SDD-MIMO: Ubiquitous Embedded MIMO for community broadband

Gerard Borg, Zia-Ud-Din Javaid and Asaduzzaman Khandaker
Research School of Physics and Engineering ANU College of Science.
Australian National University
ACT 2601 Australia
gerard.borg@anu.edu.au

***Abstract*—Multi-user and massive or large-scale MIMO have proven very effective customer access technologies for serving multiple users on the same frequency resource. However the technological cost and complexity of large scale cellular deployments to sparsely populated areas makes them unsuitable for deployment by individuals or the communities themselves. In this paper we investigate an alternative approach to large scale MIMO deployment in which a huge network of private, single-antenna radios forms a customer access network by coordination over existing back-haul. Such a network increases its range and aggregate capacity in proportion to the number of units deployed on a private basis. In this paper we consider the physical issues of base station size, spectrum availability, terrestrial propagation, capacity, range and power scaling that must be solved to make such a network a reality.**

***Index Terms*—MIMO, wireless, scalable, distributed, decentralised, Internet, broadband, regional, remote.**

I. Introduction

Remote populations the world over remain virtually disconnected from the Internet, especially in the poorest and most war-stricken countries [1]. However a recent study of world population demographics by FaceBook [2] shows that 99% of the world's population lives within 63 kms of a city. In many situations, these populations are spread out in difficult terrain or isolated by sea. For such a demographic, existing wireless communications technologies do not provide a good fit. Cellular mobile, community WiFi and point-to-point microwave or fibre trunking links and the array of technologies proposed for 5G, are all costly or impractical to deploy in these scenarios.

The provision of fixed broadband to large geographically isolated populations is a grand challenge for which we propose a grand solution. In this paper we argue that a fully embedded, scalable, distributed and decentralised large scale antenna system has the potential to solve this problem in a low cost manner. Such a system would empower individuals and communities to run a wireless network for community broadband in a similar manner that solar microgrids provide community power. To wit, by aggregating MIMO channels from service-user single antenna nodes connected to network back-haul, isolated users can be connected wirelessly in multi-user MIMO fashion. We refer to this network as a scalable, distributed and decentralised MIMO (SDD-MIMO) network. At the ANU we are building a prototype of this network known as ANU-MIMO [3]. Our task here is to address the criteria necessary for such a network to become a reality.

In this paper we discuss the physical limitations of the previously mentioned start-of-the-art wireless networking solutions: (i) unscalable capacity per user, (ii) the need to operate at short wavelengths where there is adequate wireless bandwidth, (iii) base station size restrictions and (iv) adverse power scaling versus range. We show how the proposed solution cirmumvents these problems. The structure of this paper is as follows. In section II we describe the network architecture. In section III we present the physical constraints that must be addressed. In the following sections, we present simulations and modeling that support the claim that SDD-MIMO addresses these issues. Finally in the conclusion we summarise.

II. Network architecture

The SDD-MIMO network consists of a very large number of Internet connected base stations or service nodes (SNs) and a large but smaller number of remote nodes RNs. If there are N $\times$ SNs and M $\times$ RNs then $M \leq N$ must be satisfied. One possible configuration of the network is shown in Fig. 1. RNs (blue) are located at a large distance from a town centre. SNs (red) are located in town and connected to existing Internet back-haul. The SNs coordinate over the back-haul to form a very large-scale antenna system. They combine their powers to form high power, high resolution beams to connect each RN to the Internet on the same spectrum.

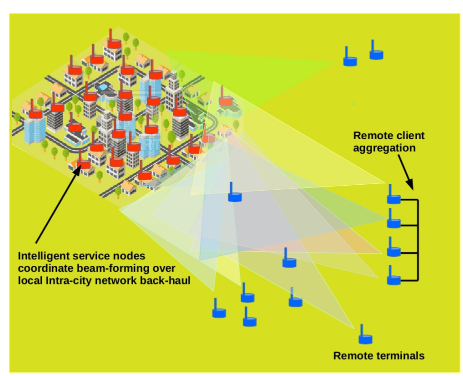

Fig. 1. One possible configuration of an SDD-MIMO network.

Each SN/RN is equipped with a single antenna. SNs employ conjugate match beam-forming on both the up and the down-link to connect the RNs to the Internet back-haul. The network may operate in either the Time Division Duplexing (TDD) or the Frequency Division Duplexing (FDD) modes. The network can be built starting with a single SN and RN and then be expanded by adding one or more SNs for each new RN added.

III. Physical constraints

The key physical limitations that prevent current centralised / cellular wireless networks from scaling to an arbitrarily large number of users are as follows.

(1) Capacity per user. Aggregate capacity must scale in proportion to the number of users that are connected.
(2) Carrier frequency. Low frequency bands are best for propagation in a variety of terrain conditions but have little wireless spectrum.
(3) Base station size. Large base stations are expensive but small base stations are diffraction limited and cannot provide scalable capacity..
(4) Power scaling and range. It must be possible to achieve long range with manageable transmit powers.

The fourth point needs qualification. In an accompanying paper [3] we demonstrate ranges of over a hundred kilometers over the sea using a large scale SDD-MIMO system with a few thousand low power stations. The Facebook 63 km benchmark can be achieved in reasonable terrain with a more modest system with less than one hundred stations. In this paper we deal with these issues. We demonstrate that the only network that can satisfy these requirements is the SDD-MIMO network.

IV. Capacity per user

We reuse results developed for a similar technology known as 'cell-free massive MIMO' (CFMM). In CFMM, $M \ll N$, but the SNs are generally not designed to be spatially scalable: their roll-outs tend to spatially follow the RNs. Despite this, we can borrow with minor modification, a result from a recent theory of CFMM [4] to describe an important underlying principle of SDD-MIMO.

For a down-link massive MIMO channel with N SNs, M RNs, signal-to-interference-plus-noise ratio (SINR) and occupied bandwidth B Hz, the capacity per user for a conjugate match precoder is bounded by [4],

$$C \geq \log\left(1 + SINR\right) \tag{1}$$

Consider first a regular CFMM network with fixed wireless access (in the long coherence time limit). For this case the SINR is given by [4],

$$SINR = \frac{N\rho_f}{M\left(1+\rho_f\right)} \tag{2}$$

where ρ_f is the average signal-to-noise ratio (SNR) for one SN and one RN. This formula assumes that the total power of the array is kept constant as $N \to \infty$ which is a reasonable precaution to take if inter-cellular interference is to be avoided. In this case, we immediately see that $SINR \to 0$ as $\rho_f \to 0$ for constant N/M, even as $N \to \infty$. We conclude that for CFMM, $C \to 0$ as $\rho_f \to 0$. *The range of the CFMM network (and hence centralised, cellular or cell-free massive MIMO) is limited.*

This limiting power constraint is not applicable to SDD-MIMO because sparsely distributed SNs can be considered to have a fixed power limit of their own. Consider an SDD-MIMO network with geographically distributed SNs where each SN emits a fixed Equivalent Isotropic Radiated Power (E.I.R.P.). Then the $SINR$ in this case is given by,

$$SINR = \frac{N^2\rho_f}{M\left(1+N\rho_f\right)} \tag{3}$$

Provided that $N\rho_f \to const.$, $SINR \to const.$ as $\rho_f \to 0$ for $N/M = const.$ as $(N, M) \to \infty$. For SDD-MIMO, equations (1) and (3) show that the capacity per user remains constant as $N \to \infty$. This proves that SDD-MIMO aggregate capacity scales with the size of the network. It also follows that range can be increased by scaling N.

V. Choice of carrier frequency

The requirement to serve RNs at large range over difficult terrain without the use of very high powers or communications towers is strongly dependent on radio wavelength and terrain profile as well as the power scaling advantages of large-scale MIMO. To demonstrate the role of carrier wavelength, we use single-diffracting-object path-loss models to compare link budgets versus frequency. We assume a tone of $10W$ power is launched from a vertical dipole to another dipole over a $32km$ link. Along the line-of-sight between the transmitter and receiver is an escarpment of relative altitude $200m$ and width $1500m$ located at $27km$ from the transmitter. The receiver is in the shadow of the escarpment and experiences typical rural ambient atmospheric noise. Landforms of relative altitude $200m$ are very common and must be managed if long-range terrestrial wireless is to be achievable.

We employ the ITM model with a simple widely available diffraction based model for a smooth diffracting obstruction [5]. Fig. 2 shows the received SNR for frequencies from $50MHz$ to $3500MHz$. Only the $50MHz$ link can be operated for a SISO system (single transmitter single receiver). We conclude in particular, that links operating on higher frequency bands than VHF are unusable for terrestrial wireless unless they are mounted on towers of suitable elevation.

The main disadvantage of such low frequency links in the sub-GHz bands is the general lack of available spectrum. One important exception however are the band I TV channels from $45 - 70MHz$ which are widely available and best suited to SDD-MIMO.

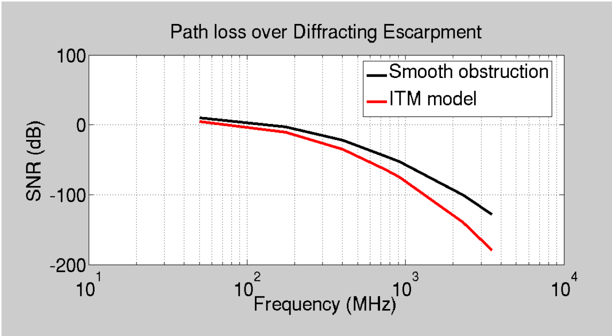

Fig. 2. Received SNR versus frequency for a $32km$ terrestrial link with $200m$ altitude hill / escarpment.

VI. Base station size

One obvious and convenient choice for deployment would be centralised, cellular massive MIMO (CMM) from a building or tower top. This is a popular approach because it leverages the central location to lower the cost of supply of network support infrastructure such as electrical power and network back-haul. However these requirements are also reinforced by centralisation in the first place. Such high power and back-haul would not be required if each base station (SN) served at most a single RN. For a centralised architecture however, all of the networks electrical power and aggregate back-haul must be supplied to the tower. *But this is not the main problem. We now show that physics alone prevents such cellular approaches from scaling to very large numbers of RNs.*

Equation (3) gives the SINR for the case of distributed down-link conjugate match beam-forming. An underlying assumption of this equation is that the channel matrix consists of complex i.i.d. gaussian coefficients. In reality, waves propagate from antennas as complex circular functions of the form $\exp{(jkx)}$, where $k = 2\pi/\lambda$ is the wave-number. If the antennas are located inside a disk of radius r_0, then it is no longer possible to place an infinite number of antennas and achieve the capacity gains of equation (1). Due to its limited aperture size, such a confined array can only form $N_{dof} \approx 2\pi e/\lambda{+}1$ independent communications channels (see equation (39) of [6]). In optics this is understood as diffraction limited imaging and is a well known telescope design issue in astronomy.

To the best of the author's knowledge, there has been no derivation of capacity for diffraction limited conjugate match beam forming in massive MIMO. So we adopt two approaches to treat the problem. First we develop a heuristic argument that captures the essential physics and then we compare its predictions to a simulation.

The effect of diffraction limiting is to cause the beams destined for one RN to be blurred. This blurring leads to the spill-over of focussed beams into the paths of other RNs, thus leading to increased interference. Consider equation (3). This equation can be rewritten as,

$$SINR = \frac{p_T N^2}{M\left(p_T N + N_o\right)} \tag{4}$$

where p_T is the average transmit power per SN, N_o is the noise power and $\rho_f = p_T/N_o$. In this form one recognises $p_T N^2/M$ as the desired power and $p_T N$ as the approximate interfering power that arises in conjugate match beam-forming. In a diffraction limited scenario, we argue that the interfering contribution $p_T N$, does not change. With difraction however, the wanted, in-phase power spills away from its target RN into the paths of other RNs. Since there are $M-1$ potential interferers each generating a power $p_T N^2/M$, then on average the interference contributes an amount $p_T N^2(M-1)/(M N_{dof})$ per degree of freedom. Thus each RN can expect on average this amount of interference.

Assuming that $M \gg 1$ and adding this diffraction-induced interference to the existing interference due to the conjugate match beam forming in equation (4), we obtain the following,

$$SINR = \frac{N^2 \rho_f}{M\left(\rho_f N\left(1 + N/N_{dof}\right) + 1\right)} \tag{5}$$

Equation (3) may be recovered from (5) in the limit as $N_{dof} \to \infty$. We may refer to (5) as the diffraction limited or centralised SINR from which we can compute the centralised capacity for conjugate match beam forming. Equation (3) however is still the correct, distributed SINR for SDD-MIMO.

In support of equation (5) we can simulate the capacity by computing the SINR at each RN produced by a uniformly distributed array of SNs with vertically polarised antennas on a disk and using equation (1) to compute the capacity per user. The RNs are uniformly distributed in an annular region of inner radius much larger that the disk radius. The disk is at the centre of the annulus. We assume Friis or line-of-sight transmission for simplicity and $\rho_f = 20dB$. We consider a network in which we attempt to provide an unlimited number of users with broadband using CMM/CFMM or SDD-MIMO with $N/M = 20$. We use a long $(2m)$ wavelength carrier frequency of $150MHz$ to mitigate terrain effects as discussed but we strike a balance between base station size and wavelength. The base station for centralised massive MIMO is a disk of radius $5m$ and the RN annulus is from $1000-1200m$.

Fig. 3 shows the results. The black line is the distributed or SDD-MIMO case of equation (3) and the blue line is the CMM case of equation (5). The blue points of the simulation agree very well with equation (5). The red curves are two independent calculations of the fundamental capacity limit of the disk. The broken line is a saturated capacity formula from equation (38) of [6] and the red line is the celebrated MIMO capacity ([7], [8]). They also agree fairly well with each other.

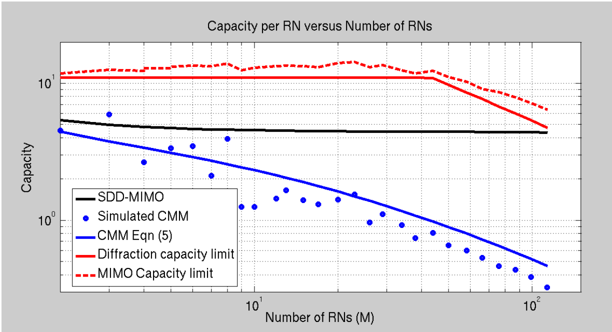

Fig. 3. The effects of base station size on capacity.

The main conclusion to be drawn from Fig. 3 is that for 100 users, SDD-MIMO reaches the capacity limit of the 10m diameter disk at 150MHz. For the more practical case of massive MIMO with conjugate match beam-forming, the diffraction limit begins to influence performance at just 10 users. One could increase the capacity of centralised massive MIMO by decreasing the wavelength, but as previously noted, long-range communications would be limited by terrain.

VII. Power Scaling

One of the key features of the SDD-MIMO network is that the power per station required to maintain a fixed capacity, decreases with the number of stations added to the network. This result is inherent in the formula, $N\rho_f \to 0$. For fixed antenna transmit power, the range of the network increases with N. In this section we derive and test simple formulas that describe this scaling.

In the simulations, we use a standard channel model, ITU-R P.1546-5 (Figure 4, sea path, SN/RN height $10m$) [9]. We model an SDD-MIMO network at $175.25MHz$, with isotropic, vertically polarised antennas and SNs distributed uniformly on a $10km$ square at altitude $10m$. The RNs are located at a range of about $155kms$ over sea. We assume that each SN combines the transmit and received signals of each RN in equal weight during the beam-forming process and that the path-loss between each SN and RN is roughly constant.

We compare some simple scaling laws with the results of a full wireless network code that sends actual data bits and computes the BER at the RNs on the down-link an after beam-forming on the up-link.

Under these assumptions, the wanted signals arriving in phase at an RN on the down-link have a received power due to beam forming that scales as $N^2 p_{Td} P_{LOSS}/M$ where p_{Td} is the transmit E.I.R.P. per node, P_{LOSS} is the path-loss and subscript d refers to the down-link. The interference arrives with power $N(M-1)p_{Td}P_{LOSS}/M$, If p_N is a typical noise power then, $\rho_{fd} = p_{Td}P_{LOSS}/p_N$.

Similar formulas apply on the up-link. After beam-forming, the wanted signal is $N^2 p_{Tu} P_{LOSS}$, with subscript u referring to the up-link. The interference is $N(M-1)p_{Tu}P_{LOSS}$. Note that the only difference physically speaking between the up and the down-links is that on the up-link each RN transmits with full power dedicated to its set of symbols, whereas on the down-link, each SN contributes only $1/M$ of its total power to the beam-formed symbols of each RN.

To derive the formulas for the scaling, we assume that the final SNR received at each detector must have a fixed value for a fixed BER. We use BER as the metric because it is the quantity most easily computed by the model.

A. Scaling of SN transmit power and RN SNR on the down-link.

Given the scaling of the wanted and interference power above, the SNR at the RNs is given by

$$SNR = \frac{N\left(N+M-1\right)}{M}\rho_{fd} \tag{6}$$

We conclude that for SNR to remain fixed, the right hand side of equation (6) must be fixed. This shows that for conjugate match beam-forming on the down-link, $\rho_{fd} \to 0$ as N increases. Range increases with N.

For a fixed SNR determined by BER, equation (6) also gives the scaling of the transmit power, p_{Td} with N and M under conditions of fixed SNR, P_{LOSS} and p_N. Since $\rho_{fd} = p_{Td}P_{LOSS}/p_N$, we obtain,

$$p_{Td} = \frac{M p_N SNR}{P_{LOSS} N\left(N+M-1\right)} \tag{7}$$

SN transmit power decreases with N at fixed BER (SNR).

B. Scaling of RN transmit power and SN SNR on the up-link.

To maintain fixed BER on the up-link, we use the effective SNR after beam-forming. We refer to this as SNR_{eff}. The quantity SNR_{eff} is not the same as the SNR at the input to the SNs but the SNR remaining after the beam-forming computation. If p_{Tu} is the RN transmit power then the received signal at an SN due to one RN is $p_{Ru} = p_{Tu}P_{LOSS}$ so that $\rho_{fu} = p_{Tu}P_{LOSS}/p_N$. The total power is the sum over all RNs. The detected SNR_{eff} after beam-forming of the signals received by all SNs is

$$SNR_{eff} = \frac{\left(N^2 + N(M-1)\right)\rho_{fu}}{N} = \left(N+M-1\right)\rho_{fu} \tag{8}$$

where the N in the denominator arises from the $N-$times addition of the noise power p_N during beam-forming. Since there are M RNs, the SNR at the input to the SNs is given by $SNR = M\rho_{fu}$ and so the scaling of the SNR is given by,

$$SNR = \frac{M}{N+M-1} SNR_{eff} \tag{9}$$

Since SNR_{eff} is constant for fixed BER, the SNR decreases with N. Finally since $\rho_{fu} = p_{Tu}P_{LOSS}/p_N$, the RN transmit power must scale as

$$p_{Tu} = \frac{p_N SNR_{eff}}{P_{LOSS}\left(N+M-1\right)} \tag{10}$$

which also shows an inverse scaling with N.

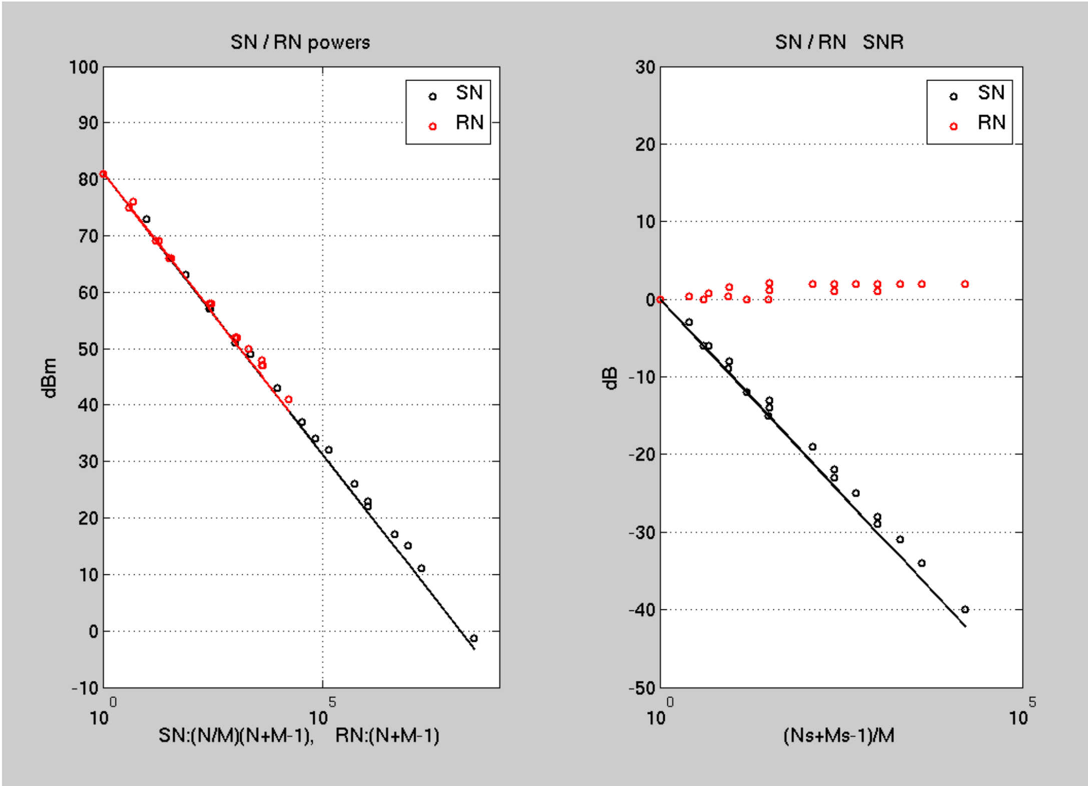

Fig. 4. Power and SNR scaling from the model (dots) and formulas (dashed).

Fig. 4 shows the scaling laws versus the network model for the path-loss data of ITU-R P.1546-5, bandwidth $10MHz$ and noise margin $10dB$ [9]. The figure to the left shows the scaling of transmit power per station. There is a decrease in the SN transmit power on the down-link from $80dBm$ to $\approx -2dBm$ as the number of SNs is increased on the network. On the up-link there is also a significant decrease in the transmit power of the RN from 80 to $40dBm$. The figure to the right shows the scaling of SNR. On the down-link the SNR at the RNs remains constant as expected for a fixed BER. On the up-link however the SNR at the SNs decreases from $0dB$ down to $-40dB$. Notice the especially large number of stations required to achieve these results. Such a deployment can only be considered for a scalable system such as SDD-MIMO that is incrementally deployed.

The agreement between the simulations and the simple scaling laws is excellent and the results confirm that there are very significant power reductions to be obtained in large scale antenna systems as the number of SNs is increased.

VIII. Conclusion

The SDD-MIMO wireless network has been described which extends existing back-haul networks by providing an omni-directional broadband service to a large and scalable number of distant users distributed over a very large area. Given the relative viability of connecting urban and regional townships to broadband, an approach in which scalable MIMO is embedded in the back-haul network may provide a viable means to extend broadband infrastructure.

In this paper we have considerd the physical limitations of the previously mentioned start-of-the-art centralised wireless networking solutions: (i) unscalable capacity per user, (ii) the need to operate at short wavelengths where there is adequate bandwidth, (iii) base station size restrictions due to diffraction and (iv) adverse power scaling versus range. We have shown that compared to the wireless state of the art, SDD-MIMO overcomes each of these key physical constraints. Moreover we have shown that by the choice of a scalable number of stations at fixed N/M as $(N.M) \to \infty$, low frequency VHF carrier frequencies and by geographically distributing the SNs over a large area subject to the availability of back-haul, these contraints can all be eliminated at the same time.

Acknowledgments

The authors would like to acknowledge the financial support of the Research School of Physics and Engineering at the Australian National University. Gerard Borg would especially like to acknowledge the hospitality of Profs. Teddy Mantoro and Media Ayu.

REFERENCES

[1] “List of Countries by number of broadband subscriptions” https://en.wikipedia.org/wiki/List_of_countries_by_number_of_broadband_Internet_subscriptions [accessed 5-07-2018].

[2] “Open population datasets and open challenges” https://code.facebook.com/posts/596471193873876/open-population-datasets-and-open-challenges/ [accessed 5-07-2018].

[3] G.G. Borg, M. Blacksell, J-C Lonchampt, L. Materne, P. Redman and D. Tempra. “ANU-MIMO: A Decentralised, Scalable and Economical Wireless 5G Building Block for Massive Broadband Connectivity,” http://users.cecs.anu.edu.au/ Gerard.Borg/public/ANU-MIMO_whitepaper.pdf [accessed 5-07-2018].

[4] H. Yang and T. Marzetta, “Performance of Conjugate and Zero-Forming Beamforming in Large-Scale Antenna Systems,” IEEE Journal On Selected Areas in Communications. vol. 31(2) 2013 pp. 172–179.

[5] “Irregular Terrain Model (ITM) (Longley-Rice) (20 MHz 20 GHz)”, https://www.its.bldrdoc.gov/resources/radio-propagation-software/itm/itm.aspx [accessed 5-07-2018]. “RF Prop –Radio Propagation Calculator for WIN3.11 or 95. (67K)”, http://www.sss-mag.com/swindexa.html#a&p [accessed 5-07-2018].

[6] T.S. Pollock, T.D. Abhayapala, and R.A. Kennedy, “Fundamental Limits of MIMO Capacity for Spatially Constrained Arrays,” Proceedings Fourth Australian Communications Theory Workshop, AusCTW2003, Melbourne, Australia, Feb 5-7, 2003, pp. 7–12.

[7] E. Telatar, “Capacity of Multi-antenna Gaussian Channels”, AT&T Bell Laboratories, Internal Tech. Memo., June 1995.

[8] G. J. Foschini and M. J. Gans, “On limits of wireless communications im a fading environment when using multiple antennas,” Wireless Personal Communications, vol. 6, no. 3, 1998. pp. 311–335.

[9] ITU-R P.1546-5, “Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz,” 2009, available at http://www.srrc.org.cn/spreadmodel/PDFile/R-REC-P.1546-5-201309-I!!PDF-E.pdf [accessed 16-10-2017].