Ad Hoc Networks 11 (2013) 1571–1587

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Clustering and power management for virtual MIMO communications in wireless sensor networks

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ARTICLE INFO

Article history:
Received 9 February 2012
Received in revised form 4 September 2012
Accepted 20 November 2012
Available online 4 January 2013

Keywords:
Virtual MIMO
Wireless sensor networks
Clustering
Routing
MAC protocol
Power control
Cooperative communications

ABSTRACT

Multi-input multi-output (MIMO) is a well-established technique for increasing the link throughput, extending the transmission range, and/or reducing energy consumption. In the context of wireless sensor networks (WSNs), even if each node is equipped with a single antenna, it is possible to group several nodes to form a *virtual antenna array*, which can act as the transmitting or receiving end of a virtual MIMO (VMIMO) link. In this paper, we propose energy-efficient clustering and power management schemes for virtual MIMO operation in a multi-hop WSN. Our schemes are integrated into a comprehensive protocol, called cooperative MIMO (CMIMO), which involves clustering the WSN into several clusters, each managed by up to two cluster heads (CHs); a *master CH* (MCH) and a *slave CH* (SCH). The MCH and SCH collect data from their cluster members during the intra-cluster communications phase and communicate these data to neighboring MCHs/SCHs via an inter-cluster VMIMO link. CMIMO achieves energy efficiency by proper selection of the MCHs and SCHs, adaptation of the antenna elements and powers in the inter-cluster communications phase, and using a cross-layer MIMO-aware route selection algorithm for multi-hop operation. We formally establish the conditions on the transmission powers of CHs and non-CHs that ensure the connectivity of the inter-cluster topology. Simulations are used to study the performance of CMIMO. The simulation results indicate that our proposed protocol achieves significant reduction in energy consumption and longer network life time, compared with non-adaptive clustered WSNs.

1. Introduction

Nodes in wireless sensor networks (WSNs) are typically powered by small batteries. Replacement or recharging of these sensors is often difficult due to two reasons: (1) Sensors are deployed in large numbers, making the process of manually recharging them expensive and time consuming, and (2) in some applications, such as relief-and-rescue and battlefields, it may be infeasible to reach the sensors once they have been dispatched. Consequently, improving the energy efficiency of a WSN has always been a primary design objective.

Multi-input multi-output (MIMO) technology has the potential to increase the throughput and/or reduce the transmission energy consumption. This is done by exploiting three types of gains: Array, multiplexing, and diversity [2]. Array (or power) gain is achieved at the receiver through coherent combining of multiple copies of the signal. Multiplexing gain is obtained when different signals are transmitted simultaneously over several antennas to increase the total transmission capacity of a link. Diversity gain, achieved by sending/receiving several highly correlated versions of a signal over independent fading paths (different antennas), is the slope of the average bit error rate (BER) curve versus signal-to-noise ratio (SNR). In this

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http://dx.doi.org/10.1016/j.adhoc.2012.11.013

work, we focus on diversity gain, leaving the exploitation of other types of gain for future research.

A typical MIMO system requires multiple antennas at the transmit and/or receive end of a link. However, in dense topologies such as WSNs, it is also possible to group two or more single-antenna nodes to form a cooperative (virtual) multi-antenna node. Forming such a virtual node requires sensor nodes to exchange information and decide on the data to be transmitted cooperatively. To ensure that the energy overhead of information exchange is manageable, only those nodes that are geographically close to each other should be part of the virtual node.

In general, data obtained by sensor nodes in dense WSNs exhibit a high degree of redundancy, which can be significantly reduced by means of aggregation/fusion [3]. Data aggregation is facilitated by node clustering, which organizes the network into a connected hierarchy [4]. In the context of WSNs, clustering involves grouping nodes and electing a cluster head (CH) such that the non-CH nodes of a cluster can directly communicate with their CH. CHs forward aggregated data to the sink directly or via other CHs. Topologically, the collection of CHs in the network forms a connected dominating set.

In this paper, we propose a distributed MIMO-adaptive energy-efficient clustering/routing protocol, coined cooperative MIMO (CMIMO), for multi-hop WSNs. According to this protocol, each cluster has up to two CHs, which are responsible for inter-cluster communications. Clustering is done based on the remaining battery lifetime (RBL), neighbor proximity, and network density. The rationale for adopting these criteria is to construct cooperative MIMO links whose effect is as close as possible to actual MIMO systems (with two antennas per node) and that have manageable overhead. The diversity gain of such a cooperative MIMO system is maximized by adapting the "transmission mode" and the transmission power of the inter-cluster virtual MIMO link on a per-packet basis. By "transmission mode" we mean one of four possible transmit/receive configurations: 1×1 (single-input single-output/ SISO), 2×1 (multi-input single-output/ MISO), 1×2 (single-input multi-output/ SIMO), and 2×2 (multi-input multi-output/ MIMO).[1] To reduce energy consumption, CMIMO considers both transmission and circuit energies. For a given target BER, a multi-antenna transmission requires less transmission power than a SISO system. However, it also requires more circuit power at both ends of the link. As a result, a distance-dependent tradeoff emerges between transmission and circuit powers [6]: For relatively small distances, circuit power is dominant, and hence a SISO mode is more energy-efficient than a multi-antenna mode. As the transmitter–receiver distance increases, the tradeoff shifts in favor of multi-antenna modes (SIMO, MISO, MIMO). Once the optimal configuration is determined for each inter-cluster link, CMIMO executes an energy-efficient routing (EER) algorithm on the virtual topology to determine the "optimal" end-to-end path that minimizes the total energy consumption.

[1] The feasibility of adapting the transmission mode on a per-packet basis was demonstrated in several experimental MIMO platforms (e.g., [5]).

It should be noted that although this work focuses on clusters with at most two CHs per cluster, the proposed methodology is actually applicable to any number of CHs. Specifically, the proposed procedure and criteria for network clustering and coordination of the cooperation process do not depend on the number of cooperating nodes. However, optimizing this number (and selection) leads to a combinatorial problem of high computational complexity. Thus, to maintain a reasonable computational overhead, we limit our treatment to two CHs per cluster.

The rest of the paper is organized as follows. Section 2 provides related work. We describe the CMIMO protocol in Section 3. The system model and the energy consumption analysis are provided in Section 4. In Section 5 we discuss some issues related to the design of CMIMO, including connectivity, synchronization, reclustering, and medium access control. The performance of the proposed protocol is evaluated via simulations in Section 6. Section 7 discusses the main conclusions of this paper as well as some generalizations and extensions.

2. Related work

In this section, we describe recent works on VMIMO systems and node clustering in WSNs. VMIMO was first proposed by Dohler in [7,8] in the form of virtual antenna arrays. Then, several VMIMO systems for WSNs have been proposed in the literature (e.g., [6,9,10]). In these systems, several single-antenna nodes cooperate on information transmission/reception to achieve energy-efficient communications. The authors in [6] studied a cooperative MIMO scheme with Alamouti code for *single-hop* transmissions in WSNs. They analyzed the best modulation and transmission strategy to minimize the total energy consumption required to send a given number of bits. The results showed that over certain distances, both the total energy consumption and the total delay can be reduced, even when the energy and delay costs associated with the local information exchange are taken into account.

A cooperative MIMO scheme for delay and channel estimation was proposed in [9]. This scheme uses two transmitting sensors and space–time block codes to provide transmission diversity in distributed WSNs. Full diversity and full rate were achieved, which enhance power/bandwidth efficiency and reliability. It should be noted that neither antenna arrays nor transmission synchronization were used. In [10] energy efficiency and training overhead of cooperative MIMO WSNs were analyzed. The author compared the performance of such systems with that of SISO-based WSNs. The dependence of energy efficiency on the coherence time of the fading process and on the communications distance was considered. The incorporation of data aggregation into cooperative MIMO was recently considered [11]. Multi-hop VMIMO communications with distributed space–time coding were investigated in [12].

All the above VMIMO schemes exploit the diversity gain using distributed space–time codes. In [13] the author exploited the multiplexing gain of VMIMO to reduce the cooperation overhead and the circuit energy consumption.