$

where $P_{DAC}$, $P_{mix}$, $P_{filt}$, $P_{LNA}$, $P_{IFA}$, $P_{filr}$, $P_{ADC}$, $P_{syn}$ are the power consumption values for the DAC, the mixer, the active filters at the transmitter side, the low-noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the receiver side, the ADC, and the frequency synthesizer, respectively. Finally, this gives the total energy consumption per bit as

$$E_{bt} = \frac{P_{PA} + P_c}{R_b} \tag{4}$$

The authors in [9] demonstrated the fact that MIMO systems are not always as energy efficient as their SISO systems counterpart. They investigated that the opposite will be true for short transmitting distances where the circuit power is dominating in this case. However, they proved that even at small distances, by adjusting constellation size MIMO can be more energy efficient.

WSN and CMIMO technology are discussed in [8]. The authors introduced several transmission modes and the total energy equations for different transmission modes were derived. Proposing framework for cluster-based cooperative MIMO transmission and introducing intra-cluster (communication inside one cluster) and inter-cluster communications (communication among clusters) concepts is investigated too. A comparison between single-hop system and multi-hop one was clearly discussed.

In [13], an energy-efficient clustering algorithm for cooperative MIMO operation in sensor networks is proposed. As such, each cluster has two cluster heads: MCH (Master Cluster Head) and SCH (Slave Cluster Head) which are mainly responsible for inter-cluster communication. MCH and SCH are typically working as one cooperative node. In intra-cluster communication phase, all nodes within this cluster have to send their data to MCH, the latter in turn aggregates the received data from all nodes and forwards it to SCH, if needed. Clustering criteria is based on the remaining energy of the nodes and neighbor proximity. The aim was adjusting transmission mode (SISO/SIMO/MISO/MIMO) as well as adjusting transmission power in a per-packet basis so as to minimize the total energy consumption (transmission plus circuit energies). The authors concluded that a distance-dependent tradeoff exists between circuit and transmission; that is for relatively small distances circuit power dominates and SISO is more favorable. However, as transmission distances increases, transmission power is the dominant factor and the favor shifts to (SIMO/MISO/MIMO).

## III. CR MIMO WSN

Herein, in our system, we extend CR with previous work on CMIMO WSN. With numerical simulations, we thoroughly investigate how this integration controls the selection of transmission mode. We handle underlay scenario where CR can use same resources of PU system as long as it maintains a sufficient protection to it. Moreover, this network is based on clustering. The proposed selection criterion is based on a single hop, where one cluster sends directly to the BS.

The system objective is to adjust transmission mode and clustering criteria (the choice of MCH and SCH) so as not to exceed an interference threshold to the PU as well as satisfying a specific BER value for the CR secondary system. There is an apparent tradeoff between both objectives, however, the former objective has the first priority.

As shown in Fig.1, the WSN interferes with the PU link. This interference is evident by the two channels; M-PU (Master to Primary User) channel and S-PU (Slave to Primary User) channel. It is also assumed that the instantaneous CSI (Channel State Information) for all secondary related channels are known to the SU BS. We assume Rayleigh flat fading channels per packet; that is the channel gains are constant for one packet transmission. Also, the BER for secondary system is calculated on a per-packet basis.

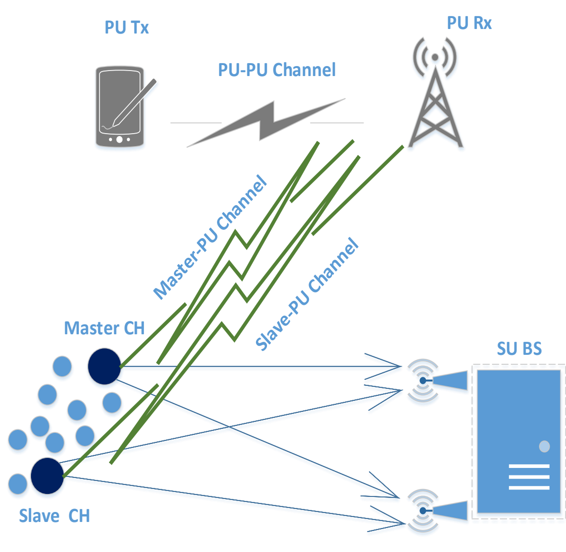


Fig. 1. System Model.

From [9], with BPSK modulation scheme, the instantaneous received SNR ($\gamma_b$) for our secondary system, under the assumption of equally split power among transmitting antennas, is given by

$$\gamma_b = \frac{\overline{E_b} \| H\|_F^2}{M_t N_0} \quad (5)$$

where $\| H\|_F^2$ is the squared Frobenius Norm of the MIMO channel matrix. The instantaneous required BER per-packet is also given by

$$\overline{P_b} = Q(\sqrt{2\gamma_b}) \quad (6)$$

where $Q$ represents the $Q$ function. Hence the instantaneous required BER per-packet will be given by

$$\overline{P_b} = e^{-\gamma_b} \quad (7)$$

substituting from (5) into (7), and rearranging, we can obtain

$$\overline{E_b} = -ln(2\overline{P_b}) \times \frac{M_t N_0}{\| H\|_F^2} \quad (8)$$

From (8), we can get the required energy per bit for a required BER value. Substituting from (8) into (2), we get the transmission power as follows

$$P_t = -ln(2\overline{P_b}) \times \frac{M_t N_0}{\| H\|_F^2} \times \frac{R_b(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f \quad (9)$$

for a fixed rate system and for a given required value for BER, we can assume $C$ as follows

$$C = -ln(2\overline{P_b}) \times \frac{N_0 R_b(4\pi)^2}{G_t G_r \lambda^2} M_l N_f \quad (10)$$

where $C$ is constant that depends on required BER value for the CR system, bit rate, link margin compensating the hardware process variations and other additive background noise or interference, the receiver noise figure, transmitting and receiving antenna gains, and carrier wavelength. Equation (10) can be rewritten as

$$P_t = C \times \frac{d^2 M_t}{\| H\|_F^2} \quad (11)$$

It is clear from (11) that the transmission power of the MIMO secondary link depends on the inter-cluster transmission distance and squared Frobenius Norm of the MIMO channel matrix.

On the other hand, there is a required interference threshold to the PU that should not be exceeded by SU. The interference constraint is given by

$$\frac{P_t}{M_t} \times \sum_{i=1}^{M_t} | h_i|^2 \leq I \quad (12)$$

where $I$ is the maximum allowable interference which PU can bear. The portion $\frac{P_t}{M_t}$ represents the transmitted power per transmit antenna. The portion $\sum_{i=1}^{M_t} | h_i|^2$ represents the summation of the instantaneous interfering channels from SU TX to PU RX which are assumed to be Rayleigh flat fading channels. Substituting from (11) into (12), and rearranging, yields

$$\frac{d^2}{\| H\|_F^2} \times \sum_{i=1}^{M_t} | h_i|^2 \leq \frac{I}{C} \quad (13)$$

According to the predefined threshold for the interference as well as the instantaneous channel gains for transmitting antenna(s) and instantaneous interfering channel gains from SU TX to PU RX, we can choose the most suitable transmission mode (SISO/SIMO/MISO/MIMO) which satisfies the interference constraint.

## IV. Proposed Selection Criterion and Simulation Results

In this Section, we study the possible settings that can satisfy both interference and BER constraints and, after that, we choose the minimum energy setting. The MCH is to be chosen as the node with the highest remaining energy in the cluster. The rationale behind this criterion, as in [13], is to prolong network lifetime as possible because MCHs always do more work than any typical nodes concerning collecting, aggregating and forwarding data. Also, in [13] the choice of SCH was based on neighbor proximity and signal strength between MCH and SCH. However, for our additional interference constraint, the above choice for SCH may be invalid as the chosen node may simply break the interference constraint leading to a dropped packet, and we have to change the selection criterion of the SCH. We choose the SCH as the node which: i) when cooperates with MCH, the link satisfies the required BER for the secondary CR system, ii) when cooperates with MCH, the link doesn't exceed the predefined value of interference threshold to PU, and iii) if more than one node satisfies i) and ii), we choose the node with highest remaining energy with the aim of prolonging network lifetime. The choice above is made for MISO and MIMO settings only, as SISO/SIMO settings don't need a SCH. After the choice of SCH, we choose the minimum energy setting (SISO/SIMO/MISO/MIMO). We run a thorough simulation using the parameters given in Table I, as in [13], to find the appropriate setting for transmission. We first show the effect of the energy consumption versus the distance, without any interference constraints, for SISO and MISO which is shown in Fig. 2. It is clear that if transmission distance exceeds 450 meters, using MISO would be more favorable to SISO as it experiences less total transmission plus circuit power. As concluded in [13], SISO is more favorable for short transmission distances as circuit power dominates. As the distance increases, the shift to use (MISO/SIMO/MIMO) increases.

TABLE I. SIMULATION PARAMETERS

| Parameter | Value |
|---|---|
| $G_t G_r$ | 10 dB |
| $\eta$ | 0.35 |
| $f_c$ | 15 MHz |
| $\overline{p_b}$ | $10^{-3}$ |
| $M_l$ | 10 dB |
| $N_f$ | 10 dB |
| $P_{mix}$ | 30.3 mW |
| $P_{syn}$ | 50 mW |
| $P_{filr} = P_{filt}$ | 2.5 mW |
| $P_{LNA} = P_{IFA}$ | 20 mW |
| $P_{ADC} = P_{DAC}$ | 15 mW |

The trend of using SISO at short distances might not be valid if there is an interference constraint taken into consideration. In the case of CR systems, with relatively small interference thresholds, SISO setting might not satisfy the interference constraint even at small distances. That is because at some values for channel gains, SISO may exceed the value of interference threshold while MISO/SIMO/MIMO satisfy it due to the lower transmission power requirement, even if these systems consume more circuit power.

Our work would consider the required values of BER,

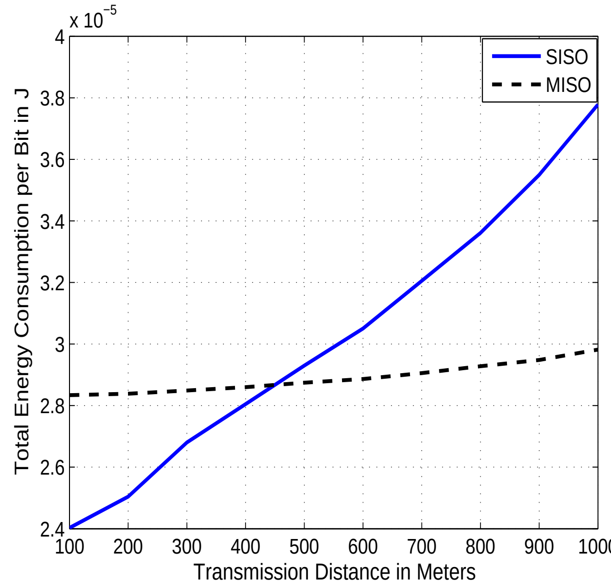


Fig. 2. Transmission distance versus total energy consumption per bit, SISO versus MISO.

interference threshold, inter-cluster communication distance, and circuit parameters and the selection criterion of transmission mode is taken by SU BS and as follows:

i) Choice of MCH and SCH, as discussed above.

ii) Finding all combinations of transmission for all settings (SISO/SIMO/MISO/MIMO) that satisfy the interference constraint.

iii) All possible settings are compared, and the mode with lowest energy consumption is chosen.

This trend is even more evident as the value of interference threshold to the PU gets smaller. In this case, the MISO/SIMO/MIMO will be the only possible choice(s) as the transmission power will be divided between several transmit antennas which will decrease the interference to the PU.

Fig.3 shows the simulation for various values of interference thresholds versus available combinations of each transmission mode (SISO/SIMO/MISO/MIMO) for inter-cluster communication distance of 200 meters and number of wireless sensor nodes in the cluster equals to 6. A 200 meters distance is considered a relatively small distance and it is expected, without including CR system and its interference constraint, that SISO will be the most favorable setting as indicated earlier in Fig.2. For large values of interference thresholds, and according to the traditional belief, SISO will be the most favorable transmission mode as it experiences less energy consumption and it satisfies the interference constraint as well. However, it is clear from Fig. 3 that as the value of interference threshold gets smaller, the SISO setting exceeds the interference threshold and fails to transmit. However, the number of combinations for other settings is still large enough.

In Fig. 4 we show the minimum energy setting for a high interference threshold value (I=1). The trend shown in [9] is

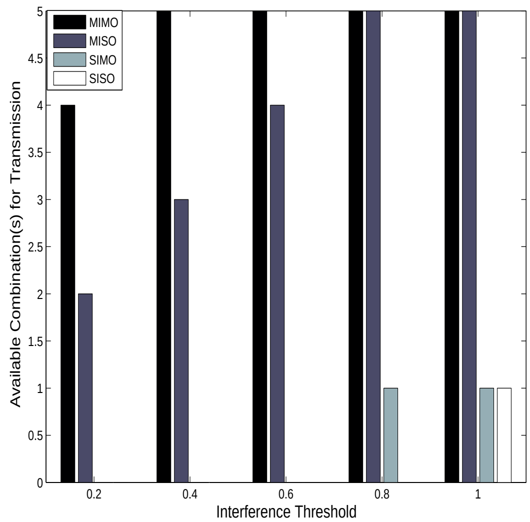


Fig. 3. Available transmission combination(s) for all modes versus interference thresholds.

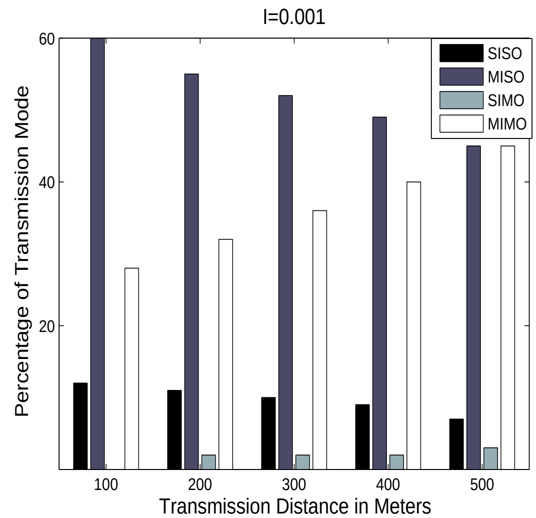


Fig. 5. Percentage of Transmission Mode versus Distance for Interference Threshold =0.001.

followed in this case. However, in Fig. 5, when the threshold was lower (I=0.001), the optimum setting was not SISO which turned out to be a non favorable setting, proving our point that in CR environment, SISO would not be the minimum energy setting for low thresholds.

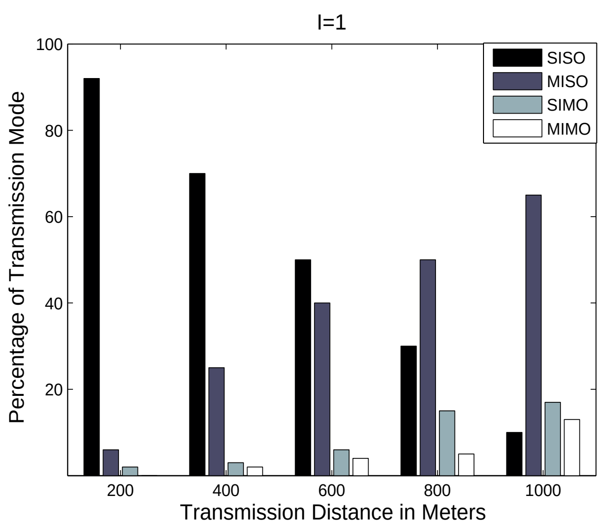


Fig. 4. Percentage of Transmission Mode versus Distance for Interference Threshold =1.

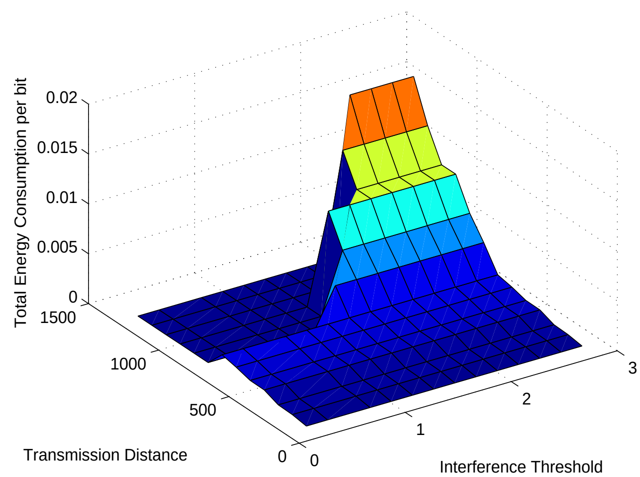


Fig. 6. Total Energy Consumption per bit versus Interference Threshold and Transmission Distance.

Fig. 6 shows a 3D plot of the energy consumption as a function of the interference threshold and transmission distance. For large interference thresholds, the total energy consumption is increasing dramatically with distance as in [8]. When the distance increase further, there will be no mode supporting such transmission and the packet is dropped (energy consumption =0).

By extending CR environment to previous work [13], we make a comparison concerning total energy consumption per bit and throughput. Throughput here is defined as the amount of data packets not dropped (due to exceeding interference threshold). We added interference constraint to the work proposed in [13] and compared both systems. This simulation is run under a tight interference constraint (I=0.001) to clarify the essence of our work. Also, it is assumed that number of packets should be delivered are 10000 packets.

Fig. 7 and Fig. 8 show that our selection criterion results in consuming more energy than that proposed in [13]; that is because in [13], according to MCH and SCH, whenever the link exceeds interference threshold it drops the packet and no energy is consumed at all. However herein, in our work, there is at least one setting (SISO/SIMO/MISO/MIMO) satisfying the interference constraint and less packets are dropped as clear in Fig. 8. Also, it should be noticed that the difference in energy consumption is only at small distances and both criteria roughly approach each other at large distances. That is because in old work, at small distances SISO is the most suitable mode and hence it consumes less energy, however more packets are dropped, but here in our work even at small distances SISO may not be the favorable transmission setting as it may break the interference threshold and the shift to other modes is preferable, however they consume much small power but no packets are dropped. Again as distance increases, with a tight interference constraint, number of dropped packets increases because transmission power dramatically increases with distance and no setting can support the transmission under this tight interference constraint and more packets are dropped.

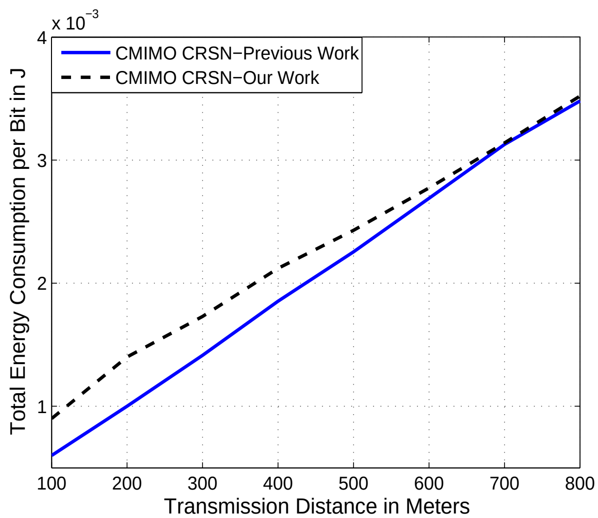


Fig. 7. Total Energy Consumption per bit versus Transmission Distance, Previous Work versus Our Work.

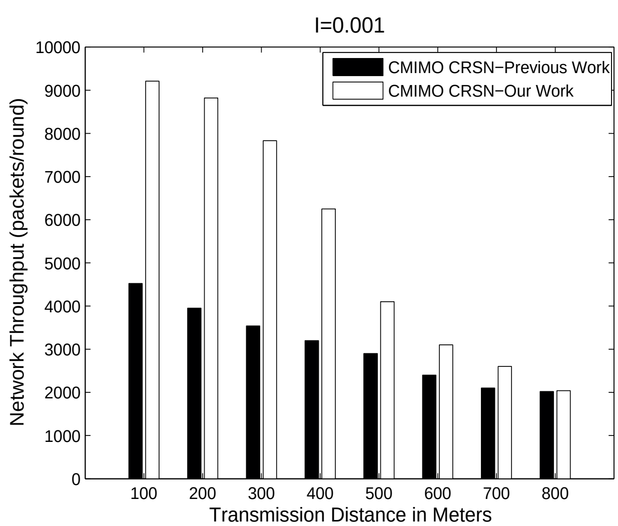


Fig. 8. Network Throughput versus Transmission Distance, Previous Work versus Our Work.

## V. Conclusion

We showed that introducing CR in CMIMO WSN may change the traditional belief that SISO is the most favorable transmission mode for cooperative MIMO WSN especially for short distance communications taking into consideration circuit power. That is because, interference constraints add some limitations on the choice. Simulations proved that SISO setting should be used if transmission distance is relatively small and interference threshold is relatively large. However, as interference threshold decreases, whatever the transmission distance is, the shift to other transmission modes will be the only choice so as not to lose the transmission of the packet. Also, it was investigated how the choice of SCH in clustering phase is important so as to satisfy the interference constraint to the PU as well as minimizing energy consumption in the secondary network.

## Acknowledgment

This publication was made possible by NPRP grant # [5-250-2-087] from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the authors.

## References

[1] J. Mitola and J. Maguire, G.Q., "Cognitive radio: making software radios more personal," *Personal Communications, IEEE*, vol. 6, no. 4, pp. 13–18, 1999.

[2] J. Mitola, *Cognitive Radio — An Integrated Agent Architecture for Software Defined Radio*. DTech thesis, Royal Institute of Technology (KTH), Kista, Sweden, May 2000.

[3] R. Zhang and Y.-C. Liang, "Investigation on multiuser diversity in spectrum sharing based cognitive radio networks," *Communications Letters, IEEE*, vol. 14, no. 2, pp. 133–135, 2010.

[4] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *Communications Magazine, IEEE*, vol. 40, no. 8, pp. 102–114, 2002.

[5] B. Mamalis, D. Gavalas, C. Konstantopoulos, and G. Pantziou, "Clustering in wireless sensor networks," in *RFID and Sensor Networks* (Y. Zhang, L. T. Yang, and J. Chen, eds.), pp. 324–353, CRC Press, 2009.

[6] O. Akan, O. Karli, and O. Ergul, "Cognitive radio sensor networks," *Network, IEEE*, vol. 23, no. 4, pp. 34–40, 2009.

[7] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *Information Theory, IEEE Transactions on*, vol. 50, no. 12, pp. 3062–3080, 2004.

[8] X. Wen, *Distributed MIMO for wireless sensor networks*. PhD thesis, School of Engineering, 2011.

[9] S. Cui, A. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative MIMO techniques in sensor networks," *Selected Areas in Communications, IEEE Journal on*, vol. 22, pp. 1089–1098, Aug 2004.

[10] S. Cui and A. Goldsmith, "Cross-layer optimization of sensor networks based on cooperative MIMO techniques with rate adaptation," in *Signal Processing Advances in Wireless Communications, 2005 IEEE 6th Workshop on*, pp. 960–964, June 2005.

[11] V. Sachan, S. Imam, and M. Beg, "Energy-efficiency of virtual cooperative MIMO techniques in wireless sensor networks," in *Computer Communication and Informatics (ICCCI), 2012 International Conference on*, pp. 1–5, Jan 2012.

[12] Z. Zhou, S. Zhou, S. Cui, and J.-H. Cui, "Energy-efficient cooperative communication in a clustered wireless sensor network," *Vehicular Technology, IEEE Transactions on*, vol. 57, no. 6, pp. 3618–3628, 2008.

[13] M. Siam, M. Krunz, and O. Younis, "Energy-efficient clustering/routing for cooperative MIMO operation in sensor networks," in *IEEE INFOCOM 2009*, pp. 621–629, April 2009.