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THEORETICAL RESEARCHES OF SMART ANTENNAS

Analyzes the technology of using smart antennas, which allow more efficient use of wireless network resources.

Keywords: smart-antenna, wireless, network performance

Problem and its relation to modern scientific and applied problems

Wireless networks are witnessing rapid advances in volume, range and cost of services. In parallel to the wireless development the evolution of the Internet has taken place. The widespread success of the mobile Internet will probably not depend on one kind of technology but on multiple technologies, including new capabilities of antenna arrays. To achieve pervasive, broadband communications require new radio communication services and also improvements in the efficiency of current systems. Smart antennas extract more capacity from current/future wireless network resources and their implementation at least at base stations (BSs) results in a more efficient network.

The purpose of the article

Purpose of the article is the analysis tehnology use of smart antennas in wireless networks. The use of smart antennas allows more efficient use of network technology, which is based on the methods of radio.

Analysis of recent studies and papers outlining an approach to solving the problem

Problems in open radio communication networks involved many scientists. On the problem of improving the use of technology antennas, performance calculations, articles written by scholars such as L. Berkman, R. Vygivskiy, M. Parnes, V. Slyusar and other Ukrainian scientists. To include foreign researchers A. Cantoni, L. Godara, S. Alamouti, A. Viterbi, J. Wolf, E. Zehavi, R. Padovani, J. Liberti, T. Rappaport, V. Erceg, J. Thompson, A. Al-Dakdouki and other.

Presentation of the basic material

Channel modelling. A wireless system is highly dependent on the channel characteristics, which are unpredictable and different for certain propagation scenarios. Physical limitations of wireless channels present a fundamental technical challenge for reliable communication. The angle of arrival (AOA) and angular spread (AS) of the channel are the key parameters for determining the performance and deployment of antenna arrays [1]. AS is a function of BS or mobile station (MS) location, distance and environment. The AS arises and varies due to multipath arrivals both from local scatterers near the MS, near the BS and remote scatterers. The typical AS values depend on propagation environment (macro/micro/pico, outdoors/indoors) and they may vary from 1 to 360 degrees. As the AS increases, so the required antenna spacing reduces. A typical example of angle spreading in AOA, θ , is shown in Fig. 1 for: (a) zero AS $\Delta = 0$ and (b) non-zero AS $\Delta \neq 0$.

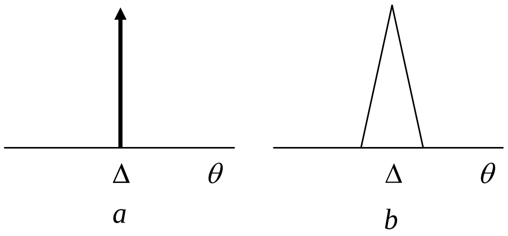

Fig. 1 – A typical plot of the angle spreading in AOA, $\theta:(a)\rightarrow\Delta=0;\ (b)\ \rightarrow\Delta\neq 0$

Channel fading can be classified into three types: path loss, shadowing and fast fading. Fading, which is a small-scale effect, refers to the combined effect of the multiple propagation paths experienced by the radio signal (on both the downlink and uplink), which changes with movements of mobile units. Multipath is a condition where the transmitted radio signal is reflected by physical features, creating multiple signal paths between the BS and the MS. Therefore, in real wireless environments and over small distances, signal power dramatically fluctuates by the time the signal arrives at the desired receiver and as the receiver moves from one place to another. A typical Rayleigh fading performance with three antennas is shown in Fig. 2.

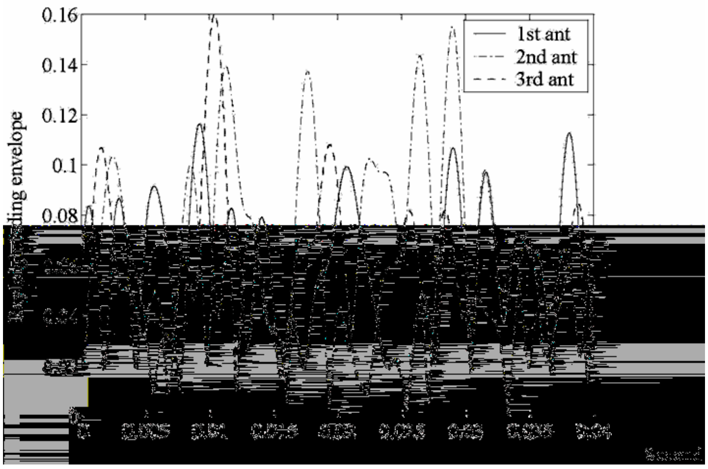

Fig. 2 – Rayleigh fading performance with three antennas

Therefore, the signal components received at different times are uncorrelated because they have travelled over different paths. The phenomenon of multipath fading on a mobile radio channel is characterised by three parameters: the multipath delay spread which is related to frequency selectivity; the Doppler spread which is related to time selectivity; the AS which is related to space selectivity. If signal bandwidth is considerably smaller than the coherence bandwidth the channel can be considered as frequency-nonselective or flat fading.

Channel capacity. The channel state information (CSI) available to receiver and transmitter may include knowledge of channel characteristics. This knowledge (or lack of it) will impact on system performance and thus the channel capacity. In particular, the CSI plays a significant role on the receive side. Here we study multiple-input multiple-output (MIMO) system with N transmit antennas and M receive antennas (Fig. 3).

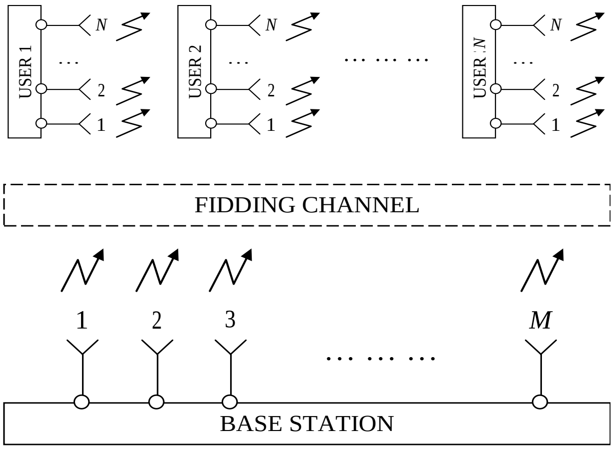

Fig. 3 – A diagram of a multi-user dual-antenna array system for wireless communications

Shannon's capacity. The Shannon capacity C is maximum error-free data rate at which information can be transmitted over the specific channel in bits per second. It is clear that by increasing the SNR (or signal power) the Shannon channel capacity formula (Fig. 4) for a given bandwidth can increase only logarithmically.

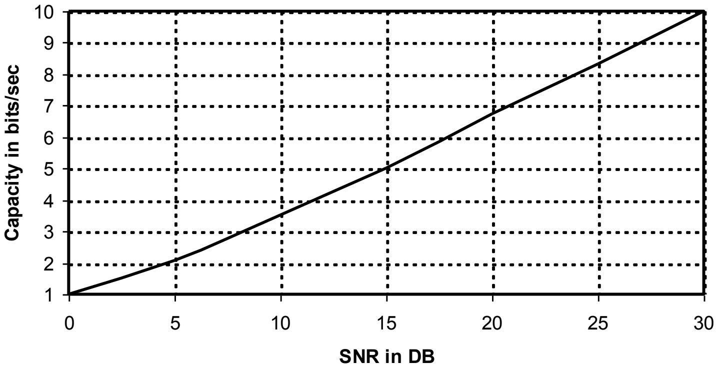

Fig. 4 – Shannon channel capacity

It is evident that for higher SNRs a 3 dB increase in average SNR gives an increase in capacity of around 1 bps/Hz. The wireless system capacity is interference limited - it can not be increased by increasing transmitted power as we maybe wish. Thus the Shannon capacity formula includes a general boundary for future high rate wireless communications.

In practice wireless channels are subject to time-varying impairments such as noise, interference and multipath and they are undergone random fading. If the channel amplitude (h) is a complex scalar random variable at any time instant, the capacity C is a random variable that is function of received SNR $\gamma = \rho |h|^2$. $\rho = P/\sigma^2$ is the mean SNR, where P is the transmitter signal power, σ^2 is the noise power. For single-input single-output (SISO) flat fading channels we can write the Shannon capacity (bits/sec) as:

$$C = W \log_2 (1+\gamma) = W \log_2 \left(1+\rho |h|^2\right) \tag{1}$$

where W is the channel bandwidth. Thus, when the channel is time-varying, the ergodic Shannon capacity can no longer be used. Hence, the Shannon channel capacity becomes a random [1]. In this case, capacity can be defined for any instance of the channel state random variable.

Capacity versus array gain. Consider Fig. 3 for an array at one end of a wireless link, where there is transmit antenna and the M signals are received on the M antennas. The output SNR is the sum of the SNR is the sum of the SNRs $\left(SNR_1, SNR_2, ..., SNR_M\right)$ on the receive antennas. Such an M-element array generally achieves an SNR improvement of $G = 10\log_{10} M$ dB over a single element antenna, in AWGN with no interference, multipath or mutual coupling. Then antenna gain (AG) in this case is clearly M. The channel capacity is improved by increasing the AG and hence the array size M [1]. Transmit diversity (TD) sends modified versions of the data bearing signal from multiple transmit antennas over several paths. For the receive diversity (RD) $\left(1\times M\right)$ scheme, or for TD $\left(N\times 1\right)$ scheme, the equivalent instantaneous SNR respectively are: $\gamma_M = \rho\sum_{m=1}^{M}\left|h_m\right|^2$ and $\gamma_N = \rho\big/N\sum_{n=1}^{N}\left|h_n\right|^2$, where h_m is the channel amplitude from the transmitter to the m-th receive antenna and h_n is the channel amplitude from the n-th transmit antenna to the receiver. The channel capacity in such a M system is simply the sum of all C in (1), substituting the γ_M instead of γ. Contrasting with Equation (1), we see that $\left|h\right|^2$ is replaced by a sum of squares. Thus, for single-input multiple-output (SIMO) system we can write the channel capacity as:

$$C = W\log_2\left(1 + M\rho\left|h\right|^2\right) \qquad (2)$$

This capacity can be achieved by multiplying the input SNR by the array gain M. In an array with N elements, the transmit power is divided into N equal parts. The channel capacity in such a multiple-input single-output (MISO) system is the sum of all C in (1), provided that γ is replaced by γ_N. As shown in Fig. 5, the higher number of elements in the array, the higher the capacity. As the number of elements becomes very large, the capacity increases proportionally to the SNR. While RD provides AG, TD does not provide AG when the channel is unknown in the transmitter.

Capacity versus diversity gain. Diversity techniques introduce redundancy into the communication system by transmitting a signal over many independent and spatially separated propagation channels, instead of a single channel. Applying diversity in a Rayleigh fading channel reduces the average transmit power required to maintain a particular BER level at the receiver. The reduction in transmitter power (or required average output SNR) is referred to as diversity gain (DG). This implies that the transmit power of the mobile terminals can be reduced, thus resulting in a huge increase in battery life. The maximum ratio combining (MRC) produces a signal with a SNR equal to the sum of the antennas individual SNRs. Antenna arrays provide DG of M against multipath fading which increases with M as well as with AS and antenna spacing. Antenna array reduces the number of interferers by a factor of M, and thereby increases the capacity M-fold [1]. Both RD and TD realise spatial DG without requiring knowledge of the channel in the transmitter.

Thus AG and DG can be translated into larger capacities. While RD requires multiple antennas which fade independently and is independent of coding/modulation schemes, TD requires special coding/modulation schemes to improve the performance (e.g. space-time coding (STC)).

Improving network coverage due to AG and DG. Another important benefit of smart antennas is an extension of network coverage (i.e., increase cell radius) due to AG and DG. Coverage determines cost of the wireless system. Extension of range gives the MSs the opportunities to communicate as far as possible from the BS without increasing the uplink power transmitted by the MS or the downlink power required from the BS transmitter. Thus using smart antennas reduces the number of BSs required to cover a given area. An M-element antenna array at the BS reduces total transmitted power by M^{-1} (10 antenna elements will reduce the power by 10 dB). Increasing the range leads to reducing power consumption and cutting down on dropped calls. Thus, any action that reduces the interference level increases the capacity and hence the power control requirements are eased.

Outage capacity. As was stated before the wireless channels are time-varying and subject to random fading. Then, the capacity of multiple antennas is determined in terms of random fading channel. In this case the channel is a random variable and hence so is the channel capacity, which can be guaranteed only for some percentage of time (e.g., for 90%) [1]. Thus capacity depends on the channel instantaneous response. If the system is designed to provide a certain data rate, a certain percentage of bursts will be erroneous. This percentage is called outage. Thus, in fading channels it is useful to consider the outage capacity instead of Shannon capacity. The $x\%$-outage capacity is the maximum data rate which could be transmitted error free in $(100-x)\%$ of the time over a specific channel, i.e. we expect $x\%$ outage. This maximum data rate can be achieved in any fading condition during non-outage. The outage capacity gives information on the outage data rate offered by the fading link. Based on this discussion, for any given rate there is an associated outage probability that the channel cannot support this rate.

Fig. 5 shows the simulation results for the 10%-outage capacity of a flat fading channel with an unequal number of $N \neq M$, where we see the impact of multiple antennas on the capacity distribution. This is due to the spatial diversity which reduces fading (i.e. DG) and thanks to the higher SNR of the combined antennas (i.e. AG). Thus outage capacity depends also on DG. In this case, DG improves the outage capacity performance, but this DG saturates when the number of receive antennas is increased. It can be seen from Equation (2) that adding a single array does provide diversity against fading, but it does not change the slow logarithmic growth of the capacity.

MIMO capacity increase. Dual-antenna arrays can be used to provide high link capacity and introduce MIMO channel. The area of MIMO communication theory and channels introduces a new approaches and challenges. Various techniques that exploit the capabilities of MIMO channels have been proposed. Among them: STC and Bell Labs Layered Space-Time (BLAST). The MIMO systems affect capacity in different ways than smart antennas at one end do. Consider a full MIMO link as shown in Fig. 3. The tap gain from transmit antenna n to receive antenna m at time t is denoted by $h_{mn}(t)$. The channel is represented by a matrix of size $N \times M$ and denoted by $\mathrm{H} = h_{nm}(t)$ containing the channel taps.

Table for Figure 5

0,0	0,2	0,4	0,7	0,8	0,8	1,0	3,0	5,1
5,0	0,5	0,7	1,0	1,4	1,8	2,2	4,5	6,7
10,0	1,1	1,7	2,2	2,7	3,1	3,5	6,1	8,5
15,0	2,3	3,1	3,7	4,1	4,5	5,0	7,8	10,1
20,0	3,6	4,6	5,2	5,6	6,2	6,6	9,4	11,9
25,0	5,0	6,1	6,8	7,3	7,9	8,4	11,1	13,8

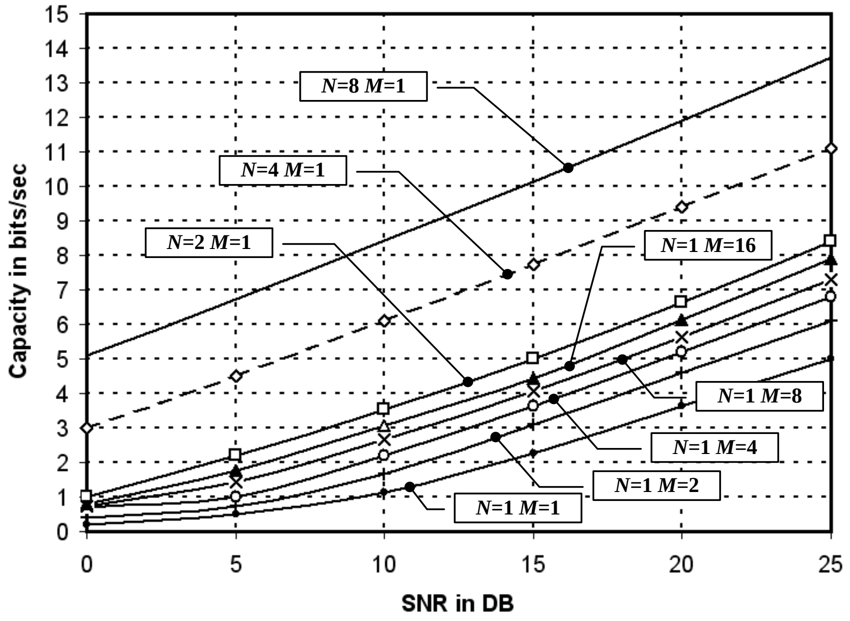

Fig. 5 – Comparison of 10% outage capacity of flat fading SIMO and MISO channels

The total transmitted power is the same as for a single antenna link, but here it is equally distributed over all transmit antennas. It is assumed that the channel taps or CSI are unknown to the transmitter but perfect known to the receiver. Assuming flat fading channel, the Shannon capacity (bits/sec), as random variable, of an (N, M) MIMO system is

$$C = W\log_2(1+\gamma) = W\log_2\left(1+\frac{P}{\sigma^2 N}\sum_{n=1}^{N}\sum_{m=1}^{M}\left|h_{nm}\right|^2\right) = W\log_2\left\{\det\left(\mathrm{I}_M + \frac{\rho}{N}\mathrm{HH}^*\right)\right\}. \quad (3)$$

Where "det" denotes matrix determinant operator, I_M is the $M \times M$ identity matrix and "*" the Hermitian operator. Fig. 6 shows the simulation results for the 10%-outage capacity of a flat fading MIMO channel with an equal number of $N = M$. It can be observed that the outage capacity increases linearly with $N = M$, i.e. when the number of antennas is increased at both ends. If $N = M$, diversity order of $M \times M$ is possible and capacity increases linearly with M; if N fixed, diversity order increases linearly with M and capacity increases logarithmically with M. The MIMO method can create up to $\min\{N, M\}$ parallel channels on which independent data may be transmitted. The principle is that increasing power in a single channel is not as effective as sharing that power between separate channels. With dual arrays link, the bandwidth efficiency growth is linear with the number of antennas and it is proportional with $\min\{N, M\}$. This is in contrast with the logarithmic capacity growth with SNR obtained with a single array link. Multiplexing gain (MG) is capacity gain at no additional power or bandwidth consumption obtained through the use of MIMO. In this case, the capacity increases much faster almost linearly with SNR (transmitted power) as the number of antennas increases, keeping the corresponding bandwidth constant. Note that in Equation (3) the bandwidth W does not change, while in classical Shannon equation the bandwidth is infinite.

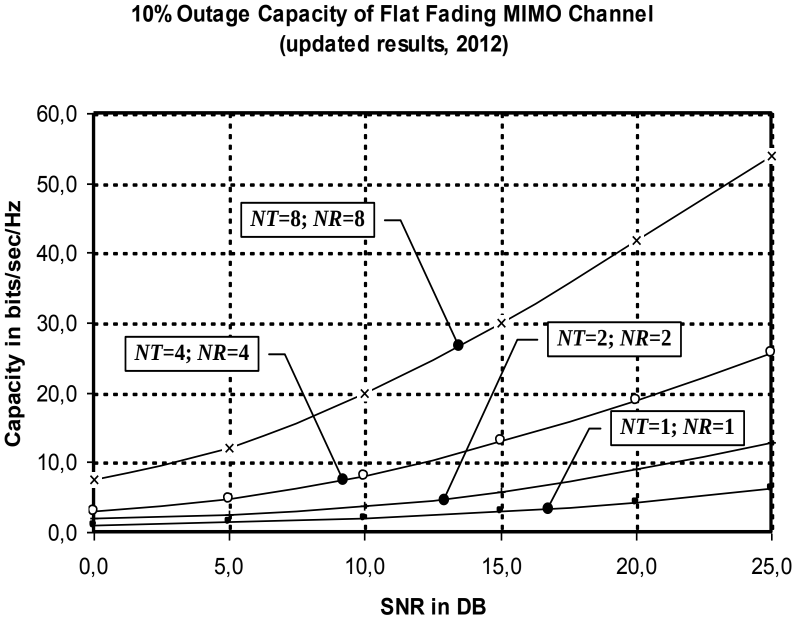

Fig. 6 – 10% outage capacity of flat fading MIMO channel

Table for Figure 6

0,0	1,0	2,0	3,0	7,5
5,0	1,5	2,5	4,8	12,0
10,0	2,0	3,8	8,1	19,8
15,0	3,0	5,9	13,0	30,0
20,0	4,3	9,1	18,8	41,8
25,0	6,3	12,8	25,7	54,0

Therefore, a MIMO system can be decomposed into SISO systems and the total capacity can be calculated as the sum of the single capacities. The capacity in MIMO wireless links mainly increases by increasing the number of channels and by providing temporal, TD, and RD (channel reliability is highly improved for higher data rates). Consequently, the outage capacity for high certainty will increase with a higher data rates. Thus, higher capacities can be achieved in MIMO systems. However, practical implementation will highly depend on the transmission algorithms and real hostile propagation channels. Increasing spectral efficiency with multiple transmit and receive antennas opens a new dimension - space - offering exceedingly high bit rates without increasing transmitted power and bandwidth allocation.

Finally, note that AG, DG and MG can translate into improved capacity (large number of users per square mile), coverage (higher penetration of service area) and throughput (higher user bit rates) in wireless networks. Therefore, smart antennas have the potential to increase capacity, expand coverage and improve signal quality. Thus, information theory has an important role to play in wireless communications and in predicting capacity limits of using smart antennas.

Conclusions

Are many aspects of the use of smart antennas in wireless data networks. It is shown that the use of smart antennas allows for more efficient use of wireless networking technology.

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Розглядається технологія застосування смарт-антен, які дозволяють підвищити ефективність використання бездротових мережевих ресурсів.

Ключові слова: смарт-антенна, беспроводные технологии, сеть, эффективность