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Performance Evaluation of Sphere Decoding Algorithm for Spatially Multiplexed Multiple Input and Multiple Output System

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ABSTRACT:
The use of digital wireless communication systems has become more and more common during recent years. A multiple-input-multiple-output (MIMO) system using Space-Time Coding techniques can be implemented to enhance the capacity of a wireless link. The optimal decoder is based on the maximum likelihood principle. But as the number of the antennas in the system and the data rates increase, the maximum likelihood decoder becomes too complex to use. Examples of less complex decoding techniques used are zero-forcing and MMSE, as well as V-BLAST have been imple-mented at the price of reduced performance at the receiver. In this work, we investigate a new type of decoding algorithm called sphere decoding.
As will be apparent from the development to follow, this algorithm delivers near optimal performance with reasonably low complexity.We have investigated the performance of the sphere decoding algorithm. As it has shown in the computer simulations, the decoder based on the sphere decoding algorithm has almost the same performance of a maximum likelihood decoder with much lower complexity. Further simulations of the sphere decoding algorithms has shown, with the channel estimation error at the receiver, the decoder with the sphere decoding algorithm still has the same performance as in a ML decoder without increase the decoding complexity.

Keywords:
MIMO, Wireless communication systems, Space-Time Coding techniques, sphere decoding algorithm.

INTRODUCTION:
Concept of MIMO System:
The idea of using multiple receive and multiple transmit antennas has emerged as one of the most significant technical breakthroughs in modern wireless communications. Theoretical studies and initial prototyping of these MIMO systems have shown order of magnitude spectral efficiency improvements in communications. As a result, MIMO is considered a key technology for improving the throughput of future wireless broadband data systems MIMO is the use of multiple antennas at both the transmitter and receiver to improve communication performance. It is one of several forms of smart antenna technology.

MIMO:
Technology has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without requiring additional bandwidth or receiver incorporates multiple antennas by using space-time-frequency adaptive processing. Single-input single-output (SISO) is the well-known wireless configuration, single-input multiple-output (SIMO) uses a single transmit antenna and multiple receive antennas, multiple-input single-output (MISO) has multiple transmit antennas and one receive antenna. And multiuser-MIMO (MU-MIMO) refers to a configuration that comprises a base station with multiple transmit/receive antennas interacting with multiple users, each with one or more antennas. Transmit power. This is achieved by higher spectral efficiency and link reliability or diversity (Reduced fading). Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wi-Fi), IEEE

802.16e (WiMAX), 3GPP Long Term Evolution (LTE), 3GPP HSPA+, and 4G systems to come. Radio communication using MIMO systems enables increased spectral efficiency for a given total transmit power by introducing additional spatial channels which can be made available by using space-time coding. In this section, we survey the environmental factors that affect MIMO performance.

These factors include channel complexity, external interference, and channel estimation error. The multichannelterm indicates that the receiver incorporates multiple antennas by using space-time-frequency adaptive processing. Single-input single-output (SISO) is the well-known wireless configuration, single-input multiple-output (SIMO) uses a single transmit antenna and multiple receive antennas, multiple-input single-output (MISO) has multiple transmit antennas and one receive antenna. And multiuser-MIMO (MU-MIMO) refers to a configuration that comprises a base Station with multiple transmit/receive antennas interacting with multiple users, each with one or more antennas.

The constant advances in the world of wireless communications bring to end-users new services and features never expected in the past. Nevertheless, they also bring new challenges and issues to overcome. A major problem to solve is the quick growth of energy consumption in the Information and Communications Technologies (ICT) infrastructure. Mobile and other wireless communications are great contributors to the rapidly increasing rate of ICT traffic due to the innovative services supported by the latest mobile platforms, increasing every day the energy consumed. According to the often-cited Gartner report, the ICT Market contributes 2% of global GHG, Greenhouse Gases (CO_2) emissions. This contribution will rapidly grow if no immediate measures are taken. The first problem of the high levels of energy consumption is that it is often necessary to use fossil fuel (e.g. diesel), which produces large amounts of GHG.The major part of the huge demands of energy comes from the radio access network (RAN), which represents 57% of the energy consumption of a cellular network.

The high energy consumption of the RAN is due to two major reasons. First, the inefficient power supply conversion into transmission by base station (BS) systems, where the RF power amplifier section consumes between 60 and 70% of the energy supplied, dissipating a remarkable quantity of energy in terms of heat and only a small fraction corresponds to the useful output.Consider the downlink transmission in a single-cell cellular network. A list of all notations used in this paper for describing the considered model and its analysis is provided in the Nomenclature section. In this model, the BS can jointly utilize two CCs that are classified into primary CC (PCC) and secondary CC (SCC). The PCC is looked upon as the main CC for transmissions, while the SCC is thought of as the supplementary CC when the traffic is relatively heavy.

Assume that the two CCs are consecutively located in the same band and each has bandwidth B in Hz. The LTE-A frame structure that the scheduling process is executed subframe by subframe is followed. In each subframe, there are J subchannels and two time slots. The resource block (RB), which consists of seven OFDM symbols in one time slot and 12 subcarriers in one subchannel, is set as the smallest allocation unit.The total energy consumption in each subframe for the BS transceivers of OFDMA-based multiple CCs, while maintaining certain quality-of-service (QoS) minimum required levels and the fairness among users. Here, the QoS is considered to be the blocking probability and the data rate. This paper focuses on the downlink transmission and supports both the real-time (RT) and the nonreal-time (NRT) traffics simultaneously.

Motivated by the practical need to more reasonable energy-saving designs in this area, a novel green scheme based on the rate-and-power control design is therefore proposed for efficiently solving the considered problem. The presented scheme also includes necessary scheduling and call admission control mechanisms. Focus on energy-efficient transmission, discussing the research on some techniques like MIMO, OFDM/OFDMA, adaptive modulation, scheduling, etc. The radio resource allocation and transmission mechanisms are viewed from three different perspectives: space, frequency and time domain.

Functions of MIMO:

MIMO can be sub-divided into three main categories, precoding, spatial multiplexing or SM, and diversity coding.

Precoding:

It is multi-stream beamforming, in the narrowest definition. In more general terms, it is considered to be all spatial processing that occurs at the transmitter. In (single-stream) beamforming, the same signal is emitted from each of the transmit antennas with appropriate phase and gain weighting such that the signal power is maximized at the receiver input. The benefits of beamforming are to increase the received signal gain, by making signals emitted from different antennas add up constructively, and to reduce the multipath fading effect. In line-of-sight propagation, beamforming results in a well defined directional pattern. However, conventional beams are not a good analogy in cellular networks, which are mainly characterized by multipath propagation. When the receiver has multiple antennas, the transmit beamforming cannot simultaneously maximize the signal level at all of the receive antennas, and precoding with multiple streams is often beneficial. Note that precoding requires knowledge of channel state information (CSI) at the transmitter and the receiver.

Spatial multiplexing:

It requires MIMO antenna configuration. In spatial multiplexing, a high rate signal is split into multiple lower rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures and the receiver has accurate CSI, it can separate these streams into (almost) parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher signal-to-noise ratios (SNR). The maximum number of spatial streams is limited by the lesser of the number of antennas at the transmitter or receiver. Spatial multiplexing can be used without CSI at the transmitter, but can be combined with precoding if CSI is available. Spatial multiplexing can also be used for simultaneous transmission to multiple receivers, known as space-division multiple access or multi-user MIMO, in which case CSI is required at the transmitter.The scheduling of receivers with different spatial signatures allows good separability.

Diversity Coding:

It techniques are used when there is no channel knowledge at the transmitter. In diversity methods, a single stream (unlike multiple streams in spatial multiplexing) is transmitted, but the signal is coded using techniques called space-time coding. The signal is emitted from each of the transmit antennas with full or near orthogonal coding. Diversity coding exploits the independent fading in the multiple antenna links to enhance signal diversity. Because there is no channel knowledge, there is no beamforming or array gain from diversity coding. Diversity coding can be combined with spatial multiplexing when some channel knowledge is available at the transmitter.

Forms of MIMO:

Multi-antenna types:

Multi-antenna MIMO (or Single user MIMO) technology has been developed and implemented in some standards, e.g., 802.11n products.

- **SISO/SIMO/MISO are special cases of MIMO**

Multiple-input and single-output (MISO) is a special case when the receiver has a single antenna.Single-input and multiple-output (SIMO) is a special case when the transmitter has a single antenna.single-input single-output (SISO) is a conventional radio system where neither the transmitter nor receiver have multiple antenna.

- **Principal single-user MIMO techniques:**

Bell Laboratories Layered Space-Time (BLAST), Gerard. J. Foschini (1996)Per Antenna Rate Control (PARC), Varanasi, Guess (1998), Chung, Huang, Lozano (2001)Selective Per Antenna Rate Control (SPARC), Ericsson (2004)

- **Some limitations**

The physical antenna spacing is selected to be large; multiple wavelengths at the base station. The antenna separation at the receiver is heavily space constrained in hand sets, though advanced antenna design and algorithm techniques are under discussion.

Multi-user types:

Recently, results of research on multi-user MIMO technology have been emerging. While full multi-user MIMO (or network MIMO) can have a higher potential, practically, the research on (partial) multi-user MIMO (or multi-user and multi-antenna MIMO) technology is more active.

- **Multi-user MIMO (MU-MIMO)**

In recent 3GPP and Wi MAX standards, MU-MIMO is being treated as one of the candidate technologies adoptable in the specification by a number of companies, including Samsung, Intel, Qualcomm, Ericsson, TI, Huawei, Philips, Alcatel-Lucent, and Freescale. For these and other firms active in the mobile hardware market, MU-MIMO is more feasible for low complexity cell phones with a small number of reception antennas, whereas single-user SU-MIMO's higher per-user throughput is better suited to more complex user devices with more antennas.

PU^2RC allows the network to allocate each antenna to a different user instead of allocating only a single user as in single-user MIMO scheduling. The network can transmit user data through a codebook-based spatial beam or a virtual antenna. Efficient user scheduling, such as pairing spatially distinguishable users with codebook based spatial beams, is additionally discussed for the simplification of wireless networks in terms of additional wireless resource requirements and complex protocol modification. Recently, PU^2RC is included in the system description documentation (SDD) of IEEE 802.16m (WiMAX evolution to meet the ITU-R's IMT-Advance requirements).

Enhanced multiuser MIMO: 1) Employs advanced decoding techniques, 2) Employs advanced precoding techniques SDMA represents either space-division multiple access or super-division multiple access where superemphasises that orthogonal division such as frequency and time division is not used but non-orthogonal approaches such as superposition coding are used.

- **Cooperative MIMO (CO-MIMO)**

Uses distributed antennas which belong to other users.

- **Macrodiversity MIMO**

A form of space diversity scheme which uses multiple transmit or receive base stations for communicating coherently with single or multiple users which are possibly distributed in the coverage area, in the same time and frequency resource.[10][11][12]The transmitters are far apart in contrast to traditional micro diversity MIMO schemes such as single-user MIMO. In multi-user macro diversity MIMO scenario, users may also be far apart. Therefore, every constituent link in the virtual MIMO link has distinct average link SNR. This difference is mainly due to the different long-term channel impairments such as path loss and shadow fading which are experienced by different links.

Macrodiversity MIMO schemes pose unprecedented theoretical and practical challenges. Among many theoretical challenges, perhaps the most fundamental challenge is to understand how the different average link SNRs affect the overall system capacity and individual user performance in fading environments.[13]

- **MIMO Routing:**

Routing a cluster by a cluster in each hop, where the number of nodes in each cluster is larger or equal to one. MIMO routing is different from conventional (SISO) routing since conventional routing protocols route node by node in each hop.

Applications of MIMO:

Spatial multiplexing techniques make the receivers very complex, and therefore they are typically combined with Orthogonal frequency-division multiplexing (OFDM) or with Orthogonal Frequency Division Multiple Access (OFDMA) modulation, where the problems created by a multi-path channel are handled efficiently. The IEEE 802.16e standard incorporates MIMO-OFDMA. The IEEE 802.11n standard, released in October 2009, recommends MIMO-OFDM.MIMO is also planned to be used in Mobile radio telephone standards such as recent 3GPP and 3GPP2. In 3GPP, High-Speed Packet Access plus (HSPA+) and Long Term Evolution (LTE) standards take MIMO into account. Moreover, to fully support cellular environments, MIMO research consortia including IST-MASCOT propose to develop advanced MIMO techniques, e.g., multi-user MIMO (MU-MIMO).

MIMO technology can be used in non-wireless communications systems. One example is the home networking standard ITU-T G.9963, which defines a power line communications system that uses MIMO techniques to transmit multiple signals over multiple AC wires (phase, neutral and ground).In this paper, we adopt the notion of interference nulling in a MIMO-OFDM system and treat the IBI part as an interference channel. We propose a channel independent precoding scheme for a MIMO-OFDM system with insufficient CP or even no CP. We show that our proposed precoding scheme can eliminate the IBI caused by the insufficient CP with a higher bandwidth efficiency than the conventional zero-padding or a sufficient CP adding when the number, n , of receive antennas is no more than the number, ntr of transmit antennas, i.e., nr = nt.

Interestingly, when nt=1and n=1, i.e., the single antenna case, in this paper, the IBI incurred from the insufficient CP can be aligned to a subspace of dimensions no more than a half of the difference of the ISI channel length and the insufficient CP length, thus the other half can be used for sending more information symbols. In this paper, it is also shown that when nr>ntr, the IBI can be eliminated similarly without any zero-padding or adding CP or precoding when the OFDM block length is not too small.

Spatial Correlation:

Theoretically, the performance of wireless communication systems can be improved by having multiple antennas at the transmitter and the receiver. The idea is that if the propagation channels between each pair of transmit and receive antennas are statistically independent and identically distributed, then multiple independent channels with identical characteristics can be created by pre coding and be used for either transmitting multiple data streams or increasing the reliability (in terms of bit error rate). In practice, the channels between different antennas are often correlated and therefore the potential multi antenna gains may not always be obtainable. This is called spatial correlation as it can be interpreted as a correlation between a signal's spatial direction and the average received signal gain.

V-BLAST:

Illustrated in Figure below, spatial multiplexing or V-BLAST (Vertical Bell Labs Layered Space-Time) [3] is proposed as a multiple antenna system. The V-BLAST architecture breaks the original data stream into M substreams that are transmitted on the individual antennas without intercoding among the transmitter antennas. If we for simplicity assume that the substreams are uncoded, the transmission can be seen as using a block code of length one. The corresponding codeword can be written as

$$C = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_M \end{bmatrix}. \qquad (3.2)$$

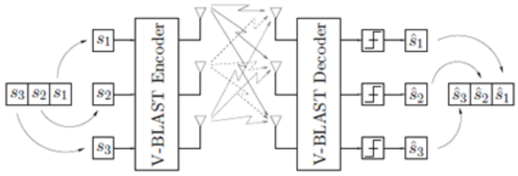

Figure : Block diagram of V-BLAST structure with M = 3, N = 3.

The V-BLAST detector decodes the substreams using a sequence of nulling and cancellation steps. An estimate of the strongest transmitted signal is obtained by nulling out all the weaker transmit signals using the zero forcing criterion, then subtract this strongest signal from the received signal, proceed to decode the strongest signal of the remaining transmitted signals, and so on.

SPHERE DECODING:

Maximum-likelihood decoding of a random code over an additive white Gaussian noise channel requires an exhaustive search over all the possi-blecodeword, and so the computational complexity of the optimal decoding scheme is exponential in the length of the codeword. A new type of the detection technique called the sphere decoding algorithm [13] is proposed to lower the computational complexity. The principle of the sphere decoding algorithm is to search the closest lattice point to the received signal within a sphere radius, where each codeword is represented by a lattice point in a lattice field [14]. In a two-dimension problem illustrated in Figure below, one can easily restrict the search by drawing a circle around the received signal just enough to enclose one lattice point and eliminate the search of all the points outside the circle.

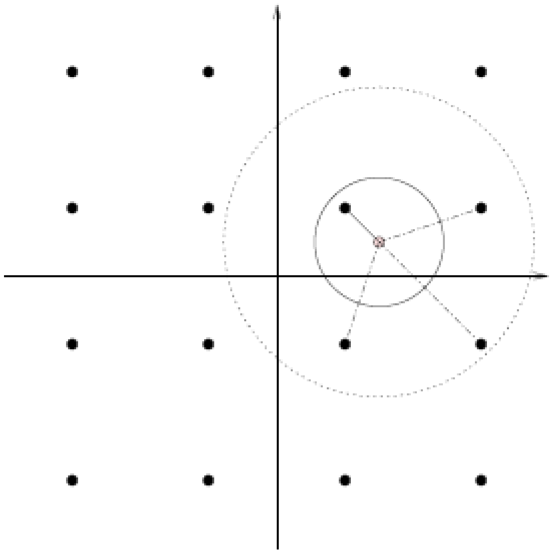

Figure : Geometrical representation of the sphere decoding algorithm.

Implementation:

The following steps shows the implementation of the sphere decoding algo-rithm

Input: R, **y**, **x**ˆ, d, s^1.

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1. Set $k = Q$,
$d_Q'^2 = d^2 - \|\boldsymbol{y}\|^2 + \|\boldsymbol{A}\hat{\boldsymbol{x}}\|^2$,
$\hat{x}_{Q|Q+1} = \hat{x}_Q$.

2. (Set bound for x_k)
$z = \frac{d_k'}{u_{kk}}$,
$UB(x_k) = \lfloor z + \hat{x}_{k|k+1} \rfloor$,
$x_k = \lceil -z + \hat{x}_{k|k+1} \rceil - s$.

3. (Increase x_k)
$x_k = x_k + s$.
If $x_k \leq UB(x_k)$ go to 5.

4. $k = k + 1$;
if $k = Q + 1$, terminate algorithm, else go to 3.

5. (Increase k) $k = 1$ go to 6.
Else $k = k - 1$,
$\hat{x}_{k|k+1} = \hat{x}_k + \sum_{j=k+1}^{Q} \frac{u_{kj}}{u_{kk}}(x_j - \hat{x}_j)$,
$d_k'^2 = d_{k+1}'^2 - u_{k+1,k+1}^2(x_{k+1} - x_{k+\hat{1}|k+2})^2$, and go to 2.

6. Solution found. Save $\boldsymbol{x}$ and go to 3.

Illustrated in Figure below, we modified the original sphere decoding algorithm. When a lattice point is found inside the sphere, the search radius is updated. Also the upper bounds are recalculated to limit the number of lattice points that need to be searched.

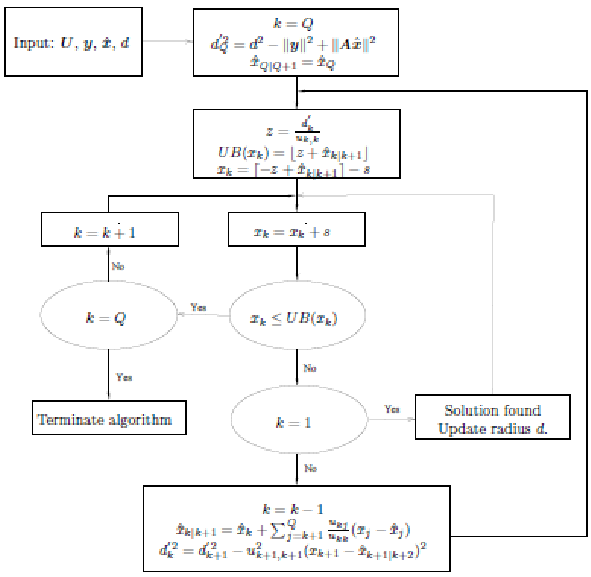

Figure : Flowchart of the sphere decoding algorithm, s is distance be-tween constellation points.

Conclusion:

In this master's thesis work, we have focused on a multiple antenna system in a flat fading environment. We compared the performance of four decoders with different techniques, including zero-forcing, V-BLAST, maximum like-lihood and sphere decoding algorithm. The zero-forcing and V-BLAST de-coder are simple decoders with low complexities. But these two decoders have low performance compared to the maximum likelihood decoder, which in some sense is the optimal decoder, but it has high decoding complexity. We used the concept of a linear system model to show that the sphere decoding algorithm offers near maximum likelihood performance with lower decoding complexity. For the original version of the sphere decoding algo-rithm, the initial radius of the sphere for the search is important to deter-mine, since the complexity depends on the search radius.

During the de-velopment process, a modified version of the sphere decoding algorithm has investigated, which operate on the assumption that after each lattice point found to be inside the sphere, the radius is decreased to the distance between the best solution and the received signal vector. In general, the sphere de-coding algorithms outperform the decoder with V-BLAST and zero-forcing techniques, with lower complexity than the maximum likelihood decoder in high order constellation and large numbers of antenna. We have also investigated the impact on the performance due to the channel estimation errors. In the computer simulation, the performance of the sphere decoding algorithms are very close to the maximum likelihood decoder. In the high SNR region, it seems that the original version of the sphere decoding algorithm has poor performance.

This is because the initial search radius has not taken channel estimation errors into consideration. In a real situation, this case will not be very common, since when noisevariance is small, the channel estimator will be much accurate. With the modified algorithm, the sphere decoding algorithm is independent of the initial search radius, which leads to a high performance algorithm with lower computational complexity compared to the maximum likelihood decoding algorithm.

Future Work :

The computational complexity of the sphere decoding algorithm with fixed radius depends on the initial search radius. We have used the noise variance to determine the length of the radius. In the computer simulations with channel estimation errors, it seems that the system has poor perfor-mance in the high SNR region. A new method should be investigated to find a new way to determine the initial search radius, which has to take the channel estimation errors into consideration.Furthermore, a more complex channel model can be studied for this algorithm, such as channel with memories. Then it is interesting to compare its performance with decoders that use decision feedback.

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