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Spatial Modulation Explained and Routes for Practical Evaluation

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Spatial Modulation Explained and Routes for Practical Evaluation

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Abstract

Spatial modulation (SM) is a novel communications scheme that combines multi-antenna enhancements with a simple decoding structure. Unlike previous approaches to multiple-input multiple-output (MIMO) communications, information is encoded not only in a conventional QAM style symbol, but also in the unique spatial signature of each transmit antenna. SM, in its most basic form, operates such that only one transmit antenna is active at any point in time. At the transmitter the information bit stream is mapped to a combination of a QAM symbol and a transmit antenna index, the received signal is then decoded through estimation of the transmitted QAM symbol and the active transmit antenna index. The configuration of SM can greatly simplify the hardware requirements of MIMO communications and avoid inter-channel-interference, while still benefiting from an increase in spectral efficiency.

The simple receive hardware requirement of SM is well suited to mobile applications, and has lead to research into its application as a 4G wireless communications technique. Research Council UK has provided €1m funding through the UK-China Science Bridges project to research aspects of 4G wireless mobile communications, including SM. This project brings researcher from seven Chinese academic institutions and six industrial partners, together with 29 UK consortium members. Through the project funding, SM techniques are jointly being investigated through a collaboration between three UK universities. The project aims to combine SM systems, developed by the University of Edinburgh, with multi-antenna channel measurements obtained from urban environments by the University of Bristol, into full system simulations, which can then be tested on a National Instruments MIMO testbed at Heriot-Watt University. The final system will then be used to evaluate the suitability of SM as a 4G wireless access technology.

1 Introduction

As 4G cellular services are rolled out over the world, researchers are focusing their efforts on methods to improve the current technology, as well as develop beyond 4G (B4G) technology. 4G and B4G technologies are expected to make extensive use of MIMO techniques [1], this will allow higher data rates, as well as more efficient mobile communications.

The research council UK (RCUK) has provided funding to create a UK-China science bridge that aims to develop (B)4G technologies, one of the tasks within the project is to develop a prototyping system to test the communication techniques.

Developing wireless communications techniques from concept to final device can be a long and arduous process, where the systems suitability must be tested against existing and competing technologies in a variety of scenarios. In initial development, of multi antenna systems, simple channel models can be used, however, as the system develops it should be tested on more realistic channels, which include the complex interactions between the environment and antennas, as well as the correlation between spatial channels. These channels can be from ray tracer models, or from channel measurements. After the system has been tested with the realistic channels, it is then possible to progress to analysing the system using a hardware testbed, these are able to incorporate hardware limitations as well as test the viability of higher layer networking protocols. After extensive evaluation on the testbed, it is then possible to prototype the system.

Multi-antenna techniques can offer significant performance gains over conventional single antenna systems, however, these gains are often accompanied by an significant increase in the computational complexity at the receiver, due to the inter channel interference (ICI) caused by the simultaneous transmission from multiple antennas. Spatial modulation (SM) was initially proposed in [2], and has been developed into a system that alleviates the complexities of decoding conventional multi-antenna systems by only activating a single transmit antenna at any point in time, thus avoiding ICI in the received signal [3–5]. SM encodes the transmitted information using both the transmitted signal and spatial signature of each transmitter, this has several benefits, including lower complexity transmit and receive hardware, and an increase in spectral efficiency compared to conventional single transmit antenna systems.

SM has attracted interest from the members of the UK-China science bridge project as a possible (B)4G technology. Funding has been made available to facilitate the collaboration of three universities in the UK, each with specialist knowledge in the field of mobile communications. The University of Edinburgh have been the main driving force behind the development of SM techniques [3–7]. The University of Bristol have significant knowledge of urban propagation channel measurement and analysis [8]. Heriot-Watt University as well as having extensive wireless communications knowledge have recently gained access to an National Instruments MIMO testbed, suitable for analysing proposed (B)4G techniques. Together the institutions aim to develop a SM based 4G system that has been analysed using both channel MIMO measurements, captured within the city of Bristol, and analysed on a hardware testbed.

This paper aims to introduce the concept of SM as well as to give an overview of the UK-China science bridges project, and details the proposed deliverables of the SM based (B)4G prototype system. The rest of the paper is structured as follows, in Section 2 an overview of SM technology will be give, detailing the concept of SM as well as the advantages and disadvantages it brings. In Section 3 details the UK-China science bridge project. Section 4 provides an in-depth plan of the work to be carried out in the project by the institutions. The paper is then concluded in Section 5 highlighting the proposed deliverables and milestones of the project.

2 Spatial Modulation Technology

Spatial Modulation (SM) is a another MIMO system, which has been proposed to increase the spectral efficiency of single–antenna systems and overcome ICI [9]. This is attained through the adoption of a new modulation and coding scheme, which foresees: i) the activation, at each time instance, of a single antenna that transmits a given data symbol (*constellation symbol*), and ii) the exploitation of the spatial position (index) of the active antenna as an additional dimension for data transmission (*spatial symbol*) [5]. Both the *constellation symbol* and the *spatial symbol* depend on the incoming data bits. An overall increase by the base–two logarithm of the number of transmit–antenna of the spectral efficiency is achieved. Note that, the number of transmit antennas must be a power of two.

In Figure 1, $\mathbf{q}(n)$ is the incoming binary data to be transmitted over the MIMO channel. In SM, each $m = \log_2(MN_t)$ bits, where M is the QAM constellation size, are transmitted at a particular time instance. The matrix $\mathbf{x}(n)$ is created by grouping each m bits from $\mathbf{q}(n)$ as the column vectors of $\mathbf{x}(n)$. The matrix $\mathbf{x}(n)$ is then mapped to another matrix $\mathbf{s}(n)$ according to the mapping table as shown in Figure 1. Each column vector in $\mathbf{s}(n)$ contains the data to be transmitted at a particular time instance over the MIMO channel. Since, however, only one element in each column vector of $\mathbf{s}(n)$ is different from zero; only one antenna will be active at a time instance.

For instance, an example is shown in Figure 1 for two time instances. The incoming data sequence $\mathbf{q}(n) = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$ is mapped to

$$\mathbf{s}(n) = \begin{pmatrix} 0 & 0 \\ -1 & 0 \\ 0 & +1 \\ \underset{(n=1)}{0} & \underset{(n=2)}{0} \end{pmatrix}. \quad (1)$$

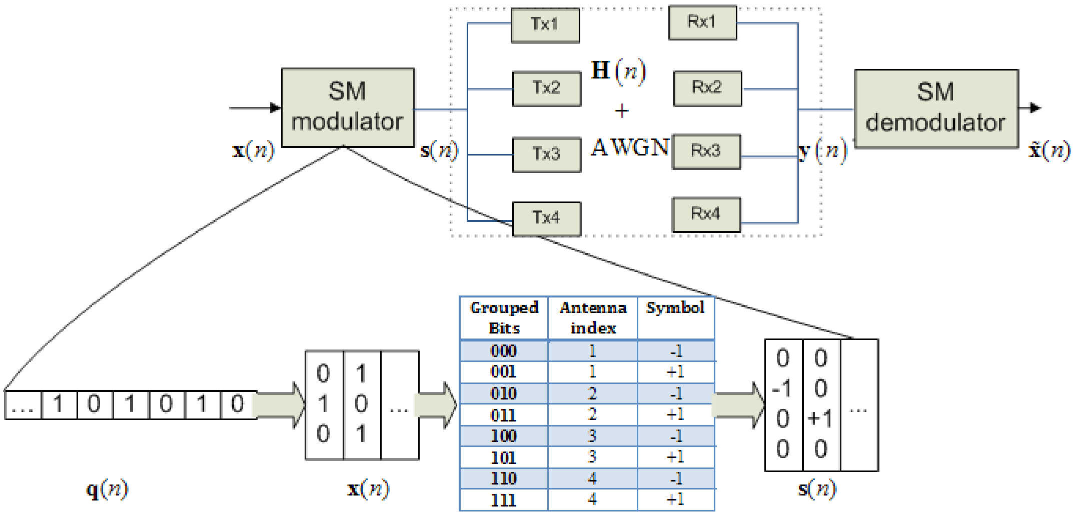

Figure 1: Spatial modulation system model and the mapping table to antenna indices and BPSK symbols. At each time instance, three bits are transmitted. Two are encoded in the antenna index and one in the BPSK symbol.

In the first time instance, the second antenna will be active and transmitting the BPSK symbol $s = -1$. All other antennas at this particular time instance will be off. In the second time instance, all transmit antennas are off except antenna three which will be transmitting the symbol $s = +1$. Hence, an overall increase in spectral efficiency by $\log_2(N_t)$ as compared to single input single output (SISO) system is achieved.

At the receiver the SM–ML detector [10] performs an exhaustive search over all possible combinations. Unlike the Spatial Multiplixing (SMX) ML detector, SM–ML offers a substantial reduction in receiver complexity as there is no ICI to be resolved, since, in SM, only one transmit antenna is active at each time instance.

3 UK-China Science-Bridges Project

The establishment of UK science bridges were created by the RCUK to develop collaboration between the UK and China, India and the US. £4m in funding was set aside for each country to help develop and share knowledge between various institutions. Four UK-China science bridges were setup, with £0.9m provided to one of the science bridges to research 4G and B4G technologies. The funding was initiated in August 2009, and will run for 3 years, ending in July 2012.

The project researching into (B)4G technologies involves 29 UK consortium members, including 10 universities, Mobile VCE and 18 industrial members of the Mobile VCE. The Chinese consortium involves 13 members, including 7 universities and 6 industrial members. The project hopes to fund visits and workshops between partners, as well as developing prototype of 4G technologies. The consortium members can be found at `http://uc4g.eps.hw.ac.uk`, as well as further details about the UK-China science bridges project researching into 4G technologies.

The three year project was divided into six work packages, each with a clearly defined objective, milestones and deliverables. Work package 4 (WP4) was tasked with prototype development and test of (B)4G wireless mobile communication technologies. It is through WP4 that SM wil be developed and analysed as a (B)4G technique.

4 SM System Development

The project aim is to prototype a SM based (B)4G system. To do this it will combine expertise from University of Edinburgh, University of Bristol and Heriot-Watt University. The University of Edinburgh will be predominantly involved in the design of the SM system. The University of Bristol will use urban channel measurement data, taken at 2 GHz, to test the proposed SM systems. Once the SM has been tested using the channel measurement data, it will then be applied to the NI multi-antenna testbed at Heriot-Watt University.

The University of Edinburgh have extensive knowledges in SM techniques, and as part of WP4 have developed a simulator written in MatLab. The simulator is designed to operate using theoretical channel models, the urban channel models captured by Bristol university and the indoor propagation environment experienced by the NI testbed from Heriot-Watt University. As one of the key advantages of SM systems is the reduction in the decoding complexity, various decoding architectures will be tested. Early SM systems tended to use maximum ratio combining to estimate the active antenna. However these systems suffered from poor performance under certain circumstances, instead maximum likelihood optimal decoders were proposed [10]. To reduce the complexity of the optimum decoders sphere decoding will be tested as well a the decoders sensitivity to imperfections in the communications link, such as frequency offset and channel estimation errors.

Theoretical channel models can account for spatial channel correlation as well as power imbalances within the channels, however, the channel properties experienced in real environments can be often produce unexpected results that are not modelled by the theoretical models. The urban channel models captured by the University of Bristol will be categorised depending on their K-factor, spatial channel correlation, channel power imbalances and other metrics so their effects on the SM system can be characterised.

The performance of the SM system will then be benchmarked using the same channel conditions against a range of other multi-antenna techniques, including Alamouti STBC and spatial multiplexing

As part of the Mobile VCE MIMO elective, extensive multi-antenna channel measurements were taken around the city centre of Bristol in mid 2005. A MEDAV RUSK channel sounder was used, operating with a 20 MHz bandwidth centred at 2 GHz, and configured as a 4×4 MIMO system. The multi-element transmitting station was based on a pair of spatially separated (3m) dual polarised ($\pm45^\circ$) commercially available panel antennas (Racal XP651772) deployed on a roof top providing elevated coverage of the central business and commercial districts of the City of Bristol. Three different 4-port receiving antenna systems were developed specially for these trials (reference dipole headset, PDA and lap-top designs) and carried by a 'user' in order to capture MIMO channel responses.

For the measurement campaign 58 locations were chosen around Bristol city centre. At each location both standing and walking measurements were taken, with each measurement time lasting about six seconds. Figure 2 shows the measurement locations around the city of Bristol.

For the UK-China bridges project the University of Bristol will work closely with the University of Edinburgh to process the channel data and apply it to SM systems. The effects on system performance of spatial channel correlation and power imbalance will be investigated, as well as performance comparisons between existing MIMO techniques.

Within the UK-China Bridges project, Heriot-Watt University offer their National Instruments (NI) wireless testbed to the work. This testbed was acquired by Heriot-Watt University in March 2011 and uses the NI family of, 'PXI', boards as well as FPGA board technology. It is depicted in Figure 3 and consists of two chassis that house the transmit and receive PXI boards. It is a 4×2 set-up having 4 four tranmit antennas, each with its own corresponding RF signal generator chain, and two receive antennas, each with its own RF receive amplifier signal chain. The transmitter is capabale of transmitting over a 100 MHz bandwidth in a frequency range of 85 MHz to 6.6 GHz at a maximum power level of 10 dBm while the receiver is capable of functioning over a frequency range of 10 MHz to 6.6 GHz over a 50 MHz bandwidth and an 80 dB spurious free dynamic range. For data acquisition purposes, the set-up also comprises a 6 TB storage unity known as a, 'RAID', storage array, which in turn is comprised of twelve 500 GB hard-disk

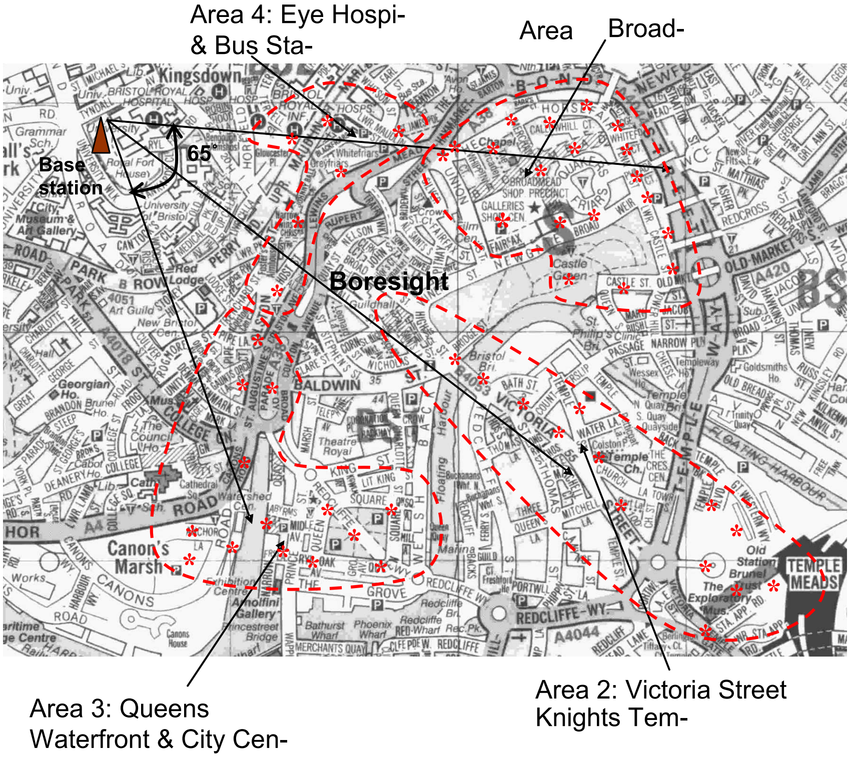

Figure 2: Measurement locations around the city of Bristol.

storage devices. The testbed can be operated in two different modes, which are referred to as, 'real-time', and, 'offline'. Since the testbed comprises FPGA boards, real-time mode refers to the implementation of an actual system using Labview to program the FPGA boards. Offline mode is an option to use to testbed by developing signal processing steps separately using MATLAB software and consequently write binary files that can be understood by software within the testbed set-up. While real-time operation may be quite efficient, offline operation is more than sufficient for demonstrating proof-of-concept for novel signal processing ideas. Regardless of which operation mode is used, the testbed can facilitate the effective performance of a variety of physical layer signal processing techniques including MIMO long term evolution (LTE) standards. However most importantly, the testbed has been used to successfully demonstrate experimentally for the first time the novel SM concept and is at present being harnessed to investigate practical aspects of SM development in real-world channels and under real-world signal processing complexity restraints.

5 Conclusion

This paper has introduced the UK-China science bridges funded project that aims to analyse spatial modulation (SM) as a B4G technology. The project aims to promote collaboration between three institutions in the UK, each with specific expertise and roles within the project.

The concept of SM has been introduced, demonstrating its novel multi-antenna technique, which allows for reduced complexity at the receiver. The China-bridges project aims to develop simulation software capable of testing SM in a verity of situations and capable of using propagation channels attained from several sources. These sources will primarily be from channel measurements taken in urban environments by the University of Bristol, and from a national instruments testbed from Heriot-Watt University.

The project aims to develop the system in to a full multi antenna B4G testbed incorporating extra hardware, with the possibility to run the system in real time on the NI testbed.

Figure 3: NI hardware testbed.

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