Impact of Adaptive Array Architectures on S-Aloha Protocol Performance

R. de Araujo/ Institut National des Télécommunications, EPH France
rodrigues.ricardo@int-evry.fr

F. R. P. Cavalcanti/ Federal University of Ceara DEE Brazil
rod@dee.ufc.br

J. C. M. Mota/ Federal University of Ceara DEE Brazil
mota@dee.ufc.br

Abstract

In this paper we evaluate the influence of several antenna array topologies and channel models on the performance of a S-Aloha MAC based network equipped with a smart antenna system at the base station. Two transmission scenarios are considered: an environment without angular dispersion and another where the angular spread is higher. Important behaviour differences between the two scenarios are observed when the network comes from an underloaded region to an overloaded one. A successive interference cancellation algorithm is used as a mean of enhancing network throughput in the overloaded regions.

1. Introduction

Due the growing interest in wireless packet networks, much work has been dedicated to access the performance of smart antenna systems in this application. Indeed, smart antennas are appointed as a factitious way for capacity increase in such systems, bringing throughput and delay performance improvements. An advantage of such an approach is that this is achieved without the required wider bandwidths of spread-spectrum systems.

In this context, Compton has analysed the performance of the S-Aloha protocol when adaptive antennas are applied [1] where a model is proposed for estimating the packet acquisition and successful transmission probabilities. In this model, it is supposed that beam formers have an angle resolution of θ in any direction. So, the packet acquisition will be successful if and only if the number of transmitted packets is less than the number of antennas and there are no interfering packets arriving from an angle within the system angle resolution of the desired packet angle of arrival. Other authors have used models based in idealised beam formers for performance evaluation [2-4].

These premises provide a simple model, which, however, may not capture all the features of the system when practical antenna arrays are employed. First, the resolution of an antenna array depends on the arrival angle and the geometry of that array. Two popular geometries are the uniform linear and circular arrays. The linear array has higher resolution in the broadside direction and small sidelobes [1]. The circular array in turn does not show the mirror-like pattern problem of linear arrays, but in general its resolution is poorer [1]. Yet, in a real system, if the SNIR is over a certain threshold, a packet acquisition can be possible even if there are more packets than antennas. In this context, the model in [3] may not describe some effects of different array topologies on system performance.

In this work we evaluate the influence of different array topologies on a wireless packet network system performance while also testing such a system through different spatial channel models such as those related to macro and micro cellular environments. For this purpose we select a multiple access medium scheme based on the S-Aloha protocol.

The paper is organised as follows: a brief description of the S-Aloha media access control (MAC) protocol, smart antenna topologies, signal and used channel models are done in sections 2,3, 4 and 5 respectively. The interference suppression algorithm is introduced in section 6. In section 7, we comment on the performance evaluation mechanisms. The results are presented in section 8 and we come to conclusions in section 9.

2. MAC description

Consider a single cell packet network formed by K users and a base station equipped with a smart antenna system composed of M elements. As in an ordinary S-Aloha protocol each user may start a transmission in the beginning of a time slot whenever he has a packet. For successful transmissions an acknowledgement is sent from the base station at the end of the corresponding time slot. Lost packets are retransmitted according to a specific policy. Packet generation follows a Poisson distribution. Each user's packet has a header that consists of orthogonal Walsh codes in order to provide synchronism. It is also used as a training sequence for the adaptive antenna weight acquisition. The codes are assigned to the users in a random fashion. In this work the length of the header is 64 bits.

3. Smart antenna topologies description

In this section we provide a brief description of the topologies that have been proposed for evaluation in this paper. We have chosen four geometries to be analysed: linear, circular, linear array with diversity combining and lastly, switched beams.

The linear equally spaced array or simply linear array is formed by M elements placed along a line and spaced from each other by a distance of $\lambda/2$,where λ is the wavelength of the carrier. This geometry is one of the most popular due to its simplicity. It has good angle resolution in the broadside direction, but it decreases along the endfire direction. A drawback of this architecture is the front-back ambiguity. A mirror of the antenna pattern appears around the antenna axis. This causes loss of performance if a source of interference is placed near to $-\theta$, where θ is the angle of arrival of the desired user. To avoid this problem and the poorer resolution along the endfire, a 120° sector can be employed.

The circular array is constituted for M elements uniformly placed over a circumference of radius $r = \lambda/2$. This topology shows worse angle resolution and bigger side lobes than the linear array, but it does not have the mirror-like pattern that permits its utilisation in non-sectorized cells.

The linear array with diversity combining is formed by two sets of standard linear arrays separated by several wavelengths in order to provide spatial decorrelation between them. The beam formers of each set are adjusted separately. Their outputs are combined according to the MMSE criterion. This scheme is illustrated in figure 5. This architecture provides better performance in a narrowband fading scenario since it permits combining spatial diversity information.

The switched beams topology consists of a set of eight fixed beams, forming a 120° sector, disposed in two groups. Each group is polarised in an orthogonal direction. These beams are placed in pairs. Each pair is formed by one beam of each group pointing to a specific angle. The beam that better receives the desired user signal will be selected. The choice of this beam is made in a manner to achieve the better SNIR for the desired user.

4. System model

Let us consider the existence of K users uniformly distributed in a single cell transmitting packets to a base station with a smart antenna system composed of M elements. The packet of the k_{th} user has the following form :

$$s_k(t) = \sum_{n=1}^{P_T} s_k(n).c(t-nT) \qquad (1)$$

, where $s_k(n)$ is the n_{th} bit of the packet, P_T is packet size in bits, c(n) is the modulation pulse shape and T is the bit period. The channel response for the user k is done by :

$$\mathbf{h}_k(t) = \sum_{j=1}^{J} \beta_j(t)\delta(t-\tau_j)\mathbf{d}(\theta_j) \qquad (2)$$

, where J is the number of multiple paths, β_j and τ_j are respectively the Rayleigh complex attenuation and the delay of the j_{th} path, the vector $\mathbf{d}(\theta_j)$ of dimension (M x 1) is the response of the antenna array in the direction of arrival θ_j . In this paper only the azimuth angle dependency is considered. The users are far enough from the base station to neglect variations in the elevation angle. The received signal has the form:

$$\mathbf{r}(t) = \sum_{k=1}^{K} s_k(t).\mathbf{h}_k(t) + \mathbf{v}(t) \qquad (3)$$

, where $\mathbf{v}(t)$ is the vector of white gaussian noise present in the antenna array. The received signal is sampled at bit rate and a beam former will be used to acquire the packet of each user, then the output signal for the k_{th} user will have the form :

$$y_k(n) = \mathbf{w}_k^H(n).\mathbf{r}(n) \qquad (4)$$

, $\mathbf{w}_k(n)$ is vector of weights for the k_{th} beam former, the superscript ^{H} denotes the hermitian transpose and $\mathbf{r}(n)$ is the vector of samples of the received signal. The weights are adapted in order to obey the MMSE criterion. For this task we utilise a trained algorithm, the Direct Matrix Inversion algorithm (DMI).

In this paper, we assume that the desired and interfering user data are independent, identically distributed random variables with zero mean and unit variance, following some modulation alphabet. Furthermore we assume that the channel is stationary during a time slot and that there is no inter symbol interference (negligible delay spread).

5. Spatial channel models

A channel model must be chosen in order to match the propagation characteristics of an environment. In this work two extreme scenarios will be exploited. The first one concerns an environment without multipaths and consequently no angular spread is observed. In this condition the transfer function of the channel represented by the equation (2) becomes simply:

$$\mathbf{h}_k(t) = \beta\mathbf{d}(\theta) \quad (5)$$

This case corresponds to a macro cell environment where the angular spread is negligible. In this situation all elements of the smart antenna system receive correlated signals. In the opposite situation we have an environment where the angular spread is quite high (tens of degrees or more). For example, in an indoor application, scattering may occur in the neighbourhood of the base station, causing large angular spread. In this case there is no preferential angle of arrival for the user signal and the antenna array acts as a spatial diversity combining. This means that each element in the array will receive signals uncorrelated with the others. In the rest of this work, this channel will be referred to as the diversity channel. These two models represent extreme scenarios. In practical cases, intermediary levels of angular spread are observed.

6. Interference suppression mechanism

In a S-Aloha MAC based network with multi capture capabilities, the maximum throughput achieved depends on the number of simultaneous packets that the system can manage. When the network is brought to an overload situation (i.e. more packets being transmitted than elements in the array) the number of failures (non delivered packets) increases rapidly and consequently the number of retransmissions can lead to an unstable state.

It is known that a smart antenna system with linear processing is able to handle up to M transmissions at a time, where M is the number of elements. To overcome this limit we can make use of non-linear schemes. The most popular techniques for multi user interference cancellation in smart antenna systems are the Maximum Likelihood Sequence Estimation (MLSE), the Parallel Interference Cancellation (PIC) and the Successive Interference Cancellation (PIC).

The MLSE has potentially the best performance at the well-known complexity cost. PIC corresponds to the simplest mechanism but with poorer results [6]. SIC algorithms constitute an intermediary option in terms of complexity and performance and will be adopted in the present work.

The successive interference cancellation was initially designed for CDMA applications, but its structure is well suited to smart antenna systems. The basic idea of this algorithm is to recover the data from one user at a time and to try to eliminate its interference contribution from the received signal vector. In this way, users being detected afterwards will suffer less interference. This task is accomplished as follows.

First of all a scheduling is made based on the SNIR from all users. The user with the highest SNIR will be demodulated first, and so on. The first user signal is demodulated according to equation (4), then after the hard decision stage the data is recovered and re-modulated. At this step the re-modulated signal is applied to a channel estimation, sampled and subtracted from the received signal vector $\mathbf{r}(n)$, originating a new vector $\mathbf{r}_i(n)$ with the residual received signal at the ith iteration. At each iteration one user is treated. As the received signal vector changes from one iteration to an other the channel correlation matrix must be re-calculated. The channel estimation is performed during the training period through the expression :

$$\underline{\mathbf{h}_k} = E[\mathbf{r}(n).c_k(n)^*] \quad (6)$$

, where c_k is the walsh code for the kth user.

7. Performance evaluation

In order to evaluate the sensitivity of performance due to different array topologies and channel models, we examine the throughput vs. network load characteristic for each case. System throughput is accessed through the theorem by Ghez et. al. [7], which concerns the throughput obtained for an infinite user population, with a multiple capture receiver, in a S-Aloha system under optimal retransmission control. In this case, the throughput S as function of the offered load g is given by:

$$S(g) = e^{-g}\sum_{p=1}^{\infty}\frac{g^p}{p!}C_p \quad (7)$$

, where C_p is the average number of successes given that p packets are transmitted in a particular time-slot. In this work C_p is obtained from Monte Carlo simulations for throughput evaluation. The network offered load corresponds to the packets generated per time slot. Note that the equation (7) corresponds to a idealised system where it is possible to apply an optimal retransmission control and thus it represents an upper limit.

8. Simulation results

Simulation results for the scenarios proposed here are presented in this section. For all simulations BPSK modulation is used.

As our first experiment, we compare three configurations: a linear array (linear), a circular array (circular), both following the channel model in eq.(5) and a spatial diversity combining array (diversity) in a diversity channel. For all cases a six elements antenna array is considered. Initially we evaluate these three situations in an infinite population network with optimal retransmission control. The results can be seen in figure 1.

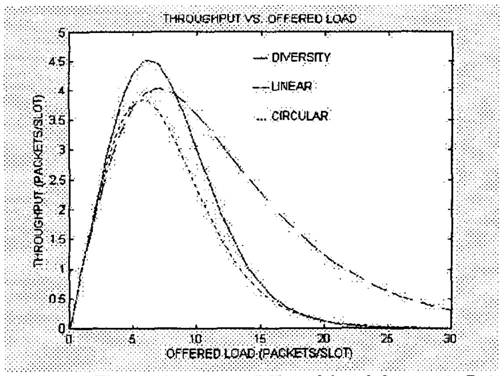

Figure 1. Throughput vs. Offered load for an infinite population under optimal retransmission control S-Aloha MAC network.

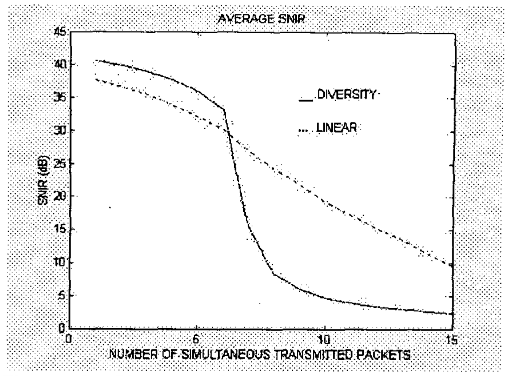

Figure 2. SNIR as function of the number of transmitted packets.

In this case, the linear array presents a better performance than the circular topology. This can be explained by the linear array ability to capture users even when they are close to each other, thanks to its greater angular resolution and smaller sidelobes than in the second topology.

An interesting characteristic, illustrated in figure 1, is the change of relative performance between the linear array configuration and the spatial diversity combining array, when the system goes from an underloaded to an overloaded condition. When the number of active transmissions is smaller than the number of elements in the antenna array, the system can benefit from the elevated degree of spatial diversity that is present in a microcell environment (diversity channel). However, in an overloaded condition the linear topology yields better performance. This can be explained from the different capabilities of handling the multiple user interference in each case. As the degrees of freedom are consumed with interference cancellation, the spatial diversity effect is lost and indeed brings a performance loss. Such a phenomenon is clarified in figure 2 by showing average SINR as a function of the system load.

As a way of improving the performance in the overloaded region, we examine the use of the successive interference cancellation algorithm (SIC) previously described. The same previous configurations are used to compare the SIC scheme gains. See figure 3 for results.

Notice that the SIC algorithm produces different enhancement in performance in the two channel models studied. The throughput peak of both the linear and circular arrays surpasses the one obtained by the array in a diversity channel.

The next topology considered is the linear array in a diversity combining mode. This architecture has as goal to obtain spatial diversity within an environment where the coherence distance is large. To achieve this goal two linear arrays of three elements are placed far enough in order to undergo differentiated attenuations. The angle of arrival of each user is considered as the same for the two sets of antennas. All the coefficients in such structures are adjusted obeying the MMSE criterion through the DMI algorithm.

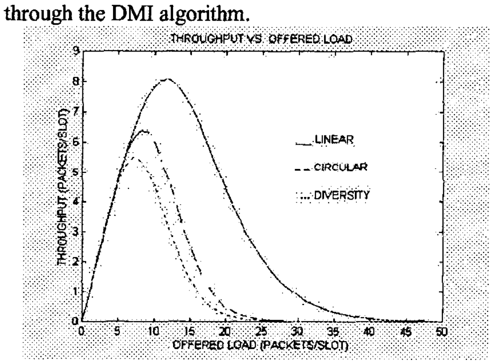

Figure 3. Throughput vs. Offered load for an infinite population under optimal retransmission control S-Aloha MAC network. System with SIC.

In figure 5 the result of this topology is compared to the linear array. Both architectures are simulated under the same conditions (i. e. 6 elements in each system, infinite population and optimal retransmission control). This result shows us how a greater degree of spatial diversity can enhance the performance in a network.

As a last topology verified in this work we examine a switched beam system. The architecture used here is inspired from commercial product [8]. It consists of eight fixed beams that, thanks to a polarisation orthogonality,

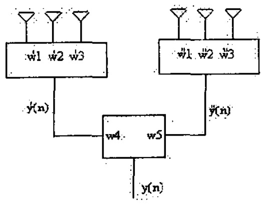

Figure 4. Schematic of the linear array in a diversity combining mode. The output of the system is represented by y(n).

can be constructed with four antenna elements. A switched beam system has a smaller level of intelligence than a beam forming scheme. This means that it does not have the same ability to accomplish captures. This can be observed in the next result (figure 6). For the sake of comparison, the switched beam system is confronted to a 4-element MMSE beam former. Both configurations are simulated in a 120° sector with the model in eq.(5).

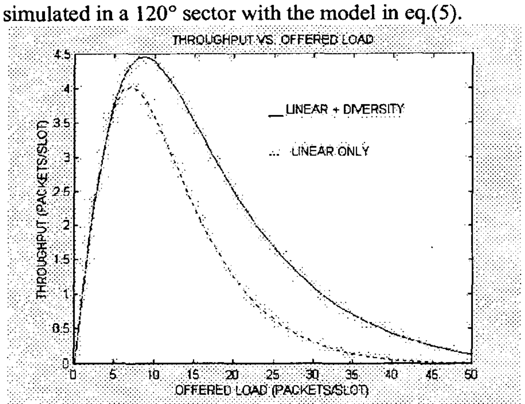

Figure 5. Comparison between the linear array in a diversity combining mode (LINEAR + DIVERSITY) and a simple linear array (LINEAR ONLY)).

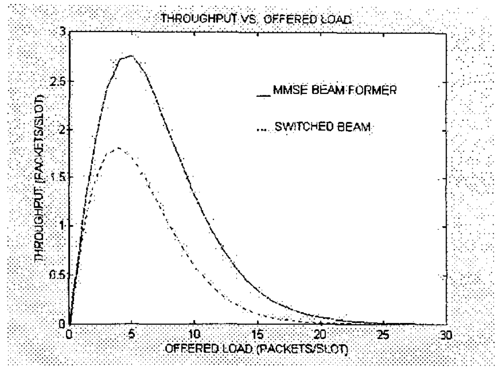

Figure 6. Curves of Throughput vs. Offered load for a switched beam and MMSE beam forming systems.

As expected the beam former provides higher throughput. Actually, switched beams systems represent a good way to combat co-channel interference for improving frequency re-use, but it is relatively limited to implementing SDMA schemes.

9. Conclusions

In this work we evaluated the performance of an S-Aloha MAC based network with a system at the base station receiver in terms of throughput. It was evidenced how the network smart antenna behaviour can be influenced by the topology of the antenna array and the characteristics of the wireless channel. Based on these observations it is clear that a system described by the idealised beam former is not able to capture the performance sensitivity due to different array topologies and channel models.

A successive interference cancellation algorithm was used as a way of enhancing the performance of the network. It was noted that greater improvements are obtained with correlated arrays rather than in spatial diversity arrays. Another method exploited here to increase the throughput was accomplished by means of a higher spatial diversity, as was demonstrated in figure 5.

10. References

[1] Ward, J. , Compton, R., "High Throughput Slotted Aloha Packet Radio Networks with Adaptive Arrays", IEEE Trans. Comm. v.41., n.3, pp.460-470, 1993

[2] Sugihara, A., Sasase, I.; "Throughput Performance of Slotted Nonpersistent CSMA with an Adaptive Array", Electronics and Communications in Japan, Part I, Vol. 80, No 9, pp.34-43, 1997.

[3]Chockalingan, A., Ramesh, R.;"MAC Layer Performance with Steerable Multibeam Antenna Arrays". 9th PIMRC, IEEE , NY, vol. 3, pp. 934-937, 1998..

[4] Kobayashi, T.,Sugihara, A.;"Slotted Nonpersistent CSMA with an Adaptive Array and Cancelling Signal", GLOBECOM '96. Vol. 1 , pp. 565 -569, 1996.

[5] Litva, J. e T.K. Lo. "Digital Beamforming in Wireless Communications". Artech-House, 1996.

[6] Münster, M.; Hanzo, L. "Co-Channel Interference Cancellation Techniques for Antenna Array Assisted Multiuser OFDM Systems". First International Conference on 3G Mobile Communications Technologies, Conference Publication No 471, IEE, pp. 256-260, 2000.

[7] Ghez, S.; Verdu, S., "Optimal Decentralized Control in the Random Access Multipacket Channel" , IEEE Trans. On Autom. Control, vol 34, no 11, pp 1153-1163, Nov, 1989.

[8] Demeryd, A., Johannisson, B.; "Adaptive Base Station Antenna Arrays", Ericsson Review No 3, pp. 132-137, 1999.