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A Cooperative MIMO Framework for Wireless Sensor Networks

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We explore the use of cooperative multi-input multi-output (MIMO) communications to prolong the lifetime of a wireless sensor network (WSN). Single-antenna sensor nodes are clustered into virtual antenna arrays that can act as virtual MIMO (VMIMO) nodes. We design a distributed *cooperative clustering protocol* (CCP), which exploits VMIMO's diversity gain by optimally selecting the cooperating nodes (CNs) within each cluster and balancing their energy consumption. The problem of optimal CN selection at the transmit and receive clusters is formulated as a nonlinear binary program. Aiming at minimizing the imbalance in the residual energy at various nodes, we decompose this problem into two sub-problems: finding the optimal number of CNs (ONC) in a cluster and the CN assignment problem. For the ONC problem, we first analyze the energy efficiency of two widely used VMIMO methods: distributed Space Time Block Code (DSTBC) and distributed Vertical-Bell Laboratories-Layered-Space-Time (DVBLAST). Our analysis provides an upper bound on the optimal number of CN nodes, which greatly reduces the computational complexity of the ONC problem. The second sub-problem is addressed by assigning CNs based on the residual battery energy. To make CCP scalable to large WSNs, we propose a multi-hop energy-balanced routing mechanism for clustered WSNs (C-EBR) with a novel cost metric. Finally, we derive sufficient conditions on the intra- and inter-cluster ranges, under which CCP guarantees connectivity of the inter-cluster topology. Extensive simulations show that the proposed approach dramatically improves the network lifetime.

Categories and Subject Descriptors: C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms: Design, Algorithms, Performance

Additional Key Words and Phrases: Cooperative communication, wireless sensor networks, media access control, virtual MIMO, clustering, routing, connectivity.

1. INTRODUCTION

Wireless sensor networks (WSNs) have been successfully used to support various civilian and military applications. These networks are sometimes operated in harsh or adversarial environments, e.g., space missions, oceanic exploration, underground monitoring, battlefields, etc., making it expensive or impossible to replace their batteries. Hence, it is critical to design the network in an energy-efficient manner. This work advocates using cooperative communications to conserve energy by having groups of nodes cooperate in transmitting or receiving data. We specifically address the questions of how, when, and who to cooperate with, so as to prolong the network lifetime.

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Cooperative communications (see [Scaglione et al. 2007] and references therein for an overview) exploit the spatial diversity that arises from transmitting the same signal (or highly correlated versions of it) over several, spatially separated antennas. As such, the theory of cooperative communications is closely related to multi-input multi-output (MIMO) technology. Under a given power budget and fading conditions, MIMO communications offer much higher throughput (spatial multiplexing gain) or more reliable communications (diversity gain) than single input single output (SISO) systems [Salz 1985; Brandenburg and Wyner 1974; Foschini and Gans 1998]. For a conventional MIMO system, space time block codes (STBCs) [Tarokh et al. 1999] can be used to provide diversity gain. To realize the multiplexing gain, the VBLAST technique [Foschini 1996] is often used.

Full exploitation of MIMO gains requires a rich scattering environment with well-spaced cooperating antennas (at least half-wavelength apart) at the transmit and receive sides. This way, the signals emitted from the transmit antennas traverse independent paths before arriving at the receive antennas. The environments in which WSNs operate, both indoor and outdoor (e.g., forests or urban settings) often possess rich scattering.

However, due to size considerations, it may be impractical to mount multiple antennas on a sensor node. To harvest MIMO gains in WSNs, independent paths between the transmit and receive sides can be realized by having spatially separated nodes function as a virtual MIMO node (VMIMO) [Dohler et al. 2002b]. This VMIMO concept has led to the invention of distributed VBLAST (DVBLAST) [Jayaweera 2007] and distributed STBC (DSTBC) [Dohler et al. 2002a; Laneman and Wornell 2003; Cui et al. 2004] coding techniques, as virtual counterparts of conventional VBLAST and STBC. DSTBC differs from the conventional STBC in that the codewords are stored distributedly at various nodes, which jointly encode a message before forwarding it to the next VMIMO node.

WSNs that involve a large number of nodes are often organized into clusters, each with its own cluster head (CH). Clustering provides scalability with regard to communications and processing tasks, facilitating various functions such as data aggregation. It can also be used to support VMIMO communications, whereby a subset of the nodes in each cluster, herein called the *cooperating nodes* (CNs), serves as a virtual transmit (Tx) or receive (Rx) antenna array [Chen et al. 2005][Yuan et al. 2006a][Siam et al. 2009]. Within each cluster, nodes communicate their data to their CH, which itself is one of the CNs. Along with other CNs in the cluster, the CH forwards the data to the sink, either directly or via a multi-hop inter-cluster path. For each inter-cluster link comes the problem of *optimal CN selection* (OCS), which aims at identifying the appropriate CNs in the Tx and Rx clusters so as to minimize the required energy over that link.

Several works considered the problem of optimizing the number of CNs (ONC) in a cluster (e.g., [Yuan et al. 2006a][Cui et al. 2004][Yuan et al. 2006b]). ONC is a less general problem than OCS, because it aims at determining the size rather than the elements of the CN set. There are three limitations to these works. First, in [Cui et al. 2004] the authors relied on the Chernoff bound to approximately compute the per-bit transmission energy (E_b) for STBC in the high SNR regime. Such a regime does not apply to WSNs, whose transmissions are characterized by low SNR and low bit rates. Secondly, the number of candidate nodes from which CNs are to be selected is assumed to be known in [Yuan et al. 2006a][Yuan et al. 2006b]. Thirdly, cooperation overhead has not been accounted for in [Cui et al. 2004][Siam et al. 2009]. Due to the absence of an analytical solution to the ONC problem, the number of CNs in a cluster has often been limited to two [Siam et al. 2009][Gong et al. 2010], or that the set of transmitting or receiving CNs (but not both) contains only one node. This limits the diversity gain to that of a 2×2 system [Siam et al. 2009][Gong et al. 2010] and to a 3×1 system [Yuan et al. 2006a]. Although the treatment in [Siam et al. 2009][Cui et al. 2004] may be extendible to more than two CNs per cluster, we show later that such extension requires solving the OCS problem, which is NP-hard.

We define the "transmission distance between two clusters" as the farthest distance between a transmitting CN and a receiving CN[1]. This distance depends on specific sets of CNs in both clusters (see Figure 1). Previous works overlooked such dependence and assumed that the transmission distance is known and fixed a priori. Moreover, the transmission distance often used in the literature is the average distance between the two clusters [Y. Zhuang and Wu 2009], which has been recently reported to underestimate the energy consumption of a WSN [Yanyan Zhuang and Cai 2010]. In this paper, we do not assume prior knowledge of the transmission distance when dealing with the OCS and ONC problems.

Implicitly, the OCS problem addresses the tradeoffs between diversity gain, multiplexing gain, circuit/transmit energy consumption, and cooperation overhead. Regarding the tradeoff between multiplexing and diversity gains, so far it is still not known whether DSTBC or DVBLAST is preferable for energy minimization (both techniques have been proposed for WSNs). Because nodes are spatially separated, the overhead of coordinating their VMIMO operation (e.g., estimating the transmission distances between the Tx and Rx CNs and solving ONC in real time) may overshadow any potential diversity/multiplexing gain.

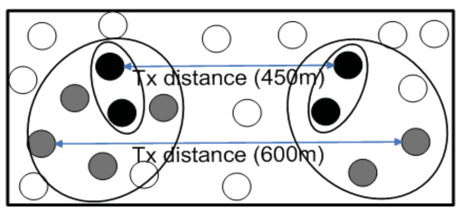

Fig. 1. Dependence of the "transmission distance" on the selected CNs. Transmission distances are 600 and 450 meters for 6x4 VMIMO (grey and black) and 2x2 VMIMO (black only), respectively.

Motivated by the above, we propose a framework for exploiting VMIMO in WSNs. Our main contributions are as follows:

— First, we analytically evaluate the energy efficiency of DSTBC and DVBLAST. We show that long transmission distances[2] favor the use of DSTBC over DVBLAST.
— Given the NP-hardness of the OCS problem, we approximately decompose this problem into two sub-problems: the ONC and CN assignment problems. The two subproblems are solved in a distributed fashion with reasonable overhead. ONC provides the number of CNs in a cluster. Knowing that, the CN assignment problem aims at minimizing the imbalance (variance) in the residual battery energy of nodes within each cluster, by forcing nodes with higher residual energy to act as CNs. For the ONC problem, we obtain an upper bound on the optimal number of CNs in a cluster. This is done offline, before network deployment. The optimal number of CNs is then determined by solving ONC subject to this upper bound.

[1]To achieve VMIMO communications, every CN in the Tx cluster must be able to control its power to reach every CN in the Rx cluster. Hence, CNs in the Tx cluster may transmit using different power levels. However, for simplicity, we assume that all Tx nodes use the same transmission power, whose value is determined by the farthest distance.
[2]Although many WSN applications involve short-range transmissions, some can have relatively long-range transmissions. For example, Zigbee PRO specifications cover transmission ranges of up to 1500 m [ZIG]. JN5139 modules of Jennic have ranges exceeding 4 km [JEN].

— Taking advantage of our analysis, we design a fully distributed cooperative clustering protocol (CCP), which performs both clustering and optimal CN selection in each cluster.
— We then extend CCP to multi-hop WSNs and propose a clustering energy-balanced routing (C-EBR) mechanism with a novel cost metric. C-EBR follows the approach in [Chang and Tassiulas 2004], which attempts to address the traffic implosion problem [Shu and Krunz 2010] (i.e., nodes around the sink tend to deplete their batteries much faster than other nodes). Our routing method can also be applied to other clustering protocols. The effectiveness of C-EBR is demonstrated via simulations, which show that at the time when the first node runs out of energy, the remaining battery level at nodes that can directly reach the sink is within 1% of the initial battery level. This value is in contrast to 48% for the case without C-EBR.
— We derive sufficient conditions on the intra- and inter- cluster transmission ranges such that with a given high probability the inter-cluster topology resulting from CCP is connected. Our conditions are tighter than those of other clustering protocols (e.g., [Younis and Fahmy 2004]), hence enabling higher spatial reuse.

We note that our design primarily targets stationary WSNs, or at best WSNs with limited mobility. Mobility affects the network topology, leading to frequent reclustering. More importantly, a rapid change in the topology can make our optimal cooperative MIMO configuration sub-optimal.

The rest of the paper is organized as follows. Related works are reviewed in Section 2. In Section 3, we formulate the OCS problem and decompose it into two subproblems. In Section 4, we analytically evaluate the energy efficiencies of DSTBC and DVBLAST, and optimize the number of CNs. The C-EBR scheme is proposed in Section 5. In Section 6, we detail the operation of CCP. The properties of CCP are discussed in Section 7. We investigate CCP's performance in Section 8, and compare it with other protocols. Finally, concluding remarks are provided in Section 9.

2. RELATED WORK

Several cooperative MIMO schemes have been suggested to reduce energy consumption in WSNs. The authors in [Cui et al. 2004] analyzed the energy efficiency of a single-hop VMIMO link while accounting for both transmission and circuit energies. They derived the optimal "modulation order" and VMIMO "mode" for a given transmission distance. In [Jayaweera 2006], the authors showed that the energy gain of VMIMO is still achievable even when one takes into account the training sequence overhead and the channel coherence time. Higher energy gain can be achieved by combining VMIMO and data aggregation [Gao et al. 2010]. Multi-hop VMIMO operation under DSTBC was investigated in [Jaafar et al. 2010]. The ONC problem for a multihop virtual MISO (Multi-Input Single-Output) was studied in [Aksu and Ercetin 2008]. Although the above works showed great potential for VMIMO in energy-constrained networks, they have not discussed how to construct the sets of CNs. The OSC problem was visited in [Zhang and Cimini 2008], but only for the MISO case. For the general VMIMO case, the OSC problem has been addressed recently in [Qu et al. 2010] for a single-hop link under transmit power and delay constraints. The cooperation scheme in [Qu et al. 2010] was based on DVBLAST. Our work supplements [Qu et al. 2010] by considering the OSC problem in the context of DSTBC, with a focus on energy efficiency and energy balance among nodes (to prolong the network lifetime). A key limitation of the above works is that clustering and multi-hop routing have not been taken into account.

The application of VMIMO in WSNs is often intertwined with the concept of clustering (see [Younis et al. 2006] for a survey on clustering schemes in WSNs). DCA

[Basagni 1999] is one such popular clustering scheme. At the beginning of the clustering process, nodes are assigned different weights. The status of a node (CH or member) is decided after it hears the decisions of its neighbors with higher weights. Because DCA was originally designed for SISO communications, its energy efficiency is expectedly inferior to CCP. This is confirmed in our simulations in Section 8. HEED is another clustering protocol [Younis and Fahmy 2004]. The key idea behind it is that all nodes have chances to serve as CHs with probabilities proportional to the residual battery lifetime and node degree. HEED aims at balancing energy consumption among nodes, which is also the philosophy behind the LEACH protocol [Heinzelman et al. 2000]. MIMO-LEACH [Yuan et al. 2006a] is the first clustering protocol to exploit VMIMO in WSNs. This protocol uses the same clustering mechanism in [Heinzelman et al. 2000]. However, its design is limited to MISO communications, resulting in unnecessary loss of diversity gain. MC-CMIMO [Gong et al. 2010] is a variant of the CMIMO protocol in [Siam et al. 2009], intended to facilitate VMIMO operation in multi-channel clustered WSNs.

3. PROBLEM FORMULATION

In this section, we first formulate the OCS problem and discuss its computational complexity. Consequently, we approximate it by sequentially solving two sub-problems: the ONC problem and the CN assignment problem.

Consider a WSN with N randomly distributed nodes of density μ. An RF signal experiences both distance-dependent (large scale) attenuation as well as multi-path (small scale) fading. Specifically, the signal power attenuates exponentially with the transmit distance, with an attenuation factor α ranging from 2 to 6. For a given distance, small-scale variations are captured using a Rayleigh distribution. Let R_{intra} be the intra-cluster communications range of a node. This range corresponds to a transmission power P_{intra}. Nodes are assumed to be capable of controlling their transmission power and adjusting the transmission range up to R_{inter}, the inter-cluster transmission range (which corresponds to Tx power P_{inter}). R_{intra} and R_{inter} are input parameters, whose values must be selected to ensure that the clustered network is connected (as analyzed in Section 7). At a given time, let the residual battery energy of a node i be e_i. The residual energy of a chemical battery can be measured using various methods (e.g., [Rong and Pedram 2006]). To facilitate VMIMO operation, we assume a synchronization mechanism is in place. We justify this assumption later in Section 7. Time is divided into slots, where a slot represents the interval between two successive re-clustering instances. In a given time slot, there are three types of nodes in the network: ordinary nodes (ONs), cooperating nodes (CNs), and a CH, which is also a CN. All nodes can sense and transmit data. Each slot starts with a clustering mini-slot, followed by a cooperation mini-slot, and finally multiple transmission slots. CH election and cluster formation are discussed in Section 6. In the cooperation mini-slot, the CH selects several CNs in such a way that the selected CNs can communicate as a VMIMO node with neighboring clusters (whose CHs are within distance R_{inter}) using the minimum possible energy.

Consider a VMIMO link between two neighboring clusters. Suppose that the number of nodes in the Tx and Rx clusters are m_t and m_r, respectively. Define the binary variable $b_t^{(i)}$ as follows: $b_t^{(i)} = 1$ if node i of the Tx cluster is chosen as a CN, and $b_t^{(i)} = 0$ otherwise. The variable $b_r^{(j)}$ is defined similarly for the Rx cluster. Let $\boldsymbol{b}_t \stackrel{\text{def}}{=} (b_t^{(1)}, b_t^{(2)}, \ldots, b_t^{(m_t)})$ and $\boldsymbol{b}_r \stackrel{\text{def}}{=} (b_r^{(1)}, b_r^{(2)}, \ldots, b_r^{(m_r)})$. The OCS problem can be stated as follows:

$$\underset{\{\boldsymbol{b}_t,\boldsymbol{b}_r\}}{\text{minimize}} \left\{E(\boldsymbol{b}_t,\boldsymbol{b}_r)+\left(\frac{PL}{R}+H\right)(M_t+M_r)\right\}$$
$$s.t.\ \ b_t^{(i)} \text{ and } b_r^{(j)} \text{ are } 0 \text{ or } 1 \text{ for } i{=}1,\ldots,m_t \text{ and } j{=}1,\ldots,m_r \tag{1}$$

where $E(\boldsymbol{b}_t,\boldsymbol{b}_r)$ is the per-packet RF energy consumption under DSTBC or DVBLAST, L is the packet size in bits, R is the transmission rate in bps, H is the protocol overhead associated with each CN, P is the circuit power consumption per CN, $M_t \stackrel{\text{def}}{=} \sum_{i=1}^{m_t} b_t^{(i)}$, and $M_r \stackrel{\text{def}}{=} \sum_{j=1}^{m_r} b_r^{(j)}$. Here we use the fact that a node consumes approximately the same amount of circuit energy for transmission and reception [Stemm and Katz 1997][Heinzelman et al. 2000]. Note that in general $E(\boldsymbol{b}_t,\boldsymbol{b}_r)$ not only depends on M_t and M_r, but also on the specific CNs of the Tx and Rx clusters.

We later show that $E(\boldsymbol{b}_t,\boldsymbol{b}_r)$ is nonlinear in the variables $\boldsymbol{b}_t$ and $\boldsymbol{b}_r$. Thus, the problem is a nonlinear binary optimization problem, which in general is NP-hard. Even if we overlook its computational complexity, an optimal solution to the OCS problem (implemented at the MAC layer) may actually accentuate the energy imbalance problem at the routing layer. This is because minimizing energy consumption for inter-cluster VMIMO communications leads to fast depletion of the battery lifetimes for CNs. Moreover, because WSNs are mission oriented, the well-being of individual nodes (e.g., their residual energies) is not as important as the operational lifetime of the network. Hence, to develop a computationally affordable distributed solution that achieves both energy efficiency and energy balance, we decompose (1) into two sub-problems: ONC and CN assignment. Our simulations in Section 8 indicate that although the energy efficiency under this decomposition approach is lower than that of the optimal OCS solution (which we obtain through exhaustive search), the network lifetime achieved by this approximation is significantly higher than that of OCS.

Consider the ONC sub-problem. Let M_t^* and M_r^* denote, respectively, the optimal numbers of CNs in the Tx and Rx clusters at a given transmission distance d. We assume that the same power is used by all CNs in the Tx cluster. In this case $E(\boldsymbol{b}_t,\boldsymbol{b}_r)$ depends only on d, M_t, and M_r, and hence can be written as $E(d,M_t,M_r)$. The values of M_t^* and M_r^* are obtained by solving the following problem:

$$\underset{\{M_t,M_r\}}{\text{minimize}} \left\{E(d,M_t,M_r)+(\frac{PL}{R}+H)(M_t+M_r)\right\}. \tag{2}$$

Note that we do not assume any constraint on the number of CNs or knowledge of the transmission distance. The estimation of d is incorporated in the design of CCP, as explained in Section 6.

Once M_t^* and M_r^* are computed from (2), the CNs are selected in such a way that the variance of the residual battery energy among all cluster nodes is minimized. Specifically, at the Rx cluster, we aim at:

$$
\begin{aligned}
&\underset{\{\boldsymbol{b}_r\}}{\text{minimize}} \ \frac{1}{m_r}\sum_{j=1}^{m_r}\left(e_j - b_r^{(j)}\frac{PL}{R} - \frac{\sum_{k=1}^{m_r} e_k - M_r^*(\frac{PL}{R}+H)}{m_r}\right)^2 \\
&s.t. \quad \sum_{j=1}^{m_r} b_r^{(j)} = M_r^* \\
&\qquad e_j - b_r^{(j)}\frac{PL}{R} \geq 0.
\end{aligned}
\tag{3}
$$

After knowing the set of CNs at the Rx cluster, the CNs at the Tx cluster (vector $\boldsymbol{b}_t$) is found by solving:

$$
\begin{aligned}
&\underset{\{\boldsymbol{b}_t\}}{\text{minimize}} \ \frac{1}{m_t}\sum_{i=1}^{m_t}\left(e_i - b_t^{(i)}\left(\frac{E(\boldsymbol{b}_t,\boldsymbol{b}_r)}{M_t^*} + \frac{PL}{R} + H\right) - \frac{\sum_{k=1}^{m_t} e_j - E(\boldsymbol{b}_t,\boldsymbol{b}_r) - M_t^*\left(\frac{PL}{R}+H\right)}{m_t}\right)^2 \\
&s.t. \quad \sum_{i=1}^{m_t} b_t^{(i)} = M_t^* \\
&\qquad e_i - b_t^{(i)}\left(\frac{E(\boldsymbol{b}_t,\boldsymbol{b}_r)}{M_t^*} + \frac{PL}{R} + H\right) \geq 0.
\end{aligned}
\tag{4}
$$

In (3) and (4), the first and second terms in the objective function represent the residual battery energy for a node j (i) after cooperation (this node may or may not be selected as a CN). The third term is the updated mean of the residual energy of all nodes (in the Rx and Tx clusters) after executing the cooperative transmission. Essentially, the objective functions in (3) and (4) reflect a fairness goal, whereby nodes are selected to reduce the differences in their residual battery energies.

Problems (3) and (4) are addressed in Section 5. Problem (2) is a nonlinear integer programming. To tackle it, we need to get some insight into VMIMO techniques, namely DSTBC and DVBLAST.

4. OPTIMIZING THE NUMBER OF CNS

4.1. Energy Consumption of DSTBC

For DSTBC, data bits are modulated into S symbols with b bits per symbol. These symbols are then mapped into an $M_t \times T$ matrix, whose columns are transmitted sequentially over T channel uses (hence, the code rate is $r{=}S/T$). The number of bits per channel use is bS/T and the transmission rate is $R = BbS/T$, where B is the channel bandwidth in Hz. Following [Shin and Lee 2002], the symbol error rate (SER) for an

$M_t \times M_r$ STBC is:

$$P_s(E_{\text{b-STBC}}) = \frac{2(1-1/\sqrt{M})\phi_\eta(1.5/(M-1))}{\sqrt{\pi}} \frac{\eta(M_tM_r+0.5)}{\eta(M_tM_r+1)} \times {}_2F_1\left\{M_tM_r, 0.5; M_tM_r+1; \frac{1}{1+\bar{\eta}\,1.5/(M-1)}\right\} - \frac{2(1-1/\sqrt{M})^2}{\pi}\frac{\phi_\eta(3/(M-1))}{2M_tM_r+1}\times F_1\left\{1,M_tM_r,1;M_tM_r+1.5;\frac{1+\bar{\eta}\,1.5/(M-1)}{1+\bar{\eta}\,3/(M-1)},\frac{1}{2}\right\} \quad (5)$$

where

$E_{\text{b-STBC}} = \frac{E_s}{b}$ $\equiv$ Energy per bit at the receiver of STBC

$\zeta \stackrel{\text{def}}{=} \|\hbar\|_F^2$ $\equiv$ Frobenius norm of the channel matrix $\hbar$

$\eta = \zeta\frac{E_s}{M_tRN_o}$ $\equiv$ Instantaneous symbol-to-noise energy ratio

$\bar{\eta} = \frac{E_s}{M_trN_o}$ $\equiv$ Average symbol-to-noise energy ratio

$M = 2^b$ $\equiv$ Modulation order

$\phi_\eta(s) \stackrel{\text{def}}{=} \text{MGF}(\eta) = E[e^{s\eta}] = (1+s\,\bar{\eta})^{-M_tM_r}$

and ${}_2F_1$ and F_1 are, respectively, hypergeometric functions with one and two variables [Bailey 1935][Abramowitz and Stegun 1972].

If Gray mapping is used to map bit patterns into modulation constellations, then the BER can be determined from the SER as follows:

$$P_b(E_{\text{b-STBC}}) = \frac{P_s(E_{\text{b-STBC}})}{\log_2(M)}. \quad (6)$$

For a given target BER, $E_{\text{b-STBC}}$ is obtained by inverting (6).

The transmission energy to send L bits at distance d is given by:

$$E_{\text{Tx-STBC}} = \psi E_{\text{b-STBC}} L d^\alpha \quad (7)$$

where ψ depends on system parameters (e.g., operating frequency, Tx/Rx antenna gains, etc.). It is worth noting that $E_{\text{b-STBC}}$ that is obtained by inverting (6) is exact. It is a nonlinear function in $\boldsymbol{b}_t$ and $\boldsymbol{b}_r$ due to their coupling in the product M_tM_r in (5). In the literature, Chernoff bound [Chernoff 1952] has been used to approximately compute $E_{\text{b-STBC}}$ under the assumption that the system operates in the high SNR regime. As explained before, such an approximation is not practical in WSNs.

The time duration needed to send L bits is $T_{\text{on}}=\frac{L}{R}$. Thus, the circuit energy consumption under DSTBC, denoted by $E_{\text{C-STBC}}$, is P_cT_{on}, where the total circuit power P_c is

$$P_c = (M_t + M_r)P. \quad (8)$$

Accordingly, the total energy consumption (RF transmission plus circuit) to send L bits under the DSTBC scheme is:

$$E_{\text{DSTBC}}(d, M_t, M_r) = E_{\text{Tx-STBC}} + E_{\text{C-STBC}} = \psi E_{\text{b-STBC}} L d^\alpha + \frac{P_cL}{R}. \quad (9)$$

Notice that E_{DSTBC} is a function of the number of CNs at both the Tx and Rx ends. In Section 4.3, we use (9) to solve the ONC problem. Before going further, we take a detour to justify the use of DSTBC instead of DVBLAST for VMIMO communications in WSNs.

4.2. DVBLAST Versus DSTBC

Both DVBLAST and DSTBC can be used to conserve energy in WSNs [Jayaweera 2007; Cui et al. 2004]. In this section, we compare the energy efficiency of the two schemes. At the maximum possible diversity gain of $M_t M_r$, DSTBC requires less E_b than DVBLAST. However, for multiplexing gain, DVBLAST can offer a significantly higher transmission rate (ideally, M_t folds). The transmission time is roughly $1/M_t$ that of DSTBC, allowing DVBLAST to save energy.

The energy per bit for VBLAST, denoted by $E_{\text{b-VBLAST}}$, was derived in [Jayaweera 2007], where M-QAM was used between the M_t and M_r CNs. It can be obtained by solving the following equation for a given BER:

$$P_b(E_{\text{b-VBLAST}}) \approx [1 - \prod_{t=1}^{M_t} (1 - \wp(t))] \left(\frac{1}{8} + \frac{1}{bM_t}\right) \tag{10}$$

where

$$\wp(t) \stackrel{\text{def}}{=} 4\left(1 - \frac{1}{\sqrt{M}}\right)\left(\frac{1-\eta_t}{2}\right)^{M_r - M_t + t} \times \sum_{j=1}^{M_r - M_t + t - 1} \binom{M_r - M_t + t - 1 + j}{j} \left(\frac{1-\eta_t}{2}\right)^j$$

$$\eta_t \stackrel{\text{def}}{=} \frac{3bE_{\text{b-VBLAST}}}{3bE_{\text{b-VBLAST}} + 2(M-1)N_0}.$$

Similar to (7), the transmission energy to send L bits via VBLAST ($E_{\text{Tx-VBLAST}}$) is $\psi E_{\text{b-VBLAST}} L d^\alpha$. The circuit energy for DVBLAST is:

$$E_{\text{C-VBLAST}} = \frac{P_c}{R_{\text{b-VBLAST}}} L \tag{11}$$

where P_c is the same as in (8) and $R_{\text{b-VBLAST}}$ is the transmission rate under VBLAST. Ideally, $R_{\text{b-VBLAST}}$ is M_t[3] times greater than that of STBC, so $E_{\text{C-VBLAST}}$ is M_t times less than $E_{\text{C-STBC}}$. Thus, the total required energy to send L bits under DVBLAST is

$$\begin{aligned} E_{\text{DVBLAST}}(d, M_t, M_r) &= E_{\text{Tx-VBLAST}} + E_{\text{C-VBLAST}} \\ &= \psi E_{\text{b-VBLAST}} L d^\alpha + \frac{P_c L}{R M_t}. \end{aligned} \tag{12}$$

In Figure 2, we compare (9) and (12) when BER$=10^{-4}$. We use the parameters in Table I, where λ is the operating wavelength, τ is the efficiency of the RF power amplifier [Cui et al. 2004], $\alpha = 4$, and $G_t G_r$ is the total antenna gain. We observe that DSTBC is more energy-efficient than DVBLAST for $d \geq 25$ meters. Hence, the reduction in the transmission time (consequently, circuit energy consumption) in DVBLAST cannot compensate for the higher energy needed to send data at a higher rate. DSTBC outperforms DVBLAST as it maximizes the diversity gain, therefore requiring signifi-

[3]Strictly speaking, the transmission rate of VBLAST is $\min(M_t, M_r)$ times that of DSTBC

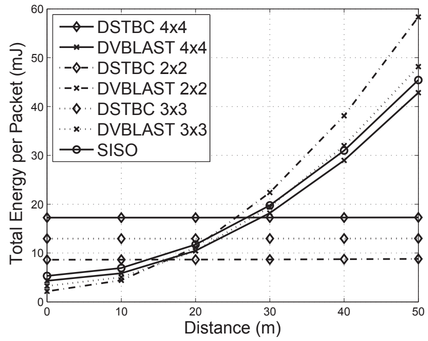

Fig. 2. Energy efficiency of DVBLAST and DSTBC vs. distance for different antenna configurations.

Table I. Parameter values used in the simulations

Transmission rate	400 Kbps
Operating frequency	$f_c = 2.5$ GHz
P	105 mW
ψ	$(1+\tau)\frac{(4\pi)^2}{G_t G_r \lambda^2}$
M	4 (4-QAM)
$G_t G_r$	5 dBi
τ	0.45658
L	2000 Bytes
H	$160 \times 3 \times E_b = 480\ E_b$
R_{intra}	180 m
μ	6.10^{-4}

cantly lower energy, though the transmission duration is M_t times longer than that of DVBLAST.

4.3. Optimal Number of Cooperating Nodes

Previous works (e.g., [Cui et al. 2004]) showed that for long-haul transmissions, more CNs are needed, as the transmission power dominates the total power consumption. On the other hand, shorter distances favor less CNs or even a SISO transmission, as circuit power becomes dominant. For a given transmission distance between two sets of CNs, we seek to find the pair (M_t^*, M_r^*) that gives the lowest total energy consumption. This optimal (M_t^*, M_r^*) is the solution of (2), a nonlinear integer programming problem. It can be solved by the branch-and-bound method, with exponential complexity in the worst case. Here, we use the method of strong inequalities [Bertsimas and Weismantel 2005], which first requires determining upper bounds on M_t^* and M_r^*. These bounds are found offline and are embedded into CCP as design parameters.

Consider (2) at the maximum possible transmission distance $d = R_{\text{inter}}$. The optimization problem can be stated as:

$$\underset{\{M_t, M_r\}}{\text{minimize}} \left\{ E_{\text{Tx-STBC}}(R_{\text{inter}}, M_t, M_r) + (M_t + M_r)(\frac{PL}{R} + H) \right\}. \quad (13)$$

The variables M_t and M_r are upper-bounded by the number of nodes in a cluster of radius R_{intra}, which depends on the node density μ. Note that the problem can be solved offline, once before deploying the network. Thus, its complexity is not of great concern. The solution to (13), denoted by (M_t^+, M_r^+), is the best tradeoff between transmission energy and circuit energy plus cooperation overhead at distance R_{inter}. Let $U \stackrel{\text{def}}{=} \max(M_t^+, M_r^+)$ and let $u \stackrel{\text{def}}{=} \min(M_t^+, M_r^+)$.

THEOREM 4.1. *For a given transmission distance d, $d \leq R_{inter}$, and given system parameters (e.g., transmission rate, modulation order, etc.), there is no energy benefit to have more than U CNs at either the Tx or Rx side in Problem* (2).

Proof (by contradiction): Assume that for a given $d < R_{\text{inter}}$, (M_{t1}, M_{r1}) is the optimal solution to (2). Suppose that M_{t1} (and/or M_{r1}) is greater than U.

Case 1*:* $M_{t1} + M_{r1} \geq U + u$.

Assume that (M_{t1}, M_{r1}) is the optimal VMIMO configuration at distance d. Then, $E_{\text{DSTBC}}(d, M_{t1}, M_{r1})$ should be smaller than any other VMIMO configuration. In other words:

$$E_{\text{DSTBC}}(d, M_{t1}, M_{r1}) = \psi E_{\text{b-STBC}}^{(M_{t1}, M_{r1})} L d^{\alpha} + (M_{t1} + M_{r1})(\frac{PL}{R} + H)$$
$$\leq \psi E_{\text{b-STBC}}^{(u,U)} L d^{\alpha} + (U + u)(\frac{PL}{R} + H).$$

Hence,

$$E_{\text{b-STBC}}^{(u,U)} - E_{\text{b-STBC}}^{(M_{t1}, M_{r1})} \geq \frac{\Theta}{\psi L d^{\alpha}} \tag{14}$$

where

$$\Theta \stackrel{\text{def}}{=} (M_{t1} + M_{r1} - U - u)(\frac{PL}{R} + H).$$

Note that $\Theta \geq 0$ since we assumed that $M_{t1} + M_{r1} \geq U + u$ for Case 1.

Now, at $d = R_{\text{inter}}$, assume (u, U) is the optimal VMIMO configuration. Then:

$$E_{\text{DSTBC}}(R_{\text{inter}}, u, U) = \psi E_{\text{b-STBC}}^{(u,U)} L R_{\text{inter}}^{\alpha} + (U + u)(\frac{PL}{R} + H)$$
$$\leq \psi E_{\text{b-STBC}}^{(M_{t1}, M_{r1})} L R_{\text{inter}}^{\alpha} + (M_{t1} + M_{r1})(\frac{PL}{R} + H).$$

Accordingly,

$$E_{\text{b-STBC}}^{(u,U)} - E_{\text{b-STBC}}^{(M_{t1}, M_{r1})} \leq \frac{\Theta}{\psi L R_{\text{inter}}^{\alpha}}. \tag{15}$$

Inequality (15) contradicts (14), as $R_{\text{inter}} > d$ and $\Theta \geq 0$.

Case 2*:* $M_{t1} + M_{r1} < U + u$.

If the $E_{\text{b-STBC}}$ requirement under (M_{t1}, M_{r1}) is lower than or equal to that under (u, U) (or (U, u)), then (M_{t1}, M_{r1}) must be the optimal combination at $d = R_{\text{inter}}$, leading to a contradiction (as (U, u) or (u, U) is the optimal solution at transmission distance R_{inter}).

Suppose that the $E_{\text{b-STBC}}$ requirement under (M_{t1},M_{r1}) is higher than that under (U, u) or (u, U). Let $K \stackrel{\text{def}}{=} M_{t1} + M_{r1}$ and $m \stackrel{\text{def}}{=} \lceil \frac{K}{2} \rceil$. If K is even, $K = 2m$. If K is odd, $K = 2m - 1$. Clearly, $m \leq U$ and $m^2 \geq M_{t1} M_{r1}$ if K is even, and $m(m - 1) \geq M_{t1} M_{r1}$ if K is odd (Cauchy's inequality). We show a contradiction by proving that an (m,m)- or an (($m-1$),m)-DSTBC configuration conserves more energy than an (M_{t1},M_{r1})-DSTBC configuration. For $2m = K$, (m,m) and (M_{t1},M_{r1}) DSTBC consume the same amount of circuit and overhead energy. However, (m, m) DSTBC offers higher diversity gain than (M_{t1}, M_{r1})-DSTBC (m^2 gain compared with $M_{t1} M_{r1}$ gain). Then, the (m, m) combina-

tion is more energy efficient than the (M_{t1}, M_{r1}) combination. Similarly, if $2m = K+1$, $((m-1)$,$m)$-DSTBC is more energy efficient than an (M_{t1}, M_{r1}) configuration. This leads to a contradiction (as (M_{t1}, M_{r1}) is the optimal configuration at transmission distance d). This completes the proof.
□

Using the parameters in Table I, Figure 3 depicts the total energy per packet for different DSTBC configurations versus d. At the transmission range $R_{\text{inter}} = 380$ meters, the optimal number of CNs is bounded by 5. This bound is 7 at $R_{\text{inter}} = 580$ meters and 8 at $R_{\text{inter}} = 720$ meters.

Accordingly, the ONC problem has the same solution as the following problem:

$$\begin{aligned} &\underset{\{M_t, M_r\}}{\text{minimize}} \left\{ E_{\text{Tx-STBC}}(d, M_t, M_r) + (M_t + M_r)(\frac{PL}{R} + H) \right\} \\ &s.t. \;\; M_t \leq U \\ &\qquad M_r \leq U. \end{aligned} \tag{16}$$

Although the complexity of the ONC problem depends on node density and the intra-cluster range, the size of (16) is independent of these parameters, and is determined by U. The optimal pair (M_t^*,M_r^*) is found by inspecting all U^2 possible combinations.

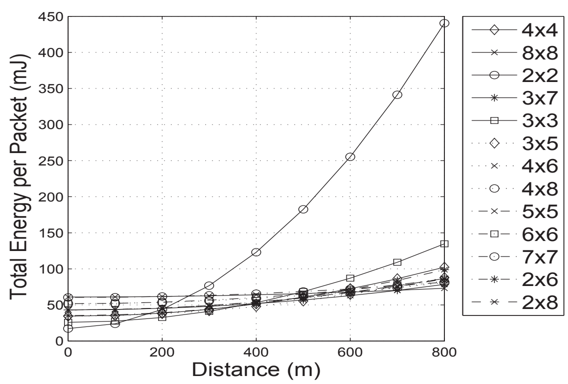

Fig. 3. Energy per packet vs. distance for DSTBC under different (M_t,M_r) combinations.

The solution space of (16) is reasonably small (e.g., 25, 49, 64 for the above R_{inter} values) to be embedded on every sensor. Using the parameters in Table I, with probability of 0.998 there are at most 89 nodes per cluster. Therefore, if we do not exploit the upper bounds, in the worst case a sensor node would have to examine 7921 possible combinations to solve problem (2).

4.4. CN Assignment Problem

In this section, we achieve energy balancing within each cluster by solving problems (3) and (4). Consider problem (3). The first two terms inside the parenthesis of the objective function represent the residual energy of the jth sensor after cooperation. The third term is the average residual energy of all sensors in the receiving cluster. This term does not depend on how CNs are selected, because it does not depend on the transmission distance. Hence, to minimize the variance of the residual energy after cooperation, we assign the CN role to sensor nodes with higher residual energies.

The following procedure solves (3) with complexity of $O(m_r \log m_r)$:

(1) Sort the m_r nodes of the Rx cluster in a descending order of their residual energy.

(2) Pick the top M_r^* nodes in the list as CNs for the Rx cluster.

Even after identifying the set of CNs at the Rx cluster, (4) is still a nonlinear binary programming problem. A heuristic solution to it can also be obtained using the same procedure above.

In the VMIMO design in [Siam et al. 2009], two CNs per cluster are used: the CH and a node that has the highest number of common neighbors with that CH. In [Chen et al. 2005][Yuan et al. 2006a], CNs are selected based on the ratio of their residual energies and their distances to the CH. Our CN assignment approach yields better energy balancing and improves network lifetime by 80%.

For given numbers of CNs at the Tx and Rx clusters, the sets of CNs and their corresponding energy consumption can be determined using the CN assignment mechanism. By inspecting U^2 possible (M_t^*,M_r^*) pairs, we find the "optimal" CNs for both the Tx and Rx clusters with computational complexity of $O(m_r \log m_r + m_t \log m_t + U^2)$. The above process is motivated by the antenna selection technique in MIMO communications [Qu et al. 2010][Narasimhan 2003], where an optimal subset of antennas is selected at each user to maximize the system throughput.

5. ENERGY-BALANCED ROUTING IN CLUSTERED WSNS

In this section, we propose a distributed energy-balanced routing (EBR) mechanism for clustered WSNs. At given intra-cluster range and node density, the intra-cluster traffic is almost the same for all clusters. However, the closer a cluster is to the sink, the more inter-cluster traffic it must relay, leading to faster energy drainage of its CNs. This phenomenon is known as *traffic implosion* [Shu and Krunz 2010]. In [Shu and Krunz 2010], the authors proposed to balance power consumption of CHs by balancing inter- and intra-cluster traffic. Specifically, CHs that lie on more popular routes to the sink were designed to have smaller cluster sizes, i.e, carry less intra-cluster traffic, and vice versa. However, this method does not apply to our setup for three reasons. First, it does not consider node cooperation, as there is only one node, the CH, that is responsible for inter-cluster communications. Second, the authors in [Shu and Krunz 2010] treat CHs and ordinary nodes as two different types, whereas in our clustering approach, any node can be a CH or a CN. Third, the approach in [Shu and Krunz 2010] was intended for network planning under centralized control.

In their pioneering work, Chang and Tassiulas [Chang and Tassiulas 2004] formulated the basic EBR problem as a linear programming problem, with the goal of maximizing network lifetime. A heuristic algorithm called Maximum Residual Energy Path Routing (MREP) was proposed, which achieves 96% of the optimal performance. MREP routes packets along the path that has the maximum remaining energy. In the context of clustered WSNs, in addition to the per-bit energy consumption along the inter-cluster virtual MIMO link, we propose to incorporate into the routing metric the minimum residual energy (e_v) of all CNs in the Rx cluster v. Specifically, for two neighboring clusters u and v, we assign the weight $w(u,v)$ to their inter-cluster link:

$$w(u,v) \stackrel{\text{def}}{=} \beta \frac{c(u,v)}{c^{\max}(u,v)} + (1-\beta)\frac{e_0 - e_v}{e_0 - e_v^{\min}} \tag{17}$$

where $c(u,v)$ is the per-bit energy consumption for a VMIMO transmission from cluster u to v, $c^{\max}(u,v)$ is the maximum of all $c(u,v)$ values, e_0 is the initial battery level, $e_v^{\min}$ is the minimum of all e_v values, and β is a tradeoff factor between energy-efficient routing and EBR, $0 < \beta < 1$. If $\beta = 1$, a shortest-path algorithm that uses the above cost metric would return the minimum-energy VMIMO path to the sink. On the other hand, if $\beta = 0$, the algorithm reduces to *pure* EBR, which favors the path whose CNs' minimum residual energy is the maximum among all paths. We refer to the routing strategy that uses the metric w as clustering-EBR (C-EBR). Implementing of C-EBR does not require establishing a lexicographical ordering of possible paths, as in [Chang and Tassiulas 2004]. In fact, its complexity is equal to that of the distributed Bellman Ford algorithm. In the next section, we provide the operational details of CCP, which incorporates C-EBR and the OCS algorithms.

6. COOPERATIVE AND CLUSTERING PROTOCOL (CCP)

CCP consists of three phases: clustering/re-clustering, cooperation, and transmission. The first two phases are executed less frequently than the last one. These two phases are required only when the network is deployed, or if a cluster reaches its re-clustering threshold (a threshold on the residual energy of a CN). In the clustering phase, each node learns about its neighbors and their residual energies. The network is then partitioned into clusters, each having one CH, at most $U-1$ other CNs (U is found from (13)), and other non-CNs. In the cooperation phase, the CH of each cluster calculates and updates other clusters with the cost from itself to its direct neighbors (as defined in (17)). After a few message exchanges, each CH establishes its optimal route to the sink. During the transmission phase, intra- and inter-cluster communications are conducted, where nodes send data to their CHs for aggregation and CHs cooperate with CNs to forward traffic to the sink along paths established during the cooperation phase. The details of the these phases are provided next.

Phase 1*: Clustering*

Step 1: Neighborhood discovery

Each node u contends for the channel using a CSMA/CA-like procedure. Node u then broadcasts a *hello message* (HM) at power P_{intra}. HM contains the node's ID, its residual energy, and a list of so-far-known neighbors. After receiving the HM, a neighboring node v updates its neighbor list with u's ID and residual energy. The retransmission of a HM is used in case of collisions of previous HMs. Sending a second or third HM from node u may be triggered if and only if u receives a HM from a node whose neighbor list does not include u. Each node decides to terminate the neighbor discovery stage if no more HM messages are received within a certain time duration. At the end of the neighborhood discovery stage, each node u maintains a list of its neighbors plus itself, sorted in an descending order of residual energy. Let such a list be denoted by $\mathcal{N}(u)$.

Step 2: CH election

Node u declares itself as a CH (it changes its status to CH) if it is in the first position in $\mathcal{N}(u)$ (has the highest residual energy among its neighbors). CH declaration is done by contending for channel access and broadcasting a "CH announcement message" (CHM), which contains u's ID. This CHM is sent at power P_{intra}. Upon hearing a CHM, a node v changes its status to *member*, estimates the distance from itself to that CH, updates its tentative CH if u's CHM is the first CHM that v receives or if the newly announced CH is closer to v than previously announced CHs, and finally broadcasts a *member* announcement message (MAM). The MAM contains v's ID. After receiving a MAM from v, its neighbors with undetermined status mark node v's status (i.e., do not consider v in the CH election process anymore) and reorder their neighbor lists. Again, each node whose status has not been determined checks its position in the neighbor list and declares itself a CH if it is the first in the list. The process is repeated until there are no unmarked nodes in any neighbor list. At the end of the CH election stage, there are two types of nodes: CHs and members. Each member node has one tentative CH.

Step 3: Member association and clustering

A member node contends for the channel and sends a membership request message (MRM) with its ID to its tentative CH. A CH may receive multiple MRMs intended to it. After a certain interval, the CH sorts its member list according to their residual energies and broadcasts a membership confirmation message (MCM). The MCM contains a list of all IDs from which the CH received MRMs and their time slot assignment for sending data to the CH. At the end of this stage, the network consists of multiple clusters, each with one CH and zero or more member nodes. The sink itself is assumed to be as a cluster with only one node, equipped with U antennas.

Step 4: CN invitation

Using power P_{intra}, each CH broadcasts a CN invitation message (CIM) to the first $U-1$ nodes in its member list (if the list contains less than $U-1$ nodes, the CIM contains the IDs of the whole list). Upon receiving a CIM, each member node checks if the message is from its CH. It then sends a CN confirmation message (CNM) to its CH. At this point, selected CNs and CHs are ready to enter the cooperation phase.

Phase 2*: Cooperation*

When a cluster u is formed, its CH and CNs sequentially broadcast a cost update request message (CURM) at power P_{inter}. Similar to pilot tones in [Jakllari et al. 2006], these CURMs are used by CNs at neighboring clusters to estimate the distance between the two farthest nodes of two sets of CNs, e.g., based on the received signal strength indicator (RSSI). RSSI-based distance estimation has accuracy in meters [Awad et al. 2007]. For an intra-cluster range in the order of hundreds of meters, the relative accuracy of the RSSI method is quite acceptable.

After solving problems (2), (3), and (4), the CHs of neighboring clusters determine the optimal CNs for the Tx and Rx clusters. The CH in each neighboring cluster v of cluster u broadcasts the link cost (as in (17)) and the optimal number of CNs for cluster u at power P_{inter}, so as to inform cluster u and other neighboring clusters of v of the cost of the VMIMO link from u to v. The CH of each cluster maintains a cost-and-forwarding table to any cluster that it may have learnt about, including the sink. Note that different sets of CNs may be used to communicate with different neighboring clusters (see Figure 4).

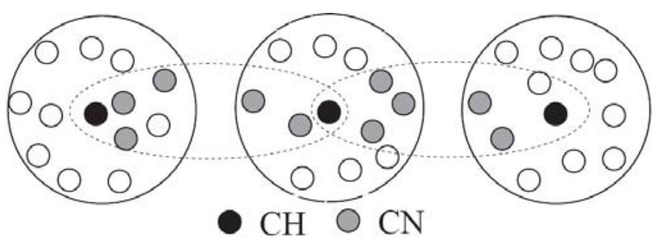

Fig. 4. Middle cluster uses two different sets of CNs to communicate with the left and right clusters.

Phase 3*: Data Transmission*

Each node transmits data to its CH in that node's time slot (specified in the MCM). After receiving data from various members, the CH performs aggregation/data fusion. It then broadcasts the fused data to its CNs at power P_{intra}. The CH then sends a request-to-send (RTS) message at power P_{inter} to the cluster in its forwarding table. If not busy, the CH of this Rx cluster sends a clear-to-send message (CTS) to the source cluster and coordinates its CNs to receive data. Upon receiving the CTS, the CH of the Tx cluster synchronizes its CNs to send data to the Rx cluster.

Phase 4*: Re-clustering*

At some point, the energy of a CH/CN may reach the re-clustering threshold (e.g., 50% of the average residual energy of the cluster's CNs). The CH/CN will send a re-clustering request message (RCRM) at power P_{inter}. CHs that receive a RCRM terminate their transmission phase if they were transmitting/receiving and broadcast

RCRMs at power P_{inter}. After a few time slots, all nodes become aware of the RCRM and begin the clustering phase (phase 1). A summary of CCP is given in Algorithm 1.

Algorithm 1: Cooperative and Clustering Protocol

At time instance T:
During clustering mini-slot t_{cl}:
Start neighborhood discovery: node u maintains a neighbor list $\mathcal{N}(u)$.
CH election based on $\mathcal{N}(u)$ lists.
Member association and clustering.
CN invitation: at most U CNs per cluster, U is found from (13).
During cooperation mini-slot t_{co}:
Exchang cost-update messages between CHs and CNs.
Execute problems (2), (3) and (4) at Rx clusters.
Finding optimal paths from clusters to the sink by executing the distributed Bellman Ford with the cost metric (17)
During transmission mini-slot t_{data}:
Intra/inter cluster transmissions and data fusion take place using parameters and paths determined during the clustering and cooperation mini-slots.
Re-clustering, the network moves to the next time instance $T + \Delta T$.

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7. PROPERTIES OF CCP AND PRACTICAL DESIGN ISSUES

7.1. CCP Properties

PROPOSITION 7.1. *The clustering phase requires $\mathcal{O}(N_{\text{deg}}T)$ time, on average, where N_{deg} is the maximum node degree in the network, and T is the time duration for a node to successfully access the channel and send a message (assuming signalling messages are of the same size). In the worst case, the clustering phase requires $\mathcal{O}(NT)$ time. The total number of exchanged messages in the clustering phase is $\mathcal{O}(N)$, hence $\mathcal{O}(1)$ per node.*

Proof: The clustering phase consists of neighborhood discovery, CH election, member association, and CN invitation. To complete the first three steps, each node has to send three messages: HM (possibly sent multiple times), CHM (or MAM), and MRM. Hence, the total number of exchanged messages for N nodes is $\mathcal{O}(N)$. The total amount of time to send these messages by a given node is $\mathcal{O}(N_{deg}T)$. The average value of N_{deg} is $\mu\pi R_{\text{intra}}^2$, leading to an average time complexity for the clustering phase of $\mathcal{O}(\mu\pi R_{\text{intra}}^2 T)$. The worst case happens when all nodes are within the transmission range of each other (i.e., a single-hop network). In this case, the maximum node degree is $N-1$ and the total amount of time for the clustering phase is $\mathcal{O}(NT)$. □

As CCP uses a CSMA/CA-like mechanism to access the channel, T can be expressed as:

$$T = T_{backoff} + \text{DIFS} + T_{prog} + T_{tsm} \tag{18}$$

where $T_{backoff}$ is the backoff delay, DIFS is the distributed inter-frame space interval, T_{tsm} is the transmission time of a packet, and T_{prog} is the propagation delay.

The energy balancing effect of CCP is claimed in the following proposition:

PROPOSITION 7.2. *At least $U-1$ out of U CNs in each cluster are the nodes with the highest residual energies out of all nodes in that cluster.*

The proof follows directly from the CN assignment algorithm. □

PROPOSITION 7.3. *No two CHs are within the intra-cluster range of each other.*

As discussed before, once a node hears a CHM, it stops competing for the CH role. Therefore, there is no chance for two CHs to be within the intra-cluster range of each other. It is also clear that any member node reaches its CH in only one hop.

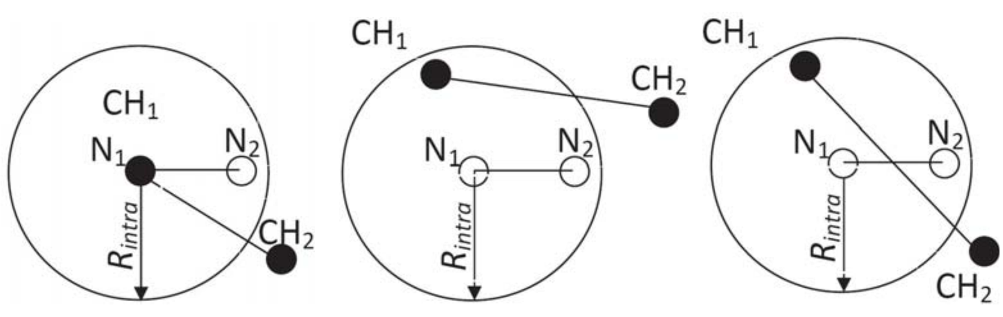
7.2. Connectivity

We now provide sufficient conditions for the intra- and inter-cluster ranges under which CCP results in a connected graph of CHs. In [Younis and Fahmy 2004][Zhao et al. 2007], connectivity was established using the results of [Gupta and Kumar 1998], which showed that the network is connected if R_{inter} is $\mathcal{O}(\sqrt{\frac{\log n_0}{n_0}})$, where n_0 is the number of CHs in a unit square (CH density). CH density can be indirectly adjusted by tuning the intra-cluster range. By doubling n_0, R_{inter} is reduced by a factor of $\sqrt{\frac{2}{\log 2}}$. Another approach that has been used to guarantee connectivity in clustered networks is to set $R_{\text{inter}} = (1+\sqrt{5})c_s$, where c_s is the size of a *cell*, defined as a group of nodes such that a node in the cell can communicate with all nodes in eight surrounding cells [Ye et al. 2003]. Using this criterion, one needs to relate the intra-cluster range to the cell size, as done in [Younis and Fahmy 2004][Blough and Santi 2002].

In contrast to above methods, we derive conditions on the transmission range based on Euclidean geometry and the characteristics of CCP. We present two approaches for setting R_{inter} and R_{intra}. The first approach is intended for WSNs whose R_{intra} has already been designed to guarantee network connectivity (e.g., using [Gupta and Kumar 1998]). The question is if these existing networks adopt CCP, how should R_{inter} be set? The second approach is aimed at WSNs for which both R_{inter} and R_{intra} are to be set. Note that in the first approach, the flat network is connected under the given R_{intra}, while in the second approach, this is not a guaranteed priori.

7.2.1. Method 1

LEMMA 7.4. *If the network of sensors is connected under a transmission range of R_{intra}, then after executing CCP, any two neighboring nodes must either have the same CH or that their CHs are within a range of $3R_{intra}$.*



(a) (b) (c)

Fig. 5. CHs of any two neighboring nodes are within the inter-cluster range of each other if $R_{\text{inter}} = 3R_{\text{intra}}$.

Proof: The proof is illustrated in Figure 5. Because the network is connected under a transmission range R_{intra}, any node has at least one neighbor. Let node N_1 be a neighbor of node N_2. After running CCP, N_1 and N_2 may belong to one cluster (they have the same CH) or to two different clusters. In the later case, N_1 and N_2 cannot be CHs at the same time (because no two CHs can be within an intra-cluster range). If N_1 is a CH (Figure 5(a)), it is easy to show using the triangle inequality that the distance between the two CHs is less than $2R_{\text{intra}}$. For the case when both N_1 and N_2 are non-CHs (Figures 5(b) and 5(c)), we apply the triangle inequality twice to show that the distance between the two CHs is less than $3R_{\text{intra}}$. □

THEOREM 7.5. *The graph of CHs generated by CCP is connected if $R_{inter} = 3R_{intra}$.*

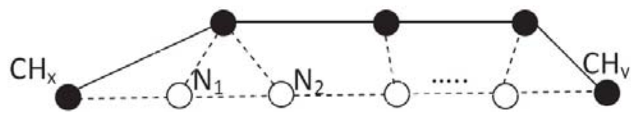


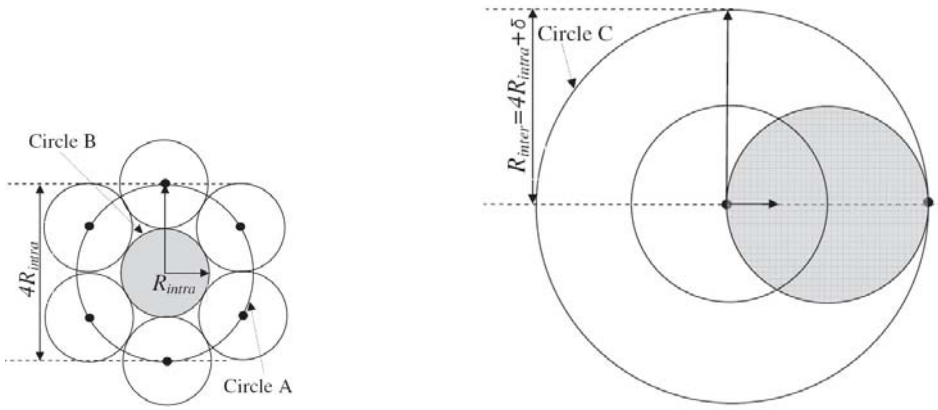
Fig. 6. Inter-cluster path between any two CHs can always be constructed when $R_{\text{inter}} = 3R_{\text{intra}}$.

Proof: Let $\acute{G}$ be the graph of CHs. Two CHs on $\acute{G}$ are directly connected if their distance is less than R_{inter}. We will show that if $R_{\text{inter}} = 3R_{\text{intra}}$, then there exists a path on $\acute{G}$ between any two CHs. Consider two such nodes, denoted by CH_x and CH_v (see Figure 6). It is assumed that before executing CCP, the network graph G (which includes all nodes) is connected at transmission range R_{intra}. Thus, there exists a path $Q = (\text{CH}_x, N_1, N_2, \ldots, N_Q, \text{CH}_v)$ on G that connects CH_x and CH_v using the transmission range R_{intra}. We call Q the primary path. Suppose that CH_x and CH_v are not neighbors on path Q (otherwise, the assertion is proved). Consider the next two nodes on Q, N_1 and N_2. After running CCP, if these two nodes belong to the same cluster, then we can replace their direct link on Q by their common CH. According to Lemma 1, this common CH is itself CH_x or is at most $3R_{\text{intra}}$ away from CH_x. Because $R_{\text{inter}} = 3R_{\text{intra}}$, this common CH has a direct link to CH_x at transmission range R_{inter}. If N_1 and N_2 belong to different clusters, their corresponding CHs must be separated by no more than $3R_{\text{intra}}$, so they are directly connected on $\acute{G}$. The process of replacing the links on Q by direct links on $\acute{G}$ can be repeated for every link on Q, leading to a path between CH_x and CH_v on $\acute{G}$. □

7.2.2. Method 2. Next, we present the second approach in which we have to determine both the intra- and inter-cluster ranges. We start with the condition for the intra-cluster range.

LEMMA 7.6. *Consider a WSN with a Poison distributed nodes of density μ. If $R_{intra} \geq \left(\frac{\ln p^{-1}}{\pi\mu}\right)^{1/2}$, then with probability $1-p$ there is at least one node in any circle of radius R_{intra}.*

Proof: Let p_1 be the probability that the number of nodes in a circle of radius R_{intra} is at least 1. We have $p_1 = 1 - p = 1 - e^{-\mu\pi R_{\text{intra}}^2}$, where p is the probability of no node being found in a circle of radius R_{intra}. It is clear that if $R_{\text{intra}} \geq \left(\frac{\ln p^{-1}}{\pi\mu}\right)^{1/2}$, then $p_1 \geq (1-p)$. □



(a) (b)

Fig. 7. (a) Circle with radius $2R_{\text{intra}}$ has at least one CH (black dots). (b) At least two CHs (black dots) in any circle with radius $4R_{\text{intra}}$.

LEMMA 7.7. *Given that there is at least one node in any circle of radius R_{intra}, then there is at least one CH in any circle of radius $2R_{intra}$.*

Proof: The proof is illustrated in Figure 7(a). Assume that there exists a circle with radius $2R_{\text{intra}}$ that does not contain any CH (call it circle A). Consider another circle B with radius R_{intra} (the grey circle in Figure 7(a)) which is concentric with circle A. Circle B contains at least one node whose status is decided after the clustering phase. As circle A does not contain any CH, the node in circle B should not be a CH. This member node must be served and within the intra-cluster range of a CH not in circle A. However, the only CHs whose intra-cluster range can reach a node in circle B are the ones on the circumference of A (e.g., the centers of the six small white circles). Hence, circle A must contain at least one CH. □

LEMMA 7.8. *Given that there is at least one node in any circle of radius R_{intra}, there must be at least another CH within a transmission range greater than $4R_{intra}$ of any CH.*

Proof: The proof is illustrated in Figure 7(b). Consider a CH at the center of a circle (call it circle C) with radius $4R_{\text{intra}}+\delta$ ($\delta > 0$). We always can fit another circle of radius $2R_{\text{intra}}$ (the grey circle in Figure 7(b)) which is completely contained in circle C and does not touch the center of C. The grey circle must have at least one CH (Lemma 7.7). Thus, if the CH at the center of circle C has a transmission range $4R_{\text{intra}} + \delta$, it can certainly reach another CH. □

The following theorem claims the connectivity of the set of CHs produced by CCP.

THEOREM 7.9. *After the clustering phase, the graph whose vertices are CHs is connected with probability $1 - p$, given that the intra- and inter-cluster ranges satisfy the following conditions:*

$$R_{inter} > 4R_{intra}$$
$$R_{intra} \geq \left(\frac{\ln p^{-1}}{\pi\mu}\right)^{1/2}$$

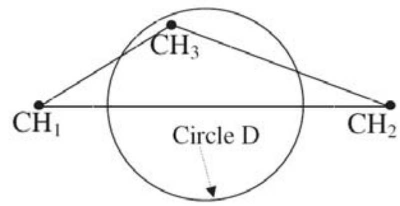


Fig. 8. If the graph of CHs is not connected, then for the two closest CHs (CH_1 and CH_2) of the two disconnected components, there always exists another CH_3 whose distance to CH_1 or CH_2 is less than that from CH_1 to CH_2.

Proof: Under the two conditions above, Lemmas 7.6, 7.7, and 7.8 hold. Assume that the network of CHs is not connected. Without loss of generality, assume that the CH graph consists of two mutually disconnected components, O_1 and O_2 (O_1 is to the left of O_2). The distance between the two closest CHs (CH_1 of O_1 and CH_2 of O_2) must be greater than R_{inter}, hence greater than $4R_{\text{intra}}$. According to Lemma 7.7, we can find a circle (call it circle D) with diameter $4R_{\text{intra}}$ whose center is on the line connecting the two CHs (Figure 8) so that D does not contain either CH_1 and CH_2 but contains at least another CH, say CH_3. Using basic Euclidean geometry, we can show that the distance from CH_1 to CH_3 is less then the distance from CH_1 to CH_2, so is the distance from CH_2 to CH_3. Either CH_3 belongs to O_1 or O_2, CH_1 and CH_2 are not the two closet CHs between O_1 and O_2. This contradicts our assumption. Hence the graph of CHs must be connected. □

It should be noted that our conditions on the inter- and intra- cluster ranges (Theorems 7.5 and 7.9) are tighter than those of the HEED protocol [Younis and Fahmy 2004], which requires the inter-cluster range to be at least six times the intra-cluster range. Hence CCP yields a higher spatial reuse than HEED, giving higher chances for inter-cluster communications.

7.3. Synchronization between Cooperative Nodes

In this section, we discuss the synchronization requirement for realizing distributed MIMO and facilitating CCP's operation. In cooperative communications (which distributed MIMO is a special case of), the received signal at is often a superposition of replicas of different phases. This is attributed to having different physical locations of the transmitters and receivers as well as clock drifts (e.g., due to imperfect crystal oscillators). Consequently, the sampling rate at the matched filter cannot be optimized for all received copies. As a result, symbols sent from different transmitters interfere with each other, leading to inter-symbol-interference (ISI), as observed in frequency-selective fading channels.

Different methods at the physical layer have been proposed to effectively combat synchronization errors (e.g., [Mei et al. 2005][Wei et al. 2006][Li et al. 2005][Li and Xia 2008]). One method is to use time-reverse space-time code (TR-STC) [Larsson et al. 2002][Lindskog and Paulraj 2000]. Another approach to combat ISI induced by synchronization errors is to use OFDM-based methods, whereby the channel is decomposed into multiple frequency-flat channels, e.g., space-time OFDM [Shin et al. 2007]. At the network layer, a recently developed mechanism [Zhang and Shin 2010] can realize VMIMO at a packet synchronization level. Given the availability of the above methods, we believe that DSTBCs can achieve the same diversity order as the centralized STBCs, even without perfect synchronization.

To facilitate intra-cluster communications in CCP, we need to synchronize nodes at the frame level, which is coarser than the symbol-level synchronization discussed above. One of the popular approaches is the reference broadcast synchronization method (RBS) [Elson et al. 2002]. Using this method, one of the CHs serves as a “beacon CH”. It broadcasts a beacon to its neighboring CHs. Any CH that hears the beacon adjusts the start of its frame accordingly, then relays the beacon to other nearby CHs. The process continues and ensures that frames at different CHs are in sync.

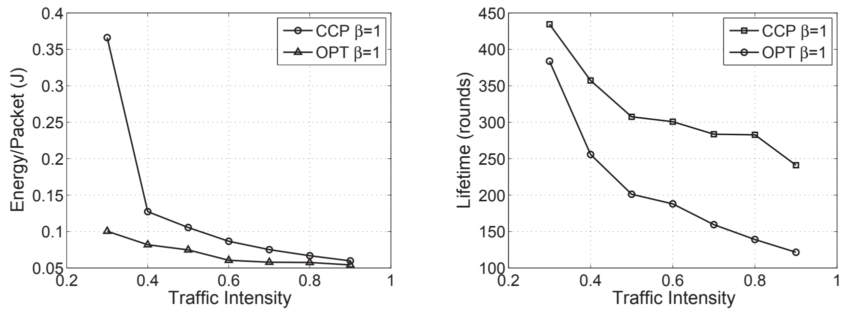
8. SIMULATION RESULTS

8.1. Simulation Setup

In this section, we evaluate the performance of CCP, which incorporates the OCS algorithm, the CN assignment algorithm, and the C-EBR routing mechanism. Our simulation programs were written in CSIM [CSI]. The performance metrics include network lifetime, the energy consumption per packet, and the residual energy variance (averaged over the network lifetime). These performance metrics are recorded until a node runs out of battery (similar to the lifetime definition in [Chang and Tassiulas 2004]) and also until the network becomes disconnected. We note that the first definition is rather conservative, as the network can still operate even after the failure of a few nodes. Under both definitions, network lifetime is measured in the number of transmission slots (*rounds*). In each transmission slot, a node generates a packet with probability q, which reflects the traffic intensity. The WSN consists of 600 sensors, which are randomly distributed on a square of length 1000 meter. The sink is located at the bottom right corner of the field, and is equipped with U antennas. The value of U is obtained from (13). We use the same parameters as in Table I, which results in $U = 8$ at $R_{\text{inter}} = 720$ meters. The values of R_{intra} and R_{inter} comply with the connectivity conditions presented in the previous section, and are in line with the latest Zigbee specifications and the IEEE 802.15.4 release [ZIG]. To highlight the diversity gain of VMIMO, we do not consider data fusion at CHs, whose benefit has been extensively demonstrated in the literature. The routing method is C-EBR, where the tradeoff parameter β is varied from 0 (pure EBR) to 1 (energy-efficient routing). We set the target BER to 10^{-4}. Each control packet is 160-bit long. In CCP, we need 3 control messages (CIM, CNM and CURM) to select a CN. Thus, $H = 480\ E_b$ in Table I. It is worth noting that the fading conditions at any two CNs of the same cluster are very likely to be independent, so that VMIMO diversity gain can be realized. This follows from the fact that the probability of finding two neighboring nodes that are too close to each other (i.e., their distance is less than half of the operating wavelength) is very small (for our setup, this probability is $1.3e-4$). At the beginning of a simulation run, each node is equipped with a battery that can deliver 500 Joules. Each point in our plots represents the average of 20 runs. Each run is obtained for a different (randomly generated) network topology.

8.2. Optimal Selection of CNs

We first justify the decomposition approach we followed to address the OCS problem by comparing the network performance metrics under the optimal solution of (1) (referred to as OPT) with CCP. Specifically, given that each cluster has at most U CNs, for each inter-cluster link, the CNs at both the Tx and Rx sides are found by solving the OCS problem through exhaustive search on a binary tree of 2^{2U-2} nodes. Figure 9(a) shows that the energy per packet under OPT is much lower than that of CCP (since OPT aims at minimizing the energy consumption for each inter-cluster link). However, the network lifetime of CCP is significant longer than that of OPT (Figure 9(b)). The reason is that, besides targeting energy efficiency, CCP also aims at energy balancing by selecting CNs so as to minimize the variance of the residual energy of various nodes.



(a) (b)

Fig. 9. (a) Average energy per packet; (b) network lifetime vs. traffic intensity under OPT and CCP.

Next, we compare the network lifetime under CCP with its predecessors: MIMO-LEACH [Yuan et al. 2006a] and CMIMO [Siam et al. 2009]. Because CCP is a clustering protocol, it is worth comparing its performance with other clustering protocols that were intended for SISO communications, e.g., DCA [Basagni 1999]. For MIMO-LEACH, we set the number of CNs to three. To isolate the effect of the routing mechanism, this comparison is made using energy-efficient routing ($\beta = 1$).

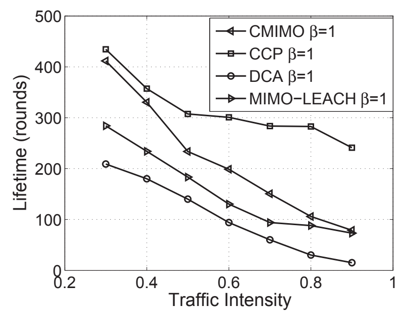


Fig. 10. Network lifetimes vs. traffic intensity for CCP, CMIMO, MIMO-LEACH, and DCA.

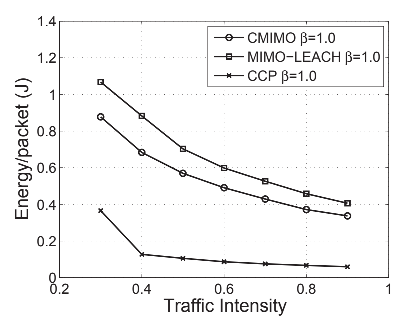


Fig. 11. Average energy per packet from a node to the sink vs. traffic intensity.

Figure 10 shows that, on average, the network lifetime under CCP is about 105%, 90%, and 50% higher than that of DCA, MIMO-LEACH, and CMIMO, respectively. For all protocols, the network lifetime decreases with the traffic intensity (q). However, as q increases, CCP's network lifetime improvement over the other protocols becomes more pronounced. This is due to the fact that CCP considers the cooperation overhead when searching for optimal CNs, whereas the other protocols do not. As q increases, the relative (per-packet) cooperation overhead to form VMIMO links goes down. It is not surprising that CCP outperforms DCA, as it consumes less energy for every link (as demonstrated in [Siam et al. 2009][Cui et al. 2004]).

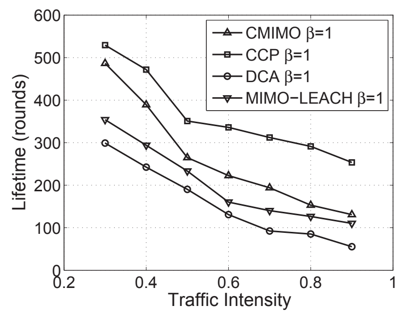


Fig. 12. Network lifetime until disconnectivity vs. traffic intensity.

The per-packet energy consumption for CCP, CMIMO, and MIMO-LEACH is depicted in Figure 11. CCP is superior to CMIMO and MIMO-LEACH, as it enjoys full diversity gain of DSTBC and adapts the number of CNs to the transmission distance, nodes' residual energies, and the cooperation overhead.

The disconnectivity-based network lifetime is depicted in Figure 12. CCP achieves about 93%, 78%, and 47% longer lifetime than DCA, MIMO-LEACH, and CMIMO, respectively. These relative gains are lower than those in the case of first-node-to-die lifetime in Figure 10. This is because other protocols result in higher energy imbalance than CCP but the network-disconnection lifetime definition is less sensitive to the energy imbalance than the first-node-to-die lifetime.

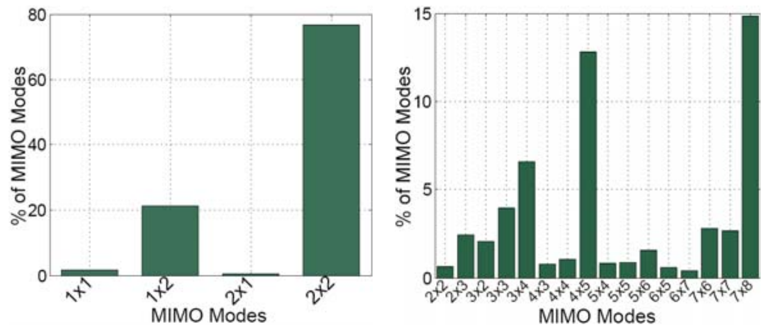
Figure 13 shows the percentage for MIMO modes of CMIMO and CCP cases. As can be observed, the maximum diversity gain of CCP is $7 \times 8 = 56$. For MIMO-LEACH, its transmission mode is MISO or SIMO, so the maximum diversity order is less than or equal to three. MIMO-LEACH's link diversity gain is less than that of CMIMO ($= 4$). That explains the inferior performance of MIMO-LEACH compared with CMIMO.

Figure 13(a) shows that for CMIMO the number of times that 2x2 mode is used is relatively high. This trend suggests that it is more beneficial to have more than 2 CNs. Figure 13(b) confirms that conjecture, using OCS, the number of CNs can be up to 8 and there are a variety of communication modes, other than 2x2.

8.3. Clustering Energy-Balanced Routing

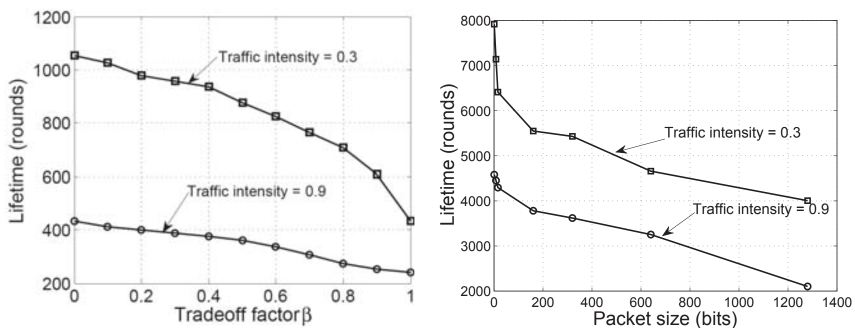
First, we investigate the network lifetime vs. the tradeoff factor between energy-efficient routing and energy-balanced routing. Figure 14(a) shows the network lifetime of CCP versus β for low (0.3) and high (0.9) traffic intensities. As can be seen, the network lifetime monotonically increases when moving towards EBR ($\beta = 0$).

Figure 14(b) depicts the network lifetime vs. the data packet size. At a given traffic intensity (in packets per time unit per node), an increase in the packet size results in a reduction in the network lifetime. This is expected because the larger the packet size,



(a) (b)

Fig. 13. Histogram of the MIMO modes in (a) CMIMO and (b) CCP.



(a) (b)

Fig. 14. (a) Network lifetime vs. β; (b) network lifetime vs. data packet size.

the more traffic (in bits/second) is pushed into the network. In the extreme case (1-bit data packets), the network lifetime is the longest.

To evaluate the proposed C-EBR, we incorporate it into CMIMO and MIMO-LEACH as well. In Figure 15, we compare network lifetime of CCP, CMIMO and MIMO-LEACH for $\beta = 0$ with their counterparts when $\beta = 1$ (energy-efficient routing). As seen, C-EBR improves the network lifetime by about 111%, 104% and 95% on average for MIMO-LEACH, CMIMO and CCP, respectively.

On average, CCP with both OCS and C-EBR improves the network lifetime by 226% and 172%, compared with the original MIMO-LEACH and CMIMO protocols. Beside the higher diversity gain, these results can be interpreted as the effect of balancing energy consumption by routing packets on paths that have CNs with higher energy. This fact is confirmed by the variance of the residual battery energy.

Figures 16(a)(b) depict the residual energy variance of CMIMO and CCP under $\beta = 0$ and $\beta = 1$. For both protocols, EBR reduces the variance of the residual battery energy. Figure 16(c) compares the energy variance of CMIMO with CCP while using C-EBR, energy variance of CCP is less than that of CMIMO. It is attributed to the fact that having more CNs not only increases link diversity gain but also spreads out traffic more evenly among nodes in the network, yielding better energy balance.

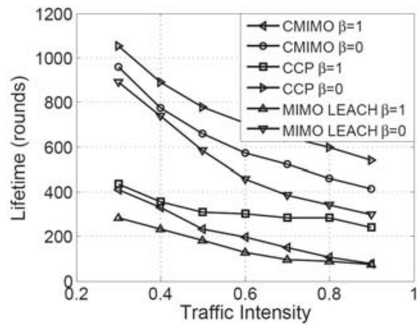
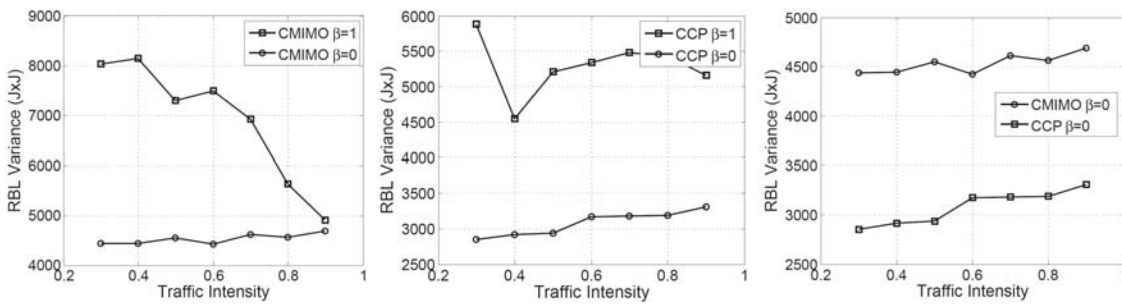


Fig. 15. Network lifetime under different protocols using C-EBR vs. traffic intensity.



(a) CMIMO (b) CCP (c) CMIMO vs CCP

Fig. 16. Energy variance vs. q under EER and EBR.

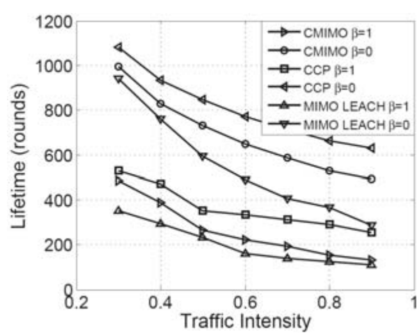


Fig. 17. Network lifetime until disconnectivity vs. traffic intensity under different protocols.

The network lifetime until disconnectivity is shown in Figure 17. C-EBR increases the network lifetime by about 107%, 98%, and 96% over MIMO-LEACH, CMIMO, and CCP, respectively.

Figure 18 compares the per-packet energy consumption under energy efficient routing (EER) and C-EBR. As expected, the energy per packet of the former is less than that of C-EBR as it just searches for the least-cost path, regardless of the energy status of CNs on that path. By contrast, C-EBR balances residual energy among CNs of the path at the expense of extra cost per packet.

To further investigate the energy balancing effectiveness of C-EBR, in Figure 19, we show the percentage of residual energy averaging over all nodes that can directly reach the sink with power P_{inter} (one-hop neighbors of the sink) when the lifetime ends. As seen, C-EBR depletes almost completely the batteries of these nodes (the remaining energy is only about 1% of the initial battery level). However, for EER, the average remaining energy of these nodes is about 45%.

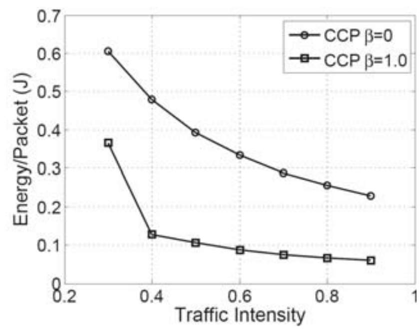


Fig. 18. Energy per packet vs. traffic intensity for EER and C-EBR.

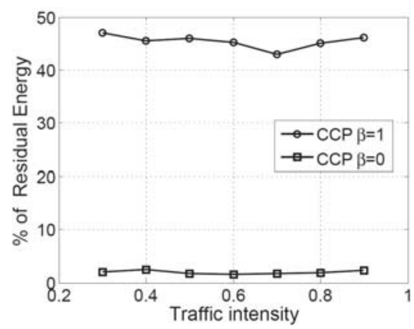


Fig. 19. Average residual energy percentage of nodes that are one hop from the sink.

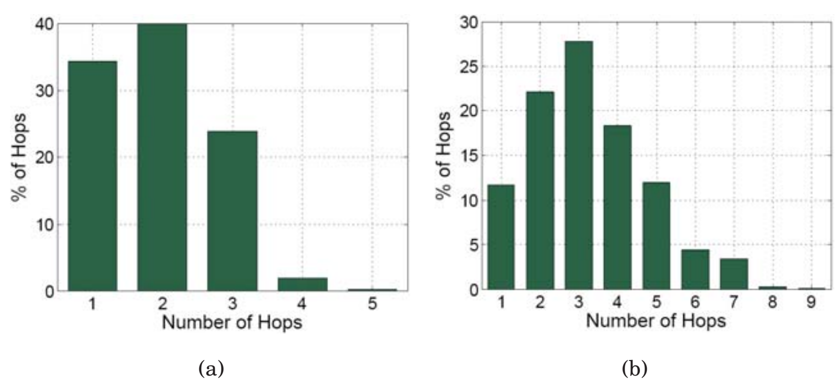
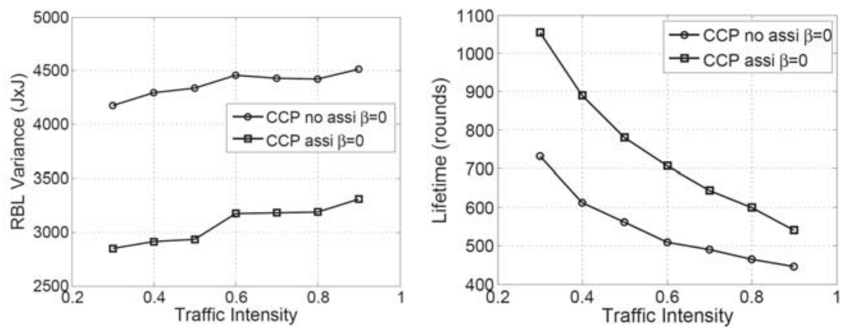


Fig. 20. Histogram of hop count for (a) energy-efficient routing and (b) C-EBR.

We further investigate the number of hops for C-EBR. Figure 20(b) represents the number of hops of C-EBR which is higher than that of EER (Figure 20(a)). The reason is that sometimes a packet may travel on a "longer" path to the sink to balance energy consumption among nodes. However, the increase in number of hops in C-EBR is not significant, compared with EER, and hence it does not adversely affect packet delay.

8.4. CNs assignment problem

In [Chen et al. 2005], CNs are selected based on their distance to the CH. The rationale behind such criterion is that having CNs that are closer to their CHs facilitates their coordination and reduces the energy overhead for cooperation. Figure 21(a) shows that by using the proposed CN assignment algorithm, CCP significantly reduces the energy variance. Subsequently, as shown in Figure 21(b), its lifetime is improved by about 80%.



(a) (b)

Fig. 21. (a) Energy variance, and (b) network lifetime vs. traffic intensity with and without proposed CN assignment algorithm.

9. CONCLUSIONS AND FUTURE WORK

In this work, we developed a cooperative clustering protocol (CCP) for WSNs. CCP takes advantage of VMIMO and achieves the maximum possible diversity of DSTBC. The key engine behind CCP is the optimal CN selection algorithm. To tackle the NP-hard OCS problem, we decomposed it into two sub-problems: finding the optimal number of CNs and the CN assignment problem. The ONC algorithm serves as a framework for protocol designers in deciding the number of CNs per cluster in clustered WSNs. We also proposed an energy-balanced routing mechanism, which can be used with any clustering mechanism. The conditions for the intra- and inter- cluster transmission ranges to guarantee network connectivity were also derived. Our extensive simulations show that CCP prolongs the network lifetime by about three times compared with existing cooperative protocols (MIMO-LEACH, CMIMO).

Our future work will focus on extending CCP to the case of multiple channels. Another unvisited problem is how to cluster and cooperate when taking into account the nonlinear battery behavior. We believe that clustering and cooperation strongly affect the load profile of each sensor, especially when jointly considered with routing in multi-hop networks. Hence, they also affect the battery's discharge time and network lifetime. Additionally, as mentioned previously, determining the optimal re-clustering threshold and the optimal transmission range remain open research problems.

REFERENCES

JN5139 Module Datasheet, UK, http://www.jennic.com/support/datasheets/jn5139.

Mesquite Software Incorporation, http://www.mesquite.com.

ZIGBEE, http://www.caba.org/standard/zigbee.html.

ABRAMOWITZ, M. AND STEGUN, I. A. E. 1972. *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*. New York, NY, USA.

AKSU, A. AND ERCETIN, O. 2008. Reliable multi-hop routing with cooperative transmissions in energy-constrained networks. *IEEE Transactions on Wireless Communications 7,* 8, 2861–2865.

AWAD, A., FRUNZKE, T., AND DRESSLER, F. 2007. Adaptive distance estimation and localization in WSN using RSSI measures. In *10th Euromicro Conference on Digital System Design Architectures, Methods and Tools*. 471–478.

BAILEY, W. N. 1935. *Appell's Hypergeometric Functions of Two Variables, Ch. 9 in Generalised Hypergeometric Series*. Cambridge University Press.

BASAGNI, S. 1999. Distributed clustering for ad hoc networks. In *Proceedings of the International Symposium on Parallel Architectures, Algorithms, and Networks*.

BERTSIMAS, D. AND WEISMANTEL, R. 2005. *Optimization Over Integers*.

BLOUGH, D. M. AND SANTI, P. 2002. Investigating upper bounds on network lifetime extension for cell-based energy conservation techniques in stationary ad hoc networks. In *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM)*. 183–192.

BRANDENBURG, L. H. AND WYNER, A. D. 1974. Capacity of the Gaussian channel with memory: The multivariate case. *ATT Technical Journal 53,* 5, 745778.

CHANG, J.-H. AND TASSIULAS, L. 2004. Maximum lifetime routing in wireless sensor networks. *IEEE/ACM Transactions on Networking 12*, 609–619.

CHEN, W., YUAN, Y., XU, C., LIU, K., AND YANG, Z. 2005. Virtual MIMO protocol based on clustering for wireless sensor network. In *Proceedings of the 10th IEEE Symposium on Computers and Communications*.

CHERNOFF, H. 1952. A measure of asymptotic efficiency for tests of a hypothesis based on the sum of observations. *Annals of Mathematical Statistics 23,* 4, 493507.

CUI, S., GOLDSMITH, A. J., AND BAHAI, A. 2004. Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks. *IEEE Journal on Selected Areas in Communications 22,* 6, 1089–1098.

DOHLER, M., LEFRANC, E., AND H.AGHVAMI. 2002a. Space time block codes for virtual antenna arrays. In *Proceedings of the PIMRC Conference, Lisbon, Portugal*.

DOHLER, M., LEFRANC, E., AND H.AGHVAMI. 2002b. Virtual antenna arrays for future wireless mobile communication systems. In *Proceedings of the ICT Conference, Beijing, China*.

ELSON, J., GIROD, L., AND ESTRIN, D. 2002. Fine-grained network time synchronization using reference broadcasts. In *Proceedings of the 5th Symposium on Operating Systems Design and Implementation*. 147–163.

FOSCHINI, G. J. 1996. Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas. *Bell Labs Technical Journal 1,* 2, 41–59.

FOSCHINI, G. J. AND GANS, M. J. 1998. On limits of wireless communications in a fading environment when using multiple antennas. *Wireless Personal Communications 6*, 311–335.

GAO, Q., ZUO, Y., ZHANG, J., AND PENG, X.-H. 2010. Improving energy efficiency in a wireless sensor network by combining cooperative MIMO with data aggregation. *IEEE Transactions on Vehicular Technology 59,* 8, 3956–3965.

GONG, D., ZHAO, M., AND YANG, Y. 2010. A multi-channel cooperative MIMO MAC protocol for wireless sensor networks. In *Proceedings of the IEEE 7th International Conference on Mobile Adhoc and Sensor Systems (MASS)*. 11–20.

GUPTA, P. AND KUMAR, P. R. 1998. Critical power for asymptotic connectivity in wireless networks. *Stochastic Analysis, Control, Optimization and Applications: A Volume in Honor of W.H. Fleming*.

HEINZELMAN, W. R., CHANDRAKASAN, A., AND BALAKRISHNAN, H. 2000. Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd Hawaii International Conference on System Sciences-Volume 8*. Washington, DC, USA.

JAAFAR, W., AJIB, W., AND HACCOUN, D. 2010. On the performance of distributed-stbc in multi-hop wireless relay networks. In *Proceedings of the European Wireless Conference*. 223–230.

JAKLLARI, G., KRISHNAMURTHY, S. V., FALOUTSOS, M., KRISHNAMURTHY, P. V., AND ERCETIN, O. 2006. A framework for distributed spatio-temporal communications in mobile ad hoc networks. In *Proceedings of the IEEE INFOCOM Conference*.

JAYAWEERA, S. 2006. Virtual MIMO-based cooperative communication for energy-constrained wireless sensor networks. *IEEE Transactions on Wireless Communications 5,* 5, 984–989.

JAYAWEERA, S. 2007. V-BLAST-based virtual MIMO for distributed wireless sensor networks. *IEEE Transactions on Communications 55,* 10, 1867–1872.

LANEMAN, J. AND WORNELL, G. 2003. Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks. *IEEE Transactions on Information Theory 49,* 10, 2415–2425.

LARSSON, E. G., STOICA, P., LINDSKOG, E., AND LI, J. 2002. Space-time block coding for frequency-selective channels. In *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*. Vol. 3. 2405–2408.

LI, X., CHEN, M., AND LIU, W. 2005. Application of STBC-encoded cooperative transmissions in wireless sensor networks. *IEEE Signal Processing Letters 12,* 2, 134–137.

LI, Z. AND XIA, X.-G. 2008. An alamouti coded OFDM transmission for cooperative systems robust to both timing errors and frequency offsets. *IEEE Transactions on Wireless Communications 7,* 5, 1839–1844.

LINDSKOG, E. AND PAULRAJ, A. 2000. A transmit diversity scheme for channels with intersymbol interference. In *Proceedings of the IEEE ICC Conference*. Vol. 1. 307–311.

MEI, Y., HUA, Y., SWAMI, A., AND DANESHRAD, B. 2005. Combating synchronization errors in cooperative relays. In *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP*. Vol. 3. 369–372.

NARASIMHAN, R. 2003. Spatial multiplexing with transmit antenna and constellation selection for correlated MIMO fading channels. *IEEE Transactions on Signal Processing 51,* 11, 2829–2838.

QU, Q., MILSTEIN, L. B., AND VAMAN, D. R. 2010. Cooperative and constrained MIMO communications in wireless ad hoc/sensor networks. *IEEE Transactions on Wireless Communications 9,* 10, 3120 –3129.

RONG, P. AND PEDRAM, M. 2006. An analytical model for predicting the remaining battery capacity of lithium-ion batteries. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems 14,* 5, 441–451.

SALZ, J. 1985. Digital transmission over cross-coupled linear channels. *ATT Technical Journal 64,* 6, 11471159.

SCAGLIONE, A., GOECKEL, D. L., AND LANEMAN, J. N. 2007. *Distributed Antenna Systems: Open Architecture for Future Wireless Communications*. Chapter Cooperative Communications in Mobile Ad-Hoc Networks: Rethinking the Link Abstraction, 87–116.

SHIN, H. AND LEE, J. H. 2002. Exact symbol error probability of orthogonal space-time block codes. In *Proceedings of the IEEE GLOBECOM conference*.

SHIN, O.-S., CHAN, A., KUNG, H., AND TAROKH, V. 2007. Design of an OFDM cooperative space-time diversity system. *IEEE Transactions on Vehicular Technology 56,* 4, 2203–2215.

SHU, T. AND KRUNZ, M. 2010. Coverage time optimization for clustered wireless sensor networks: A power-balancing approach. *IEEE/ACM Transactions on Networking 18,* 1, 202–215.

SIAM, M. Z., KRUNZ, M., AND YOUNIS, O. 2009. Energy-efficient clustering/routing for cooperative MIMO operation in sensor networks. In *Proceedings of the IEEE INFOCOM Conference*.

STEMM, M. AND KATZ, R. 1997. Measuring and reducing energy consumption of network interfaces in hand-held devices. *IEICE Transactions on Communications*.

TAROKH, V., JAFARKHANI, H., AND CALDERBANK, A. R. 1999. Space-time block codes from orthogonal designs. *IEEE Transactions on Information Theory 45,* 5, 1456–1467.

WEI, S., GOECKEL, D., AND VALENTI, M. 2006. Asynchronous cooperative diversity. *IEEE Transactions on Wireless Communications 5,* 6, 1547–1557.

Y. ZHUANG, J. P. AND WU, G. 2009. Energy-optimal grid-based clustering in wireless microsensor networks. In *Proceedings of the IEEE ICDCS Workshop on Wireless Ad hoc and Sensor Networking (WWASN)*.

YANYAN ZHUANG, J. P. AND CAI, L. 2010. Minimizing energy consumption with probabilistic distance models in wireless sensor networks. In *Proceedings of the IEEE INFOCOM Conference*.

YE, F., ZHONG, G., CHENG, J., LU, S., AND ZHANG, L. 2003. PEAS: A robust energy conserving protocol for long-lived sensor networks. In *Proceedings of the 23rd International Conference on Distributed Computing Systems*. 28–37.

YOUNIS, O. AND FAHMY, S. 2004. Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing 3,* 4, 366–379.

YOUNIS, O., KRUNZ, M., AND RAMASUBRAMANIAN, S. 2006. Node clustering in wireless sensor networks: Recent developments and deployment challenges. *IEEE Network Magazine 20*, 20–25.

YUAN, Y., CHEN, M., AND KWON, T. 2006a. A novel cluster-based cooperative MIMO scheme for multi-hop wireless sensor networks. *EURASIP Journal on Wireless Communications and Networking* 2.

YUAN, Y., HE, Z., AND CHEN, M. 2006b. Virtual MIMO-based cross-layer design for wireless sensor networks. *IEEE Transactions on Vehicular Technology 55,* 3, 856–864.

ZHANG, L. AND CIMINI, L. J. 2008. Power-efficient relay selection in cooperative networks using decentralized distributed space-time block coding. *EURASIP Journal on Advances in Signal Processing*.

ZHANG, X. AND SHIN, K. G. 2010. Dac: Distributed asynchronous cooperation for wireless relay networks. In *Proceedings of the IEEE INFOCOM Conference*.

ZHAO, Q., TONG, L., AND COUNSIL, D. 2007. Energy-aware adaptive routing for large-scale ad hoc networks: Protocol and performance analysis. *IEEE Transactions on Mobile Computing 6,* 9, 1048–1059.