Multi-Purpose Wireless Sensors Network Using Massive MIMO Technology over Hajj Area

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ABSTRACT

Multiple-input, multiple-output (MIMO) communications have attracted significant research interests lately because of their ability to improve the capacity and reliability of wireless channels. An aggressive version of MIMO communications technology using hundreds of antennas, known as large-scale or massive MIMO systems, has also recently emerged and became a candidate for the fifth-generation (5G) cellular system.

This emerging technology holds great potential for scaling up the wireless data rates to the Gigabit range targeted in the 5G cellular systems. In massive MIMO systems, large number of antenna elements, possibly hundreds or even thousands, work together to deliver huge data to multiple users on the same time-frequency resources. Massive MIMO can be employed to build a distributed Wireless Sensor Network (WSN). WSNs could be used to monitor the urban environment in real time, to facilitate automated control and to collect information for decision making. Large-scale WSNs can use thousands (or even more) of nodes, which is the case if we consider the context of smart cities.

In this paper, a distributed massive MIMO based collaboration between the sensors is proposed to be used over the Holy places in Makkah in order to improve the performances of large-scale wireless sensor networks. This configuration is expected to provide fast transmission, and high-quality dealing with huge and various data gathered from different places over the Holy places in Makkah, for various purposes including safety and monitoring from different nodes.

1 Introduction

Wireless Sensor Networks (WSNs) generally comprise of one or more sinks and large number of sensor nodes, possibly tens of thousands, which can be scattered randomly in an environment to monitor observables of interest. WSNs have been researched and developed for efficient energy performance where the sensed data should be delivered to the base station, for example, monitoring the facilities and the structures, detecting the intrusions for military defense, and observing the conditions of weather. WSNs are undoubtedly best suited to efficiently acquire and disseminate data on a large scale. These sensor nodes consist of sensing, data processing units, and communication components. Consequently, a large number of companies are proposing new small devices which can monitor different phenomena such as temperature, humidity, vibration, pressure, and several other factors. These sensors can be deployed to build a WSN. Thus, WSNs could be used to monitor the urban environment in real time, to facilitate automated control and to collect information for decision making. Nowadays, sensors are incorporated in most of our modern facilities, such as mobile phones, vehicles, buses, bus stops, bikes, etc.

Many studies have been conducted in order to apply WSNs to a wide range of applications. The majority have focused on several networking issues, such as routing, MAC, data gathering and dissemination mechanisms. Unfortunately, few studies have been conducted on large-scale WSNs, where the number of nodes can reach thousands or even more, which is the case if we consider the context of smart cities. In fact, the few studies such as that explicitly considered large-scale WSN are often optimized to meet the specific needs of the application and do not fully leverage the general network behaviors. Moreover, due to the intrinsic sensors characteristics including limited energy, limited communication range and a relatively large area of interest (urban areas), full connectivity could not be achieved. The nodes of the low levels are responsible for sensing and collecting the information from their environment, whereas the high level sensors are responsible for gathering the information from their low level sensors and then forwarding this information to the next high level. This hierarchical routing approach has proved to be more energy-efficient than a complete flat network. Unfortunately, this approach requires the deployment of higher energy nodes acting as cluster heads in order to gather, process and send the information from lower level nodes to higher level nodes. Since the cluster heads are acting as relays they will see their energy consumption fast increasing, unless they are given a high energy capability. In addition, the functioning of the cluster head can lead to a strong system degradation in terms of performance. In these environment, the requirement of networks are different from the traditional networks which have needed high throughput, low delivery delay, and large communication range, because the amount of traffic lowly presents on the environment used in WSN.

To meet these requirements, we propose to use, in this paper, a distributed massive-MIMO-based collaboration between the sensors in order to improve the performances of large-scale WSNs. Conventional Multiple-Input Multiple-Output (MIMO) wireless communication, through the use of multiple antennas both at the transmitter and at the receiver sides, has the potential of multiplying the capacity of a single channel of bandwidth W by the rank of the channel matrix. For sufficiently rich scattering, this rank is $r = \min(N_t;N_r)$, where N_t and N_r denote the number of transmitting and receiving antennas, respectively.

MIMO has the capability of multiplexing r independent channels, and therefore achieve an r-fold increase in system capacity. Recently cooperative MIMO has gained substantial research interest due to its capability to exploit conventional MIMO techniques for physically constrained mobile devices. In this case, the spectral efficiency for users is greatly improved when users share their antennas to jointly transmit and decode the data. In this paper, we focus on massive MIMO cooperative communications in the case of wireless sensor networks. This WSN makes the delivery of multimedia data, e.g., sounds, images, and videos, come true with high energy efficiency. The main idea is to use large number of antennas at the sensors nodes. By doing so, these sensors benefit from space-dimension (antennas) to increase the amount of sensed transferred data, and maintain energy efficiency thanks to massive MIMO features.

To illustrate the performance gains delivered by MIMO system as number of antennas increases comparing to a single-input single-output (SISO) system, Table 1 is constructed for a Rayleigh fading non-line-of-sight (NLoS) link with an average receive SNR of 20 dB and a constant total transmit power. The range is normalized to unity with reference to a 10-MHz SISO system.

Table 1: Bandwidth requirements and range of 1-Gbps link.

	SISO	MIMO				
Number of Antennas	1	2	4	6	8	10
Bandwidth, MHz	220	120	60	40	30	20
Coverage %, (reference w.r.t. 10 MHz)	35%	44%	55%	63%	71%	80%

It is noted that to support 1-Gbps speed by a SISO system, the required bandwidth is 220 MHz, and the reduction in range is 35%. On the other hand, a 10 × 10 MIMO system can achieve 1-Gbps performance with only 20-MHz bandwidth and still support 80% of the reference range. Clearly, MIMO technology offers a substantial performance improvement.

2 System Model

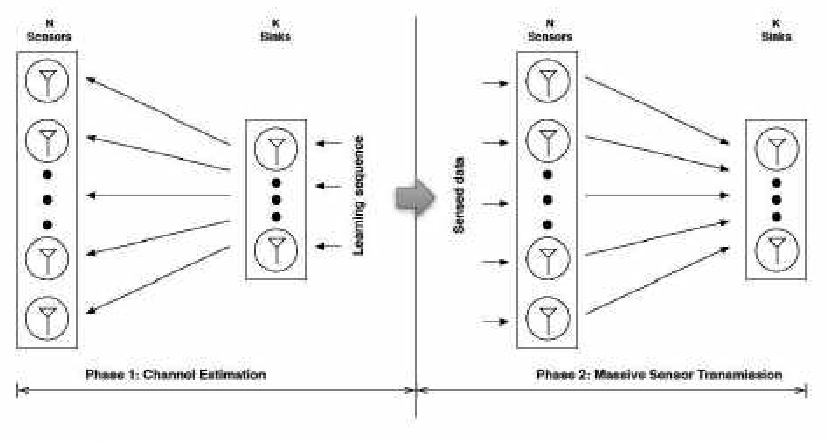

Fig. 1. Massive MIMO protocol.

Let L be a set of sensors randomly distributed in a two dimensional field. We consider that the L sensors are identical and equipped with N_t transmit antennas. In addition to the detection capability, each sensor is able to communicate in order to notify the sink of the event that has been detected.

Basically, when an event is detected, each sensor can send its message directly to the sink. In this paper, we assume that a set of K sinks are deployed within the area. In addition, we consider that the sensors are able to cooperate with each other in order to form a virtual antenna array to achieve a virtual MIMO communication system. This Virtual MIMO system is completely distributed since all the sensors are in different places. Each node is equipped with large number of antennas as depicted by Fig. 2, as shown below, and collects data matrix $\boldsymbol{X}_l$.

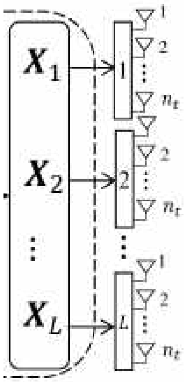

Fig. 2: L nodes each with n_t antennas, and collects L data matrices.

The functions performed at each control base station is shown in Fig.3

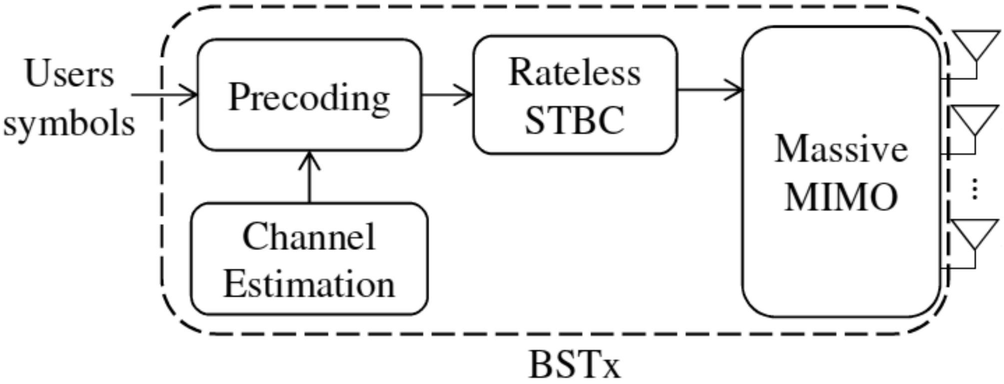

Fig. 3: Functions of the BS controller.

A layout of the proposed massive WAN is illustrated in Fig. 4, where Mina is taken as an example. Similar layouts can be configured for Muzdalefah, Arafat, or any other area. The network consists of various 7-cell clusters, where for each cluster the center base station (BS) is employed as controller. Each 500-meter radius cell contains number of uniformly-distributed nodes, as shown by Fig. 5.

The channel estimation is considered in this design since it is of a significant importance in massive MIMO systems. It is impractical to assume perfect channel estimation. In principle, the channel state information (CSI) may be acquired through transmission of orthogonal reference signals (pilots) from each transmit antenna element to the user equipment, and then feeding back the observed spatial channel from the user to the BS. This approach has the drawback that the reference signal overhead grows linearly with the number of transmit antennas. Alternatively, another method for obtaining the CSI is to utilize channel reciprocity, in particular under the assumption of TDD. Therefore, channel reciprocity can be exploited to estimate the downlink channels via uplink training. By doing so, the resulting overhead is linearly a function of the number of users rather than the number of BS antennas. In this paper, we consider the TDD-based channel estimation with the assumption of perfect calibration.

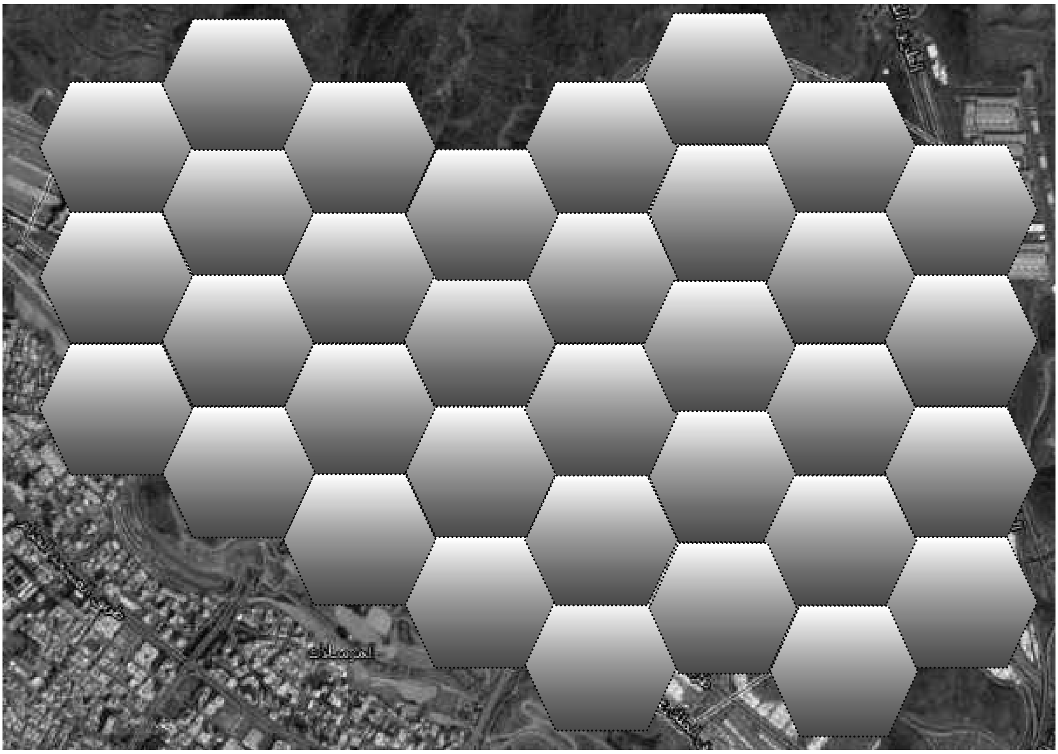

Fig. 4: Example of proposed WSN with massive MIMO systems over Mina Area

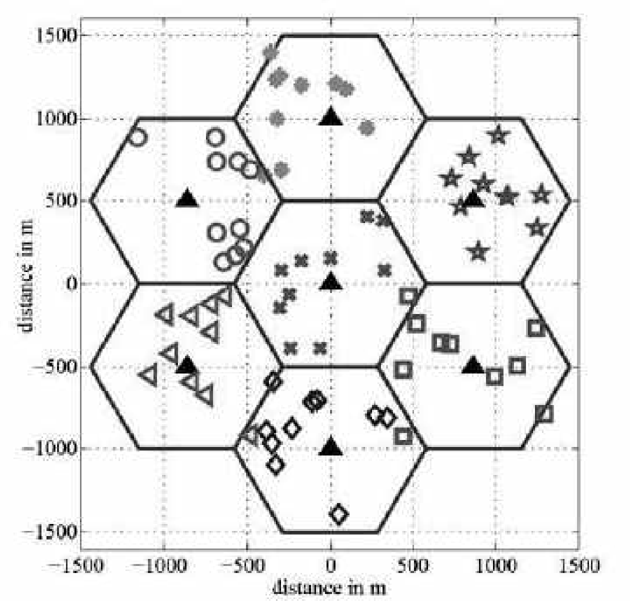

Fig. 5: 7-cell-grid where the control cell is the one in the center and the BSs are located at the center of cells. The cell radius is 500 m, and the number of nodes in each cell is the same and uniformally distributed.

3 Simulation Results and Discussion

Fig. 6 shows bit error rate (BER) MATLAB simulation against signal-to-noise- ratio (SNR) for different number of antennas N_t = 2, 8, 16, 32, 64 in a distributed MIMO system. As noted, as the number of antennas increases as BER gets better. This demonstrate the significant of using massive MIMO scheme in WSN.

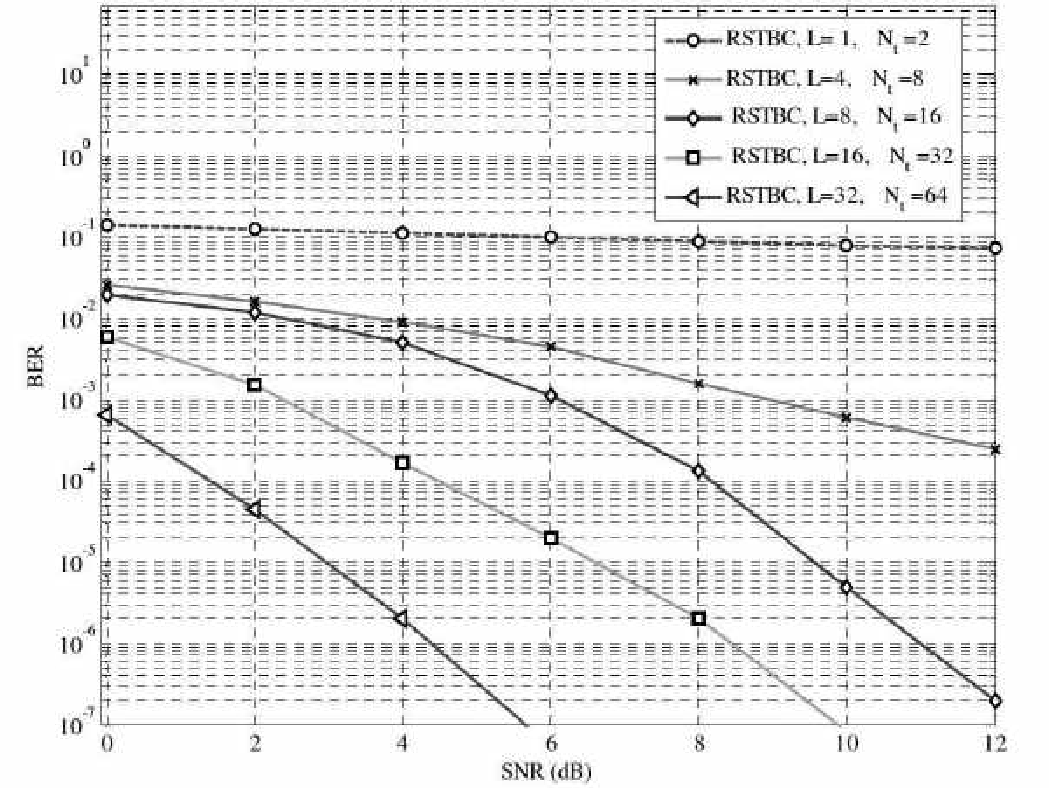

Fig. 6: BER of massive MIMO up to N_t = 64 (K = 2 users) with 16-QAM.
RSTBC: rateless space time block code

We demonstrate in this simulation that massive MIMO with N_t = 64 is capable of achieving the best performance. Specifically, from Fig. 6, for a target BER of 10^{-4}, as N_t is duplicated, a gain of almost 4 dB is achieved. The corresponding spectral efficiency is shown in Figure 5.4 where RSTBC approaches 4 b/s/Hz when 16-QAM is used. It is clear from the figure that with N_t = 64 effectively improves the efficiency of the system. Therefore, it is shown that the massive MIMO systems when deployed in WSN, exhibits a capacity-achieving characteristic and is effectively able to process huge data. Spectral Efficiency in b\Hz\s is depicted in Fig. 7. Table 2 illustrates the BER performance and spectral efficiency (at SNR = 4 dB) as inferred from Fig. 6 and Fig. 7, respectively.

It is noted by increasing the number of antennas at nodes, spectral efficiency increases, which enable to deal with more data transmitted by these nodes. This will help to use WSN nodes for collecting and monitoring more information simultaneously.

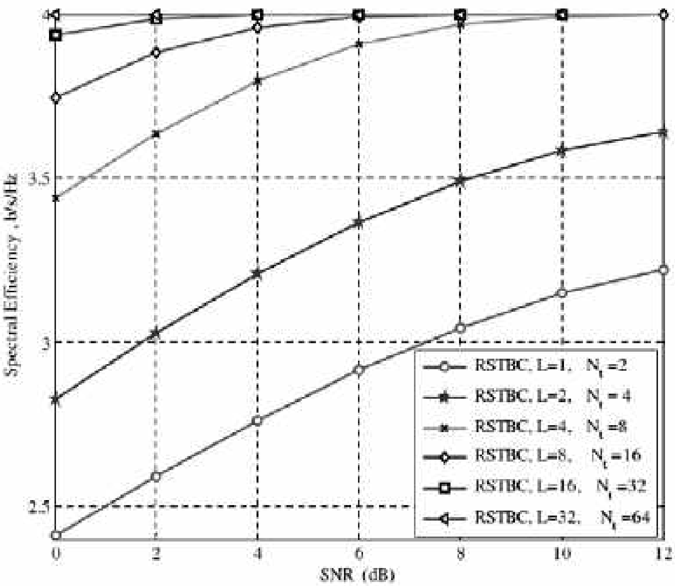

Fig. 7: Spectral Efficiency of massive MIMO up to $N_t = 64$ ($K = 2$ users) with 16-QAM.

Table 2: BER and spectral efficiency of massive MIMO with 16-QAM at SNR = 4 dB and loss rate = 25%.

L	N_t	BER, $\times 10^{-3}$	Spectral Efficiency, b/s/Hz
1	2	100	2.8
2	4	54	3.2
4	8	13	3.79
8	16	2.5	3.96
16	32	0.1	4
32	64	0.0008	4

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