Capacity Assessment in Distributed MIMO in Outdoor Environments Using Deterministic Channel Modeling

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Abstract. In this paper we present the potential advantages in terms of capacity improvements of Distributed antenna systems (DAS); also known as Distributed-MIMO (D-MIMO) environments when compared against conventional MIMO and/or SISO systems. The spatial channel parameters are calculated using deterministic modeling techniques such as Ray Tracing.

Keywords: MIMO, Ray Tracing, Distributed MIMO, Capacity.

1 Introduction

Multiple-input multiple-output (MIMO) systems, where more than one antenna element is available at each end of the communication link, has become a highly researched area since ground-breaking work during the nineties showed that large increases in capacity over the Shannon limit can be achieved without any increase in the transmit power and/or bandwidth [1]. A MIMO system takes advantage of the spatial diversity that is obtained by spatially separated antennas in a dense multi-path scattering environment. The presence of multiple antennas at each side of the communication link exploits the rich scattering channel to create multiplicity of parallel radio links over the same radio band and therefore increase the data rate through multiplexing or increase reliability through the increased antenna diversity gain. Although conventional (single-user MIMO) was proved to offer significant benefits in the performance of radio communications, research goes one step beyond and proposes the concept of distributed MIMO or "virtual MIMO" or ad-hoc MIMO. Conventional MIMO placement may end up experiencing low to high signal correlations between the formed channels. Such correlations can be reduced further by introducing the concept of distributed MIMO which utilizes distributed antennas which belong to other users, and effectively increasing capacity.

2 MIMO Channel and Capacity

Multiple Input/Multiple Output (MIMO) systems consist of an array of transmitting and an array of receiving antenna elements as shown in Fig. 1. Such systems have the

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potential to achieve high capacities as well as diversity gain depending on the propagation environment [2]. The increasing capacity of a MIMO system relies strongly on the richness of multipath rays which provide uncorrelated or low-correlated channels [3]. This means that MIMO capacity increases as correlation decreases. It has been proven theoretically that the capacity of a MIMO channel also increases linearly with the number of transmitting and/or receiving antenna elements [2, 4]. This is due to the decomposition of the channel into an equivalent set of spatial sub-channels [5].

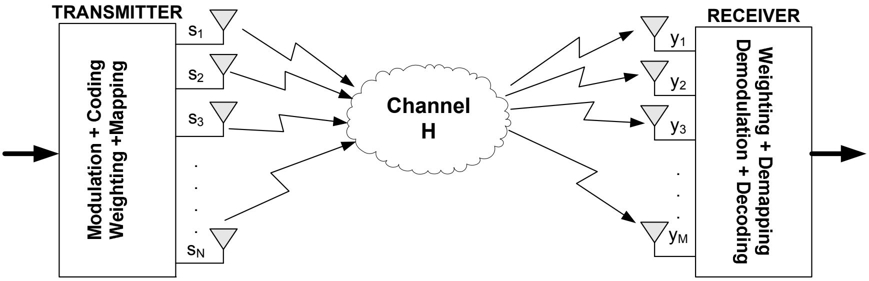

Fig. 1. The MIMO Channel

For a single user, frequency-flat channel with an array of **N** antenna elements at the transmitter and an array of **M** antenna elements at the receiver, as shown in Fig. 1, the input-output relation is then given by [6]:

$$y = H \bullet s + w \tag{1}$$

where the $N \times 1$ transmit vector is $s = [s_1, s_2, \ldots, s_N]^T$, the $M \times 1$ receive vector is given by $y = [y_1, y_2, \ldots, y_M]^T$, the $M \times 1$ noise vector is given by $w = [w_1, w_2, \ldots, w_M]^T$ and the $N \times M$ MIMO channel transfer matrix is:

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M,1} & h_{M,2} & \cdots & h_{M,N} \end{bmatrix} \tag{2}$$

where $h_{i,j}$ is the channel response of the channel between the *j*th transmit- antenna and the *i*th receive-antenna. The matrix elements are complex numbers that correspond to the attenuation and phase shift that the wireless channel introduces to the received signal. Generally, the available capacity, is highly dependent on the variation of the MIMO channel, in addition to the number of transmit and receive antenna elements and Signal to Noise Ratio (SNR).

2.1 MIMO Capacity

In Telecommunication Engineering and in Information theory, the channel capacity is defined as the tightest upper bound on the amount of information that can be reliably transmitted over a communications channel. It is denoted by **C** and it is the maximum rate at which reliable communication can be performed without any constrains on the transmitter and/or receiver complexity. It is measured in bits per second per unit bandwidth (bps/Hz). Channel Capacity was researched in detail by Claude Shannon in the late 1940s using a mathematical theory of communication [7-9] and ever since the channel capacity is referred as Shannon Capacity after its great pioneer. The Shannon upper bound limit in Capacity is given by:

$$C = \log_2 [1 + SNR] \quad bps / Hz \tag{3}$$

And when including the SISO Channel it becomes:

$$C = \log_2 \left[1 + SNR|h|^2\right] \quad bps / Hz \tag{4}$$

where h is a normalized channel complex scalar.

This capacity is a theoretical upper bound and can be approached with advanced modulation and channel coding techniques and was seen as an upper bound until half a century later, when some work at Bell- Labs changed the course of communications research. In 1987, Winters published the concept of a new technique using multiple antennas at both the transmitter and receiver [10], now known as MIMO. In 1995, Teletar published derivations of capacities in Gaussian and fading channels for MIMO systems [11] . In 1996, Foschini presented his derivation for the upper bound capacity for MIMO channels [12]. This is given by:

$$C = \log_2 \det\left[\mathbf{I}_M + \left(\frac{SNR}{N}\right) HH^H\right] \quad bps / Hz \tag{5}$$

where *det* is the determinant, $\mathbf{I}_M$ is the *M* by *M* identity matrix, *M* is the number of receive antenna elements and *N* is the number of transmit antenna elements. It is assumed that the receiver but not the transmitter has knowledge of the channel and that the channel is frequency non-selective (flat fading) over the signal bandwidth. H is the channel matrix (as per eq.2) and H^H is the complex conjugate transpose or Hermitian adjoint:

$$H = \begin{bmatrix} h^*_{1,1} & h^*_{1,2} & \cdots & h^*_{1,N} \\ h^*_{2,1} & h^*_{2,2} & \cdots & h^*_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ h^*_{M,1} & h^*_{M,2} & \cdots & h^*_{M,N} \end{bmatrix} \quad (6)$$

Fig. 2 demonstrates the benefit in capacity when using MIMO systems. It also shows the capacity increase benefit when using more antenna elements. The SISO case is compared to a 2x2 MIMO and a 4x4 MIMO. For the SISO case, a zero mean Gaussian channel is used with a received SNR of 10dB. In the 2x2 MIMO case, independent instances of the SISO channel are used with an average receive SNR of 10dB. The 4x4 sixteen independent instances of the SISO channel are also used with an average receive SNR of 10dB. It can be seen that a significant increase in capacity is possible for the same power and bandwidth.

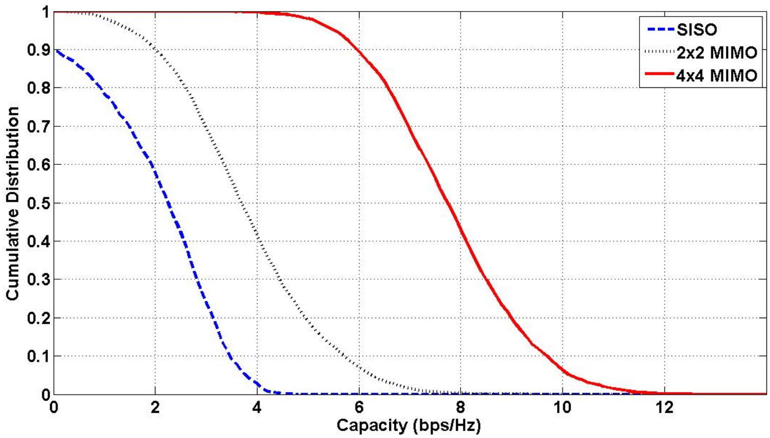

Fig. 2. MIMO capacity gain

Spatial correlations are a function of the scattering multipath environment and the antenna spacing. It is the result of angular spread at the transmitter or receiver or both. Roughly speaking, the correlation between fades experienced by different antenna elements decreases as the density of scatterers in the vicinity of the receiver increases or as the spacing between the antenna elements increases. The effect of correlation on capacity was studied analytically in [13,14]. The author considered N equal rate and equal power parallel sub-channels (with N=M), where the correlation coefficient, r is between any two channels. Capacity as a function of SNR, M and correlation is given as:

$$C_{NN} = N \log_2\left(1 + \frac{SNR}{N}(1-\rho)\right) + \log_2\left(1 + \frac{N \cdot SNR \cdot \rho}{N + SNR \cdot (1-\rho)}\right) \quad (7)$$

Fig. 3 demonstrates the potential increase in capacity of a MIMO system when correlation at the various antenna elements is reduced.

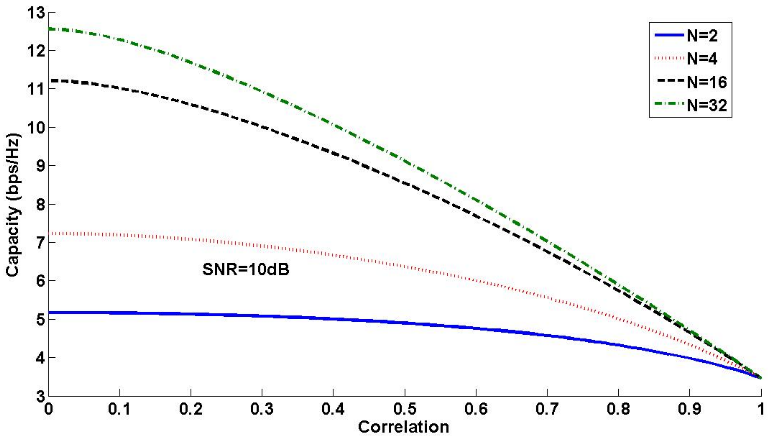

Fig. 3. Channel capacity for N coupled channel as a function of correlation between received contributions

3 Distributed MIMO (D-MIMO)

The predicted capacity gain of conventional co-located MIMO system is often severely limited in realistic propagation scenarios. In addition, the main question when designing a conventional MIMO system is whether the enormous theoretical gains predicted can actually be realized or achieved in realistic environments. For example, if increasing the antenna elements into a MIMO system, will provide the expected theoretical gains, assuming that the increased cost in deployment, hardware and computation is worthwhile. The answer to this question is no, if the antennas are to be packed together, with spacings of the order of a wavelength in the [1]. The main reason for this, is high the spatial correlation due to the existence of a few dominant scatterers, the small angular spread between the contributions arriving on the different antenna elements, and the insufficient antenna spacing. Using Distributed MIMO (D-MIMO) the spatial correlation can be decreased as the various contributions will be arriving at the terminal using different (uncorrelated) paths leading to higher capacity gains. This approach though requires high degree of cooperation between the base stations/communication entities and for this reason it is usually referred as cooperative MIMO. This can be accomplished through suitably designed protocols [15-19]. One way a D-MIMO system can be realized is when a multi-antenna mobile terminal receives contributions from multiple base stations or from multiple other cooperative users in an ad-hoc manner as illustrated in Fig. 4

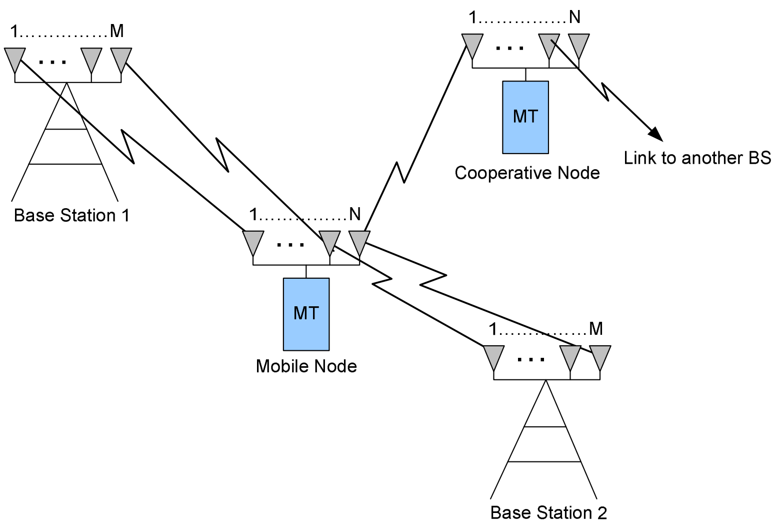

Fig. 4. Distributed Cooperative MIMO

4 Deterministic Channel Modeling

MIMO system design greatly benefits from the availability of an accurate channel model, as it allows system components to be optimized without performing time consuming and expensive field measurements. Developing a good model involves capturing all those effects that affect the particular aspect of the design under test whilst remaining simple enough to use, and offering quick simulation times.

In addition to modeling SISO channel effects like path loss, shadowing, power delay profile, time of arrival, wideband small scale fading first and second order statistics, the MIMO channel model requires additional information that models the amplitude and phase of and correlation between transmission coefficients, correlation between antennas elements, angle of arrival distribution, angle of departure distribution, and their inter-dependencies. Terrestrial models can be categorized as empirical, deterministic, statistical, geometric or physical-statistical. For this investigation we have used deterministic modeling through a commercial Ray Tracing simulator – 3DTruEM.

Deterministic or Site-specific Models are based on the application of well-known electromagnetic effects and numerical methods to a site-specific environmental description which is obtained from the particular environment building database [20]. For a given environmental description they use electromagnetic theory to estimate the field strength at every possible receiver location.

3DTruEM is a 3D polarimetric Ray Tracing Simulator developed by Sigint Solutions. 3DTruEM calculation engine uses a ray tracing algorithm offering improved accuracy and efficiency. It utilizes the 3D electromagnetic (EM) formulation of reflection, refraction and diffraction based on the Universal Theory of

Diffraction (UTD), to provide accurate site-specific radio propagation predictions for a wide range of wireless communication systems. It offers the ability to define the receiver and transmitter antenna characteristics from a wide range of standard antennas but also the flexibility to import a custom-made antenna by importing its 3D radiation pattern/characteristics including also its polarization characteristics. In addition to its sophisticated algorithm that significantly improves speed, 3DTruEM also offers the ability of running a distributed-parallel multithreaded simulation on a cluster of computers. A screenshot of the simulator is shown in Fig. 5.

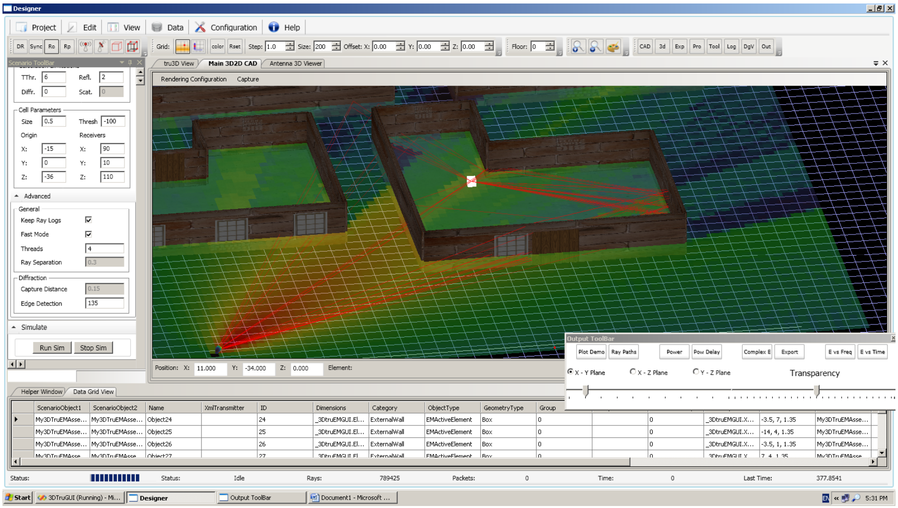

Fig. 5. 3DTruEM Screenshot

5 Simulation Scenario and Results

To prove the principle of improved capacity in D-MIMO cases a Manhattan-like scenario has been used as shown in Fig. 6. It is a 625 m by 625 m area consisting of 20 m x 20 m equally spaced (by 10 m) buildings assumed to be made of concrete. Thirteen transmitting isotropic antennas transmitting at 2.4 GHz have been defined (placed at 20 m above the ground), and various combinations of them have been used to investigate SISO, C-MIMO (2x2 and 4x4) and D-MIMO (2x2 and 4x4) capacity. To allow for C-MIMO investigations, TX1 and TX10 have been defined as a 2x2 antenna array as shown in Fig. 7 with the individual antenna elements separated by half a wavelength. One receiver route has been used for the investigations and is depicted in Fig. 6 consisting of 5986 receivers equally spaced by 2cm (less than half wavelength) in order to be able to capture fast fading effects. Every receiver location is assumed to be consisted by an array of 4 isotropic antenna elements arranged as a straight line at a height 1.5 m.

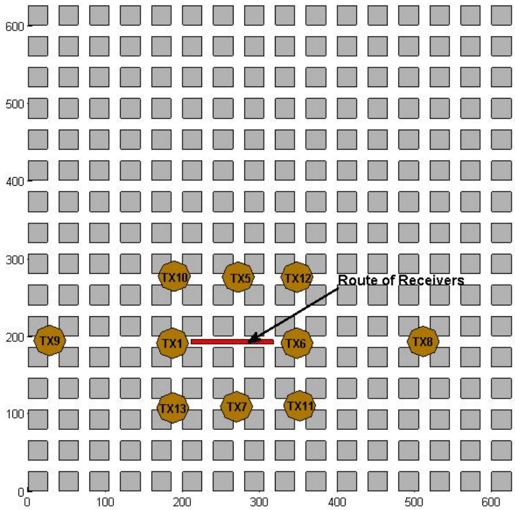

Fig. 6. Manhattan scenario for MIMO capacity investigations

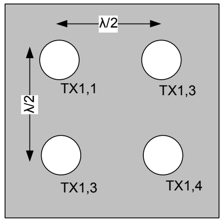

Fig. 7. Transmitter TX1 for conventional MIMO investigation

3DTrueEM has been used to calculate the channel matrices which will become the input to the MIMO capacity formulation presented earlier. The transmit power was set to 33 dBm (BW=22 MHz). The ray tracing simulator considers unlimited number of 3D reflections and transmissions and one UTD diffraction. As said, various cases have been simulated in order to investigate the potential benefit in capacity D-MIMO Environments. These cases have included both Line of Sight (LoS) and Non Line of Sight (NLoS) situations along the estimation route depicted in Fig. 6 for both C-MIMO and D-MIMO. The 4x4 and 2x2 C-MIMO and D-MIMO cases have been also compared to the standard SISO case. Fig. 8 and Fig. 9 below demonstrate some indicative results of this investigation. It can be seen that D-MIMO behaves as good as C-MIMO in terms of capacity in LoS cases but has significant improvement in NLoS situations. Although the capacity in NLoS is less compared to the LoS (this is due to the fact that the received signal to noise ratio – SNR- is higher in LoS cases) the increase in capacity in D-MIMO is higher in NLoS and this is due to the fact that the various contributions arriving on the terminal follow completely different (uncorrelated) paths. Fig. 10 demonstrates the effect of LoS transmitters. It can be seen that by increasing the number of LoS transmitters the capacity is increased and this is due to the high SNR obtained at the respective LoS receivers.

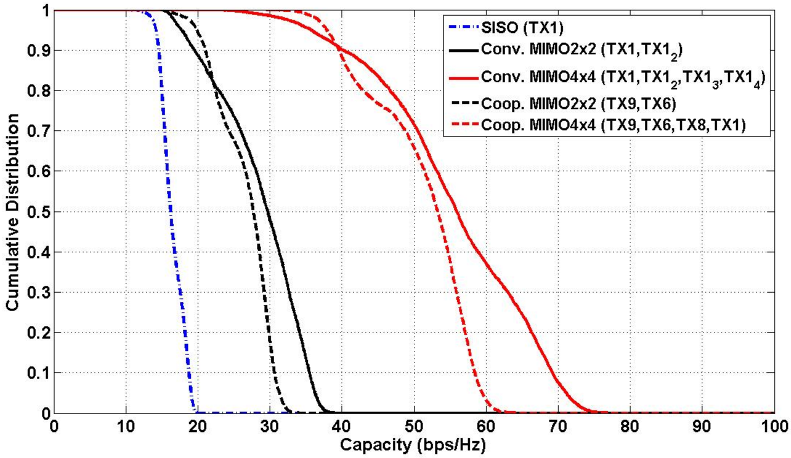

Fig. 8. Conventional vs. Distributed MIMO for LoS case

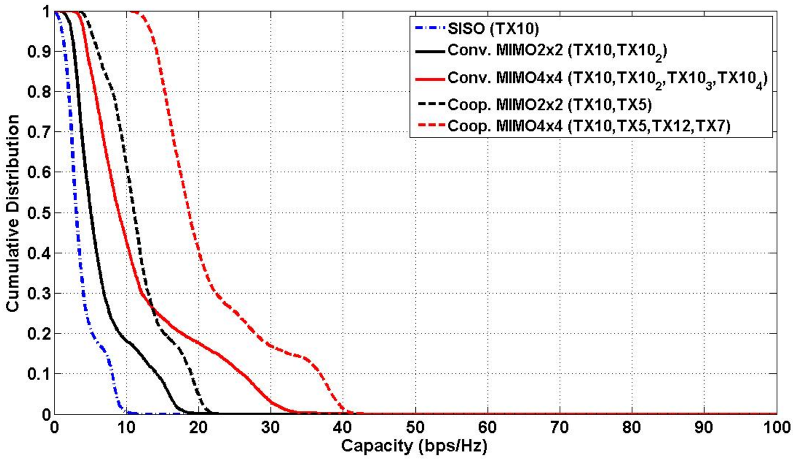

Fig. 9. Conventional vs. Distributed MIMO for NLoS case

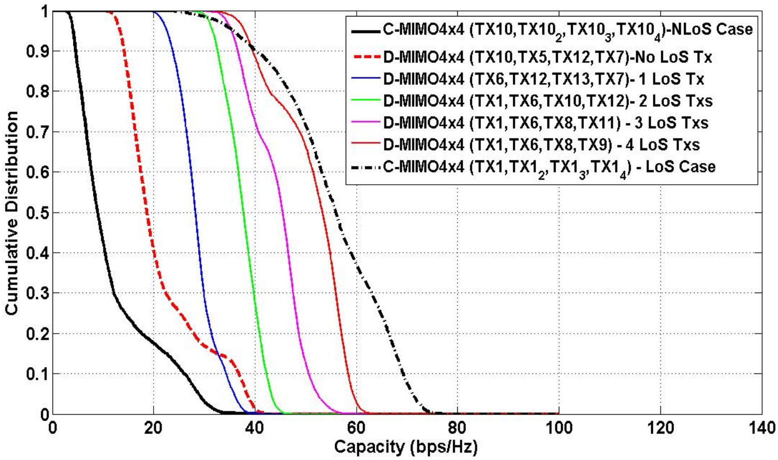

Fig. 10. 4x4 D-MIMO – The effect of LoS transmitters

6 Conclusion

The work in this paper has presented an investigation of the potential benefit in capacity in distributed MIMO (D-MIMO) systems. Using spatial channel parameters obtained from a 3D-Ray Tracing simulator developed by Sigint Solutions (3DTruEM) and an add-on MIMO module which was developed, the investigation was focused in an outdoor Manhattan-like environment where a distributed antenna system (WiFi) is installed. The results have indicated that in terms of capacity, D-MIMO behaves as good as conventional MIMO in LoS cases whereas there is a significant increase (almost double) in capacity of D-MIMO systems in NLoS situations.

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