Study of Performance of Cooperative Virtual MIMO System for WSNs.

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Abstract:

Multi-Input Multi-Output (MIMO) techniques can be used to increase the data rate for a given bit error rate (BER) and transmission power. Due to the small form factor, energy and processing constraints of wireless sensor nodes, a cooperative Virtual MIMO as opposed to True MIMO system architecture is considered more feasible for wireless sensor network (WSN) applications. Virtual MIMO with Vertical-Bell Labs Layered Space-Time (V-BLAST) multiplexing architecture has been recently established to enhance WSN performance. In this paper, we further investigate the impact of different modulation techniques, and analyze for the first time, the performance of a cooperative Virtual MIMO system based on V-BLAST architecture with multi-carrier modulation techniques. Through analytical models and simulations using real hardware and environment settings, both communication and processing energy consumptions, BER, spectral efficiency, and total time delay of multiple cooperative nodes each with single antenna are evaluated. The results show that cooperative Virtual-MIMO with Binary Phase Shift Keying-Wavelet based Orthogonal Frequency Division Multiplexing (BPSK-WOFDM) modulation is a promising solution for future high data-rate and energy-efficient WSNs.

Keywords: cooperative virtual MIMO; wavelet based OFDM; V-BLAST; wireless sensor networks

1. Introduction:

Due to advancement in Micro-Electro-Mechanical Systems (MEMS) technology, low power and low cost WSNs can be deployed in many real life applications, including environmental monitoring, home automation, traffic control, precision agriculture and health care. Wireless multimedia sensor networks (WMSNs) where sensor nodes are capable of producing different media streams (audio, video, image, textual, and scalar sensor data), are an emerging type of sensor networks which can facilitate automated real-time interpretation of situations in the monitored environment. Potential applications of such sensor networks include country borders and public spaces surveillance, wildlife habitat and seismic monitoring, in-home emergency detection for the sick and elderly, mixed reality networked gaming, and quality control of manufacturing processes. However, multimedia contents such as image or video streams require data rates that are orders of magnitude higher than what can be supported by current WSNs. Embedded sensors are also constrained in terms of energy as they are typically battery-powered. Thus, high data rates and high energy efficiency are key issues to be addressed in such networks

MIMO techniques can be used to increase data rate using spatial multiplexing and bit error rate (BER) can be improved by using spatial diversity. MIMO techniques can also be used to improve signal to noise ratio (SNR) at the receiver and to mitigate co-channel interference (CCI) along with beam forming techniques . However, MIMO systems also have a higher circuit complexity, which consumes energy. In long distance transmission, circuit energy consumption is typically much lower than transmission energy consumption. In short distance transmission, however, circuit energy consumption can be comparable with transmission energy consumption . Thus, to evaluate the performance of MIMO techniques in energy limited WSNs, where sensors are mostly powered by batteries or other exhaustible energy sources, one must take into account of both circuit and transmission energy consumption.

This paper focuses on cooperative virtual MIMO systems based on V-BLAST architecture for WSNs. Specifically, it analyzes the performance of such systems under different modulation techniques, including multi-carrier modulation techniques, which to our knowledge have yet to be investigated in literature for such systems. The modulation techniques considered include Fourier based OFDM (FOFDM), WOFDM, BPSK-FOFDM, BPSK-WOFDM, *M*-ary Quadrature Amplitude Modulation (QAM), *M*-ary Differential Quadrature Phase Shift Keying (DQPSK), and *M*-ary Offset Quadrature Phase Shift Keying (OQPSK). The analysis is performed across a broader range of performance metrics than previous related studied including BER, energy efficiency, spectral efficiency, and time delay performances. Given the critical importance of energy in WSNs, the detailed modeling and analysis of communication (circuit and transmission) energy consumption and processing (CPU or central processing unit) energy consumption of WSN nodes in different operating modes, is another key contribution of this paper. Findings of this study can provide useful insights into certain performance aspects and identify promising solutions for future high data-rate and energy-efficient WSNs.

2. Related Work:

In the energy and delay performances of cooperative virtual MIMO system with Alamouti coding for WSNs were investigated and compared with SISO system for the same throughput and BER. The performance was also compared over different transmission distances with the contemplation of circuit and transmission energy consumption. Alamouti coding is an STC technique in which space and time (two-dimensional coding) with multiple antenna setups can be used to attain coding gain and diversity gain for the same bit rate, transmission power and bandwidth as compared single antenna system. In STC techniques, information bits are transmitted according to some pre-defined transmission sequence. At the receiver, the received signals are combined by using optimal combining scheme followed by a decision rule for maximum likelihood detection .

A V-BLAST based virtual MIMO WSN with QAM was proposed in, which does not require spatial encoding on transmitting side nodes, thus eradicating the local communication and corresponding synchronization requirement on transmitting side nodes as previously involved . To make the system more energy efficient without any information loss, the use of WOFDM with V-BLAST based WSN was proposed in and evaluated under a co-located true MIMO receiver architecture. In, the BER performance of such systems was also observed using different V-BLAST detection algorithms.

With the advent of smart antennas for WSNs , a non-cooperative STC technique based MIMO system was recently proposed. By using 2-element switched antenna array, there is no requirement for local communication at transmitter and receiver side which makes the system more energy efficient. To simplify the structure of MIMO WSN for energy consumption reduction, a nonlinear MIMO technique was proposed , where real or imaginary part of the complex-valued received signal was considered for further processing which results in simpler receiver architecture at the cost of some information loss.

3. Background:

3.1. Cooperative Virtual MIMO:

MIMO techniques are capable of providing high system performance without additional transmission power and bandwidth. However, due to the small form factor and limited energy of sensor nodes, it is often not realistic to equip each sensor with multiple antennas to implement MIMO. Instead, a cluster of single-antenna sensor nodes can cooperate to form a virtual antenna array (VAA) to achieve virtual MIMO communication. Virtual MIMO systems are distributed in nature because multiple nodes are placed at different physical locations to cooperate with each other. With proper timing and frequency synchronization between constituent nodes of the VAA, virtual MIMO can realize the advantages of true MIMO techniques for WSNs.

3.2. V-BLAST:

V-BLAST is a spatial multiplexing technique to achieve spectral efficiency for a given bit rate and transmission power. It can boost channel capacity to improve the single-sensor data rate, or increase the number of supported sensors in the system. Its spectral efficiency ranges from 20–40 bps/Hz while efficiency of traditional wireless communication techniques ranges from 1–5 bps/Hz (mobile cellular) to around 10–12 bps/Hz (point to point fixed microwave system). In V-BLAST a single user's data stream is split into multiple sub-streams or multiple users can transmit their data simultaneously. An array of transmitter antennas is used to transmit all sub-streams simultaneously in the same frequency band, hence the spectrum is used very efficiently. Since the user's data is being sent in parallel over multiple antennas, the effective transmission rate is increased approximately in proportion to the number of transmit antennas used. In this system, the number of receivers is greater than or equal to the number of transmitters. The transmitted sub-streams are independent of one another. Individual transmitter power is scaled by $1/Nt$. Thus, the total power remains constant independent of the number of transmitters (Nt).

3.3. Multi-Carrier Modulation:

FOFDM is a multi-carrier modulation technique in which a high data rate substream is demultiplexed into lower data rate substreams to increase the duration of each substream so that inter-symbol interference (ISI) can be reduced. The orthogonal subcarriers are generated using sine/cosine bases and the orthogonality is achieved in a time window of width equal to the duration of the symbol. Therefore, FOFDM is not band limited. Each subcarrier produces side lobes that in turn create inter-carrier interference (ICI), which can be increased due to multipath channel effect that also cause an increase in ISI. Cyclic prefix (CP)/Guard Interval (GI) is added to each FOFDM symbol to avoid this problem at the cost of transmission efficiency degradation.

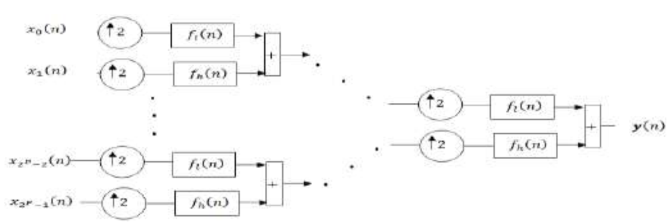

Figure 1. Symmetric multistage synthesis side QMF bank

4. System Model :

We consider a wireless communication link between *Nt* data sensing nodes (DSNs) serving as one Virtual MIMO transmitting side node, and one Virtual MIMO receiving side node which consists of one single-antenna data gathering node (DGN) and data assisting nodes (DANs), each with one antenna as shown in Figure 2

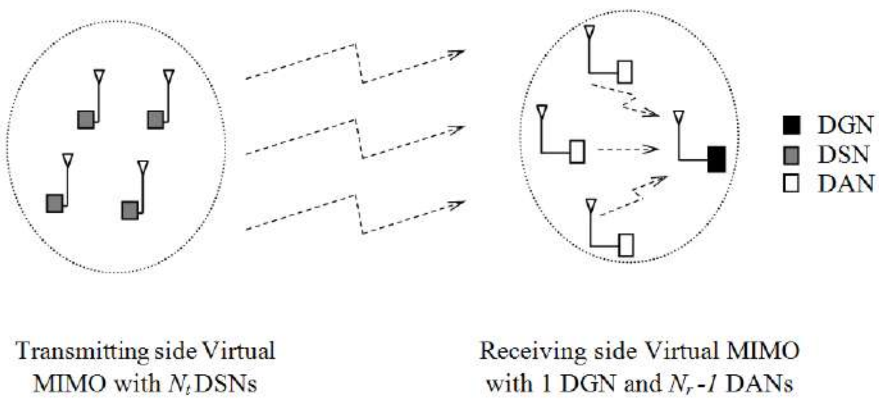

Figure 2. Communication between Transmitting and Receiving side Virtual MIMO nodes

5. Parametric Modeling of System Characteristics:

5.1. Energy Consumption:

In, the energy consumed in baseband signal processing blocks were neglected to keep the energy consumption model simple. However, in this paper, we have also computed the energy consumed by baseband (Digital) signal processing blocks. The DGN (often a more resourceful node serving as a sink) is considered to have no energy constraints unlike the DSNs and DANs .

RF (Analog) Energy Consumption:

The total energy consumption in RF section is due to long-haul communication (from DSNs to receiving side DANs and DGN itself) and receiver side local communication (from DANs to DGN). The total average power consumption along the signal path for long-haul can be divided into two main components: power consumption of all power amplifiers , and power consumption of all other circuit blocks. As, we assume that the power consumed by power amplifiers is linearly dependant on the transmit power :

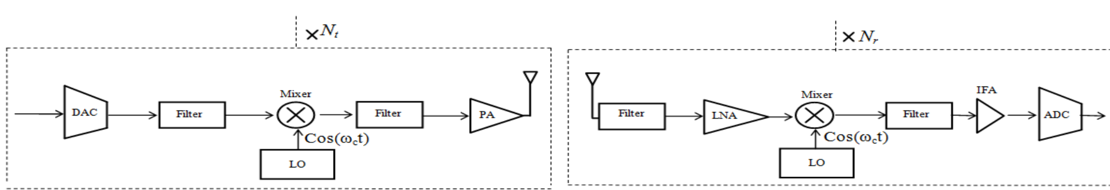

Figure 3. Transmitter and receiver architecture for WOFDM (analog).

Base Band (Digital) Energy Consumption:

The number of CPU cycles of a processing block is estimated by using Odyssey prediction model . To calculate the base band energy consumption of a block, the TelosB mote energy consumption per CPU cycle value is multiplied by the estimated number of CPU cycles. The energy consumed per bit by CPU during modulation , which also represents the base band energy consumption in transmit (Tx) mode, can be calculated by multiplying the estimated number of CPU cycles of the modulation processing block with energy consumption per CPU cycle and dividing it with total number of bits. The energy consumption per bit by CPU during demodulation and V-BLAST detection can be calculated similarly, and their sum represents the base band energy consumption in receive (Rx) mode. With *Nt* transmitters (DSNs) and *Nr* receivers (DANs and DGN),

6. Evaluation Results:

Simulations were carried out to investigate BER performance *vs.* bit-energy to noise-spectral density ratio *Eb*/*No* of 16-DQPSK, 16-QAM, 16-OQPSK, 16-FOFDM (without cyclic prefix), 16-WOFDM (4-level symmetric with Haar filter coefficients), BPSK-16FOFDM, and BPSK-16WOFDM with four DSNs (as one transmitting Virtual-MIMO node) and one DGN with three DANs (as one receiving Virtual-MIMO node) using Matlab/Simulink. Therefore, there are eight nodes in total in the system each with a single antenna. Matlab/Simulink is used as the simulation platform as it is one of the most widely used tools for physical layer modeling of wireless systems with many digital communication blocks and analyzing tools available for evaluating system performance. In addition, C and high definition languages (HDL) can be generated directly from Matlab/Simulink code for real hardware implementation.

The information source of each DSN generates data at a rate of 250 kbps according to IEEE 802.15.4-2009 standard for WSNs. The typical transmission range of IEEE 802.15.4 based radio transceivers is 10–20 m, with a nominal maximum range of about 100 m in clear line-of-scenarios. Accordingly, the distance between transmitting and receiving clusters is set to 20 m in this paper.
At each DSN, information bits are modulated into a symbol stream using 16-DQPSK, 16-QAM, 16-OQPSK, 16-FOFDM, 16-WOFDM, BPSK-16FOFDM, and BPSK-16WOFDM., the channel response matrix *H* is assumed to be known at DGN to detect the received signals using QR decomposition detection algorithm. All performance graphs are plotted with their 95% confidence intervals.

It is observed that 16-QAM and 16-DQPSK based systems are the least energy-efficient due to their poor BER performance and complex RF architecture, with the former being the more dominant factor. However, both techniques performed almost the same even though the BER performance of 16-DQPSK is poorer as compared to 16-QAM. This is due to the lower PAPR of 16-DQPSK which resulted in the RF (Analog) energy consumption performance of both techniques to be almost alike. 16-OQPSK system with complex RF architecture performs better than 16WOFDM and 16FOFDM system due to its better BER performance and lower PAPR. 16-WOFDM based system consumes less energy as compared to 16-FOFDM by approximately 40% due to its simpler RF architecture, which reduces the amount of circuit energy it consumes. For the same reason, BPSK-16WOFDM is also found to consume less energy than BPSK-16FOFDM by a similar margin. It is also observed that BPSK-16FOFDM and BPSK-16WOFDM are more energy efficient than 16-FOFDM, and 16-WOFDM, respectively, mainly due to their lower PAPR. it is clear that virtual MIMO system is more energy efficient as compared to SISO system due to better BER performance.
The base band energy consumption per bit per node for all modulation types along with their constituting energy consumed by individual modulator, demodulator, and detection algorithm are shown in Table 1. It

is observed that each modulator consumes more energy as compared to demodulator due to its higher computational complexity (in terms of CPU cycles per bit). For similar reasons, 16-DQPSK consumes less as compared to other modulation techniques. Since SISO system does not need to perform V-BLAST detection on receiver side (hence is negligible), the of BPSK-16WOFDM with virtual MIMO is higher as compared to that of the SISO system.

Modulation Type	**per bit in dBJ**	**per bit in dBJ**	**per bit in dBJ**	**per bit per node in dBJ**
16-DQPSK	–31.7203	–32.1389	–30.7033	–31.2591
16-QAM	–31.2628	–31.9686	–30.7033	–30.9803
16-OQPSK	–30.8951	–31.1203	–30.7033	–30.4600
16-FOFDM	–30.0134	–30.7192	–30.7033	–29.8781
16-WOFDM	–31.0294	–31.7203	–30.7033	–30.8009
BPSK-16FOFDM	–29.86	–30.587	–30.7033	–29.8167
BPSK-16WOFDM	–30.8764	–31.2681	–30.7033	–30.5142
SISO-BPSK-16WOFDM	–30.8764	–31.2681	$-\infty$	–31.0678

Table 1. Base Band (Digital) Energy Consumption

As discussed, the base band (digital) energy consumption and RF (analog) energy consumption is the energy consumed by the CPU, and radio transceiver, of the sensor nodes, respectively. We assume that both the CPU and radio transceiver has two active states (Transmit and Receive). For the CPU, the energy consumption in Transmit mode is the base band energy consumed by the digital modulator (hence depends on the modulation type) for processing each bit for transmission. On the other hand, the CPU or processing energy consumption in Receive mode is the base band energy consumed by the digital demodulator and V-BLAST detection algorithm

For the radio transceiver, we assume that whenever it is not transmitting or receiving, it will be put into sleep, *i.e.*, it has sleep mode as its only inactive state. The energy consumed by the transceiver in sleep mode will depend on the selected radio components that remain on during sleep state, which is design-specific. However, for most existing transceivers for WSNs, the sleep-to-receive energy consumption ratio is about 0.001, *i.e.*, the energy consumed in sleep mode is typically about 0.1% of the energy consumed in receive mode. Thus, the transceiver’s energy consumption per second in sleep mode can be calculated from (energy consumption by receiver circuits of the RF section per bit per node), which is found to be −34.8161 dBJ for 16-DQPSK, 16-QAM, 16-OQPSK, 16-FOFDM, and BPSK-16FOFDM, and −36.3601 dBJ for 16-WOFDM and BPSK-16WOFDM.

It is observed that is 1.75 μs/bit for all modulation techniques. is calculated using Equation . It is also observed that the modulator incurred a higher processing time than the demodulator . This is because more mathematical operations are involved in modulating the signal than demodulating. The total processing delay is considerably high as compared to and due to lower processing speed of TelosB mote.

Thus, is the most dominant time delay factor for the total time delay of virtual-MIMO. 16-DQPSK based system is found to incur the least total time delay due to its lower as compared to other six modulation techniques, followed by 16-QAM, 16-WOFDM, BPSK-16WOFDM, 16-OQPSK, 16-FOFDM, and BPSK-16FOFDM. is lower than because no is involved in the SISO system.

7. Conclusions:

This paper analyzes the performance of a cooperative virtual MIMO system using different modulation techniques in the context of WSNs. In terms of BER performance, BPSK-16WOFDM is found to outperform other evaluated modulation techniques by up to 95% for a given , and in terms of energy efficiency by up to a factor of two for a transmission distance = 100 m. On the other hand, DQPSK based system performs better in terms of total time delay by up to almost 23%. Thus, DQPSK based system can be a suitable option for WSN applications with less time delay requirement. Virtual MIMO system is 98% more energy efficient as compared to SISO system, which performs better in terms of total time delay by 35%. Overall, BPSK-WOFDM when combined with a cooperative virtual MIMO system architecture shows great potential as a solution for WSNs due to its simpler RF section, lower PAPR and better BER performance.

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