Antenna Architectures for CDMA Integrated Wireless Access Networks

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Abstract

In this paper we consider different antenna sub-systems for integrated wireless access networks (IWAN). The various antenna sub-systems present alternatives to the standard architecture of a cellular system where the transmission/ reception occurs via omnidirectional or directional antennas with each antenna located at a base station. The appropriate antenna sub-system is dependent on the modulation scheme used. In this paper we consider a CDMA scheme along with various antenna sub-systems such as a distributed antenna, an antenna sub-system which we refer to as a sectorized distributed antenna, and a distributed antenna utilizing sub-carrier multiplexing. These concepts lead to a network architecture consisting of network switches, radio controllers, base stations, and the various antenna sub-systems. The mix of different approaches to antenna sub-system design leads to various system design alternatives with trade-offs in design issues such as capacity, system complexity, coverage, and robustness against fading.

1.0 Introduction

The main resource in the design of a wireless multiple access bandwidth is the amount of radio spectrum allocated to the network. The requirement to provide mobile telephone services in a limited bandwidth has resulted in the development of the cellular network architecture and the cellular concept. The basic cellular architecture consists of three main components, a switch, base stations and the mobiles. The mobiles communicate with the base station via radio and the base station is connected to the switch via telephone trunk circuits which are typically hard-wired or microwave point-to-point circuits. A fundamental concept is that of hand-off. The intelligence in the system (e.g. hand-off algorithms) are contained at the switch. To increase the capacity of the system directional (or sectorized) antennas are used.

A fundamental concept which directly determines the spectral efficiency of the network is the concept of frequency re-use pattern and cluster size. The capacity of the network is inversely proportional to the cluster size. The actual cluster size depends on the robustness of the modulation scheme to protect against co-channel interference. With sectorized antennas the degree of co-channel interference is reduced; thus the cluster size can be reduced. CDMA is one of the schemes which has a large degree of robustness against co-channel interference and allows a cluster size of 1 [1].

The capacity of a CDMA cellular network is determined by the amount of interference in the network and the variability of the received signal power due to fading [1][2]. The interference depends on various parameters included in the capacity equation such as the operating value of SNR, the frequency re-use factor which accounts for inter-cell interference, the antenna sectorization angle, and the transmission activity factor for bursty information sources. Of these, the antenna sectorization angle is one of the most significant parameters. For systems like IS-95 the sectorization angle is suggested to be 120 degrees. This angle can possibly be reduced but not by a large amount since with very narrow sectors an excessive number of inter-sector hand-offs are required.

The existing cellular architecture has been developed to meet the needs of the mobile communication environment where the terminals are assumed to be located in vehicles. The capacity of the system can be increased either by decreasing the cell size or decreasing the antenna sector size. However, there is a lower limit both on the cell size and sector angle beyond which the system overhead required to implement the hand-offs becomes excessive and the positioning of base stations may not be possible. The current cellular system could be adapted to personal communication systems by decreasing the cell size in environments where the users are stationary or traveling with low speed by reducing the cell size considerably (e.g. by 100's of meters radius). However this approach is expensive since base stations are expensive to set up. What is required is a different approach where the base station is considerably reduced in complexity and the architecture of the system is modified. In this paper we discuss various modifications to the standard cellular architecture which result in networks with higher capacity and modest complexity. Our approach may be thought of as a merging of the cellular network and CATV network architectures.

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2.0 Antenna Architectures

It has long been recognized that a fundamental issue in the design of mobile radio networks is that of bandwidth management. In narrowband networks the issue of bandwidth management is tied to the system parameters of modulation bandwidth and frequency re-use cluster size. Equally as important in determining the spectral efficiency, and perhaps not recognized as early, is the issue of transmitter power management. This is especially the case in environments with significant multi-path propagation, where in spite of various control algorithms and the use of efficient receiver structures the short term average received power varies with time. The amount of variation is known as the system fading margin, and its control (reduction) is as important as the issue of bandwidth management. A well designed mobile communication link must contain efficient transmitting and receiving antenna sub-systems. Both of these may take on different forms. We may have omnidirectional antennas which radiate (or receive) the signal from a single location in all directions, directional (or sectorized) antennas which radiate the signal from a single location into a sector, or various types of radiators which radiate the same signal from different locations. Another example is a scheme where the radiation occurs continuously along a cable - the so-called *leaky feeder* cable [3]. Another alternative is to radiate the same signal from multiple discrete locations [4]. We refer to the last two as distributed antennas.

The objective in choosing a type of antenna is to minimize radiation to unwanted areas to minimize interference, to use the smallest number of elements to cover an area taking shadow fading into account, or more generally to simplify the antenna structure, and to provide diversity against fading. In the following we look at a number of structures to achieve these goals.

2.1 Cell Sectorization

First we consider sectorization with a small number of sectors. The standard approach is to consider the different sectors in the same manner as different cells and to do frequency assignment over the different sectors and perform hand-offs in the usual manner. There is a major difference, however, in the sense that inter-sector hand-offs can typically be performed at the base station without going through the switch. In IS-95 a different phase of the PN code pilot tone is assigned to each sector in the same manner as the assignment of PN code phases to different cells. The corresponding inter-sector hand-off may be performed without signaling through the switch - the so-called *softer hand-off*. Still a given amount of signaling between the base station and mobile is required and the mechanism required to track different pilot tones for potential hand-off puts a restriction on the minimum sector size that can be implemented.

An alternative approach is one that does not require hand-offs at the mobile. Such a scheme may be implemented by designing the forward link to use asynchronous CDMA as in the reverse link of the IS-95 system. With asynchronous CDMA each user is assigned a unique code for reception in the forward channel. Since the code address space is very large the code assigned to the user in the forward channel belongs to the user and is used for the remainder of the call regardless of the location (cell or sector) of the user. The asynchronous CDMA scheme allows the implementation of what we may call a *mobile transparent hand-off*. With such a hand-off the notification of an impending hand-off is given to a neighbouring cell or sector, and the neighbouring cells or sectors take on the transmission and reception of the new user. However the mobile continues transmitting on the same code. At the mobile receiver a hand-off between cells or sectors appears as a change in multi-path components. In contrast, with orthogonal CDMA each sector contains a set of orthogonal codes. The codes are assigned to users as in a classical channel assignment scheme. These advantages of an asynchronous forward link carry over to the distributed antenna systems that we discuss later.

The base station will contain a large number of sectors as shown in Fig. 1. A number of correlators (e.g. 3) are used to demodulate and combine the signal for one user using the Rake receiver principle. Extra correlators are used to search for new multi-path components. In a CDMA system with large sector angles the search for new multi-path components by the Rake receiver occurs along the time axis. In the proposed scheme with small sectors, the search would occur simultaneously along the time axis and over different sectors. A number of possible algorithms may be used to perform this search efficiently.

With this scheme the behaviour of the mobile is independent of the antenna sector size. However the base station needs to know in which sector (or sectors) it should transmit the signal. We propose that the transmission on the forward link should occur on those sectors with a large received signal power. In this case received power variations are averaged out to cancel the effect of Rayleigh fading which is frequency dependent and hence different for the forward and reverse channels.

2.2 Adaptive Arrays

The classical technique to reduce interference employing antenna techniques is to use adaptive antenna arrays [5][6]. The antenna consists of an array of elements as depicted in Fig. 2. The parameters α and τ are adjusted so that the resulting antenna pattern has nulls in the direction of the interferers. The element spacing may be in the order of a wavelength. The number of nulls in the antenna pattern is typically equal to the number of antenna elements.

The antenna parameters are adjusted to demodulate individual users, and for a given user, are adjusted to adapt the antenna pattern to a change in the positions of the user of interest and the interferers. The adaptive antenna and the sectorized antenna proposed in Section 2.1 are alternatives for a large

degree of interference reduction which utilize different signal processing techniques.

2.3 Distributed Antenna

In order to improve the performance of a radio system against Rayleigh and shadow fading the antenna can be designed to consist of various elements that are spaced apart by a relatively large distance [7][8]. If we take the above adaptive antenna, fix the delay parameters, and make the spacing between the antenna elements large (e.g. tens or hundreds of meters) then we obtain a distributed antenna as depicted in Fig. 3. The different radiating elements are fed with delayed versions of the transmitted signal. The delays may be incurred in the feeder cable or may be inserted just before the antenna element. The signal may be fed to the antenna elements by a cable. To account for loss in the cable an amplifier may be placed at each radiating element. Alternatively the signal may be fed to the elements through an optical fiber where the intensity of the optical signal is modulated by the RF signal. The RF signal is detected at the radiating element, amplified, and radiated. A further alternative is to use a cable for signal distribution, but in order to limit the loss in the cable, the signal is transmitted on a lower carrier frequency. A converter/amplifier at the element (C/A) would then up-convert the signal to the RF frequency, amplify, and radiate. A similar receiving circuit would be used for the case where the antenna is acting as a receiving antenna.

The distributed antenna performs two functions which are quite different from the function of the adaptive antenna discussed above. First, with a significant physical separation among the elements the antenna provides macro diversity and improves the coverage especially in areas with significant shadow fading. Second, with sufficiently large delays the antenna creates artificial multi-path in the channel. The result is that the coherence bandwidth is significantly reduced. This allows for the use of equalization and the consequent mitigation of the flat fading problem that may be present if the delay spread is small. With CDMA the equalization technique of choice is the Rake receiver. The distributed antenna introduces multi-path in the channel. The delays in the cable should be chosen sufficiently large so that the multi-path echoes are resolvable - typically greater than the PN code chip period.

At the system level the distributed antenna system has characteristics which are quite different from those of a standard omnidirectional or sectorized antenna. Depending on the number of elements the DA may be modelled as an omnidirectional antenna with a different power loss law than the typical R^{-4} law. Effectively the power loss is small within the cell (due to the coverage from the multiple elements) and increases drastically as we move outside the coverage area which we may consider to be the cell. Another characteristic of the DA is that we may design coverage areas (cells in the conventional system) which are non-circular and non-sectorial. We may actually design a radio cell which is non-contiguous. This flexibility in cell design will result in less inter-cell interference in the system and consequently a higher capacity.

2.4 Sectorized Distributed Antenna

If we attempt to cover a large area with a CDMA distributed antenna then the capacity of the system per antenna element decreases as a result of the multiple access interference. The system becomes inefficient especially if there are a large number of users in the area covered by the distributed antenna. The resulting system becomes analogous to a conventional cell with an omnidirectional antenna. The main difference is that the interference outside the coverage area is reduced and the transmitting power of the mobile may be less than that in the case of a conventional omnidirectional antenna.

To reduce the interference level and increase the capacity per antenna element we design the DA as a set of branches (or sectors) fed independently from the base station. The signal is then received on the branch which covers the location closest to the mobile. The transmitted signal is transmitted only on the branch which covers the area where the mobile is located. A mechanism is required to track the terminal as it moves over different areas covered by different branches. We call this structure a *sectorized distributed antenna* (SDA). This idea is synonymous with the idea of sectorization in conventional cells as we have already discussed.

At the system level the sectorized distributed antenna results in a higher capacity per antenna element than the regular distributed antenna. At one extreme we have a distributed antenna with all the elements fed from a single line, i.e. one sector. At the other extreme we have a separate feed line running to each of the antenna elements, i.e. the number of sectors equals the number of elements. In practice some intermediate level of branching (or sectorization) must be chosen. With a large number of sectors the system has a more complex SDA switch and requires more complex signal processing in order to track the various users. On the other hand the system has a large capacity which may not be required. We could say that the solution in this case is to reduce the number of elements. However such a reduction may result in less efficient coverage especially if the environment has a large degree of shadow fading.

The transceiver for the SDA may be designed to have a similar structure to the transceiver for the sectorized cell that we have already described. However there is a difference in the characteristics of DA sectors and cell sectors. In the case of cell sectors, if the sector angle is small, significant signal components may arrive from non-contiguous sectors. Also, for small sectors and with Rayleigh fading the sectors with the highest received signal power may not be the optimum sectors to transmit the forward channel signal. The reason for this is that Rayleigh fading is uncorrelated in the forward and reverse channels. With the SDA the environment in an area covered by an antenna sector is different than that in areas covered by other sectors. Strong received signal components will arrive

mostly in one sector and the sector with the strongest received signal will generally be the optimum sector to transmit the forward channel signal.

2.5 Multiplexed Distributed Antenna

The above sectorized distributed antenna requires a separate feed line for each of the antenna branches. In the example in Fig. 4 there are 5 branches, or sectors. This requirement makes the system rigid to expandability since a separate feed line running from the base station must be installed for each new branch. An alternative design which would perhaps have more flexibility would use frequency division multiplexing to transmit the various signals on the same feed line. The antenna elements would then consist of frequency converters and amplifiers. Another alternative would be to use optical fibers as in [9]. With the use of optical fiber, the multiplexing may be wave division multiplexing. The frequency converters convert the signal from a variable sub-carrier frequency on the distribution line to a fixed RF frequency.

3.0 Proposed IWAN Architecture

In the above we have discussed various antenna strategies for a radio network. They include the omnidirectional, sectored, DA, sectorized DA, and multiplexed DA. Our proposed IWAN network would utilize a hybrid of the above approaches with specific choices dependent on the local environment. The network would consist of a switch that is connected to various radio controllers or directly to base stations. The radio controllers control a set of base stations as shown in Fig. 5. The base stations would be of different types depending on the area served by the base station - e.g. rural area, urban cellular in vehicular environment, urban area with low velocity terminals, indoor areas, etc. For example in a rural area with a sparse population of users the choice would be an omnidirectional antenna system since the coverage area is large and the user density is low. For the same environment and a slightly higher density of users the choice would likely be a sectorized antenna. A similar area with a high user density would employ a sectorized distributed antenna. In an area with a low density of users, relatively short distances, and difficult propagation conditions, the choice would be the distributed antenna.

4.0 Summary

We have surveyed different antenna architectures for an integrated wireless access network. Such a network is required to provide services in a range of different environments, different user densities, and variable traffic loads. For optimum performance these conditions require the use of different antenna architectures. We have introduced some of these architectures and described them in a general framework which includes the conventional cell with omnidirectional and sectorized antennas. We have also discussed the advantages and disadvantages of the various architectures and their suitability for different environments. Research on a more quantitative analysis of the performance of these architectures is in progress.

5.0 References

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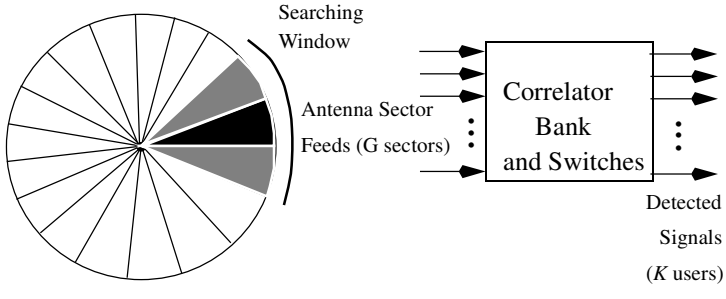

Fig. 1. Sectorized antenna with corresponding receiver structure.

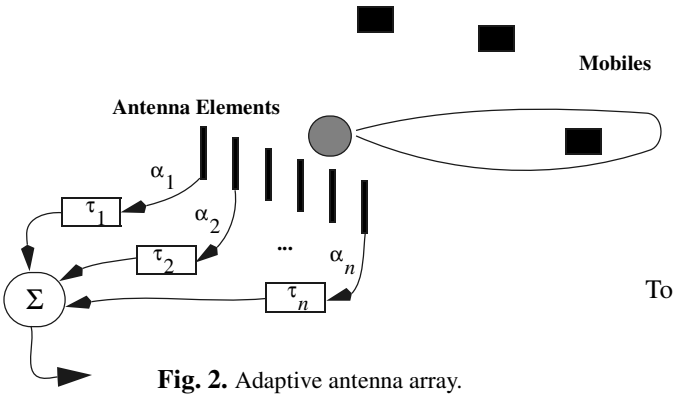

Fig. 2. Adaptive antenna array.

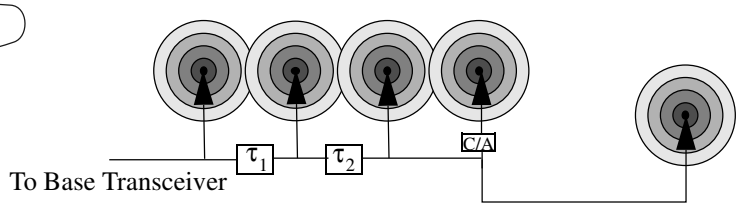

Fig. 3. Distributed antenna system.

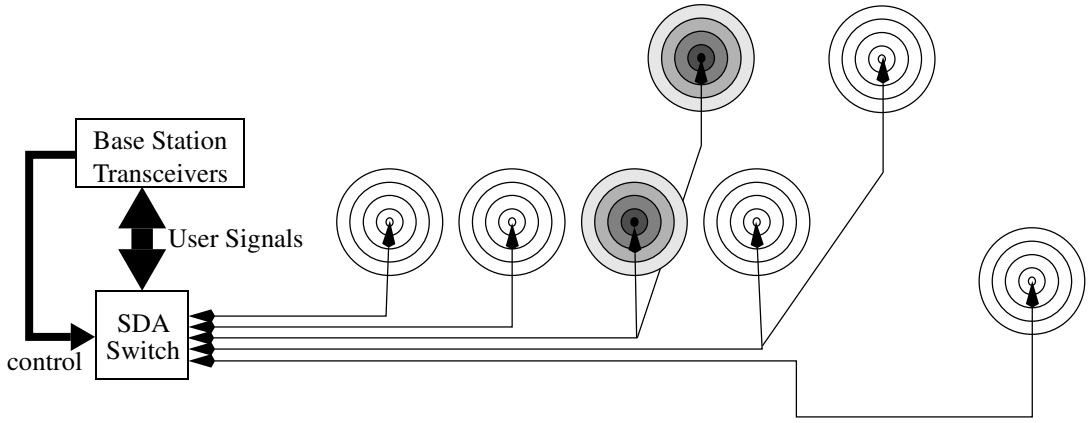

Fig. 4. Sectorized distributed antenna with 5 sectors.

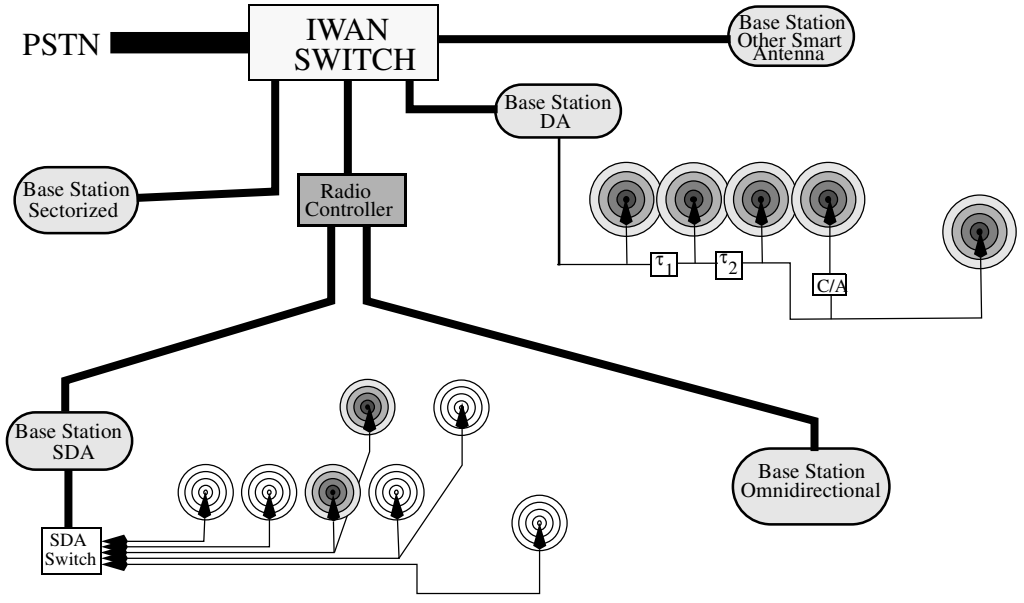

Fig. 5. Possible system architecture incorporating various antenna architectures.