On the use of Distributed Directive Antenna Arrays in mobile OFDMA Networks

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Abstract— **Distributed Omni Antenna Systems (OASs) have been proposed to increase the capacity of Broadband Wireless Access (BWA) systems. We investigate the extension of such systems by employing distributed Directive Antenna Arrays (DAAs) to support high speed users also employing multiple antenna configurations. The problem of beamforming in a single sector is considered where remote Base Stations (BS's) equipped with multiple antennas attempt to serve a separate user. Different positions of distributed BS's in the sector are studied. The beamforming design is based on partial Channel State Information (CSI). The case study for a WiMAX system show that DAAs using beamforming techniques significantly improve performance compared to OASs and lead to an optimum network infrastructure in BWA with high mobile users systems where high – bandwidth radio services are required.**

I. Introduction

Mobile Broadband Wireless Access (BWA) networks have become increasingly popular among businesses and consumers. Such networks should provide a) high throughput links shared by multiple mobile users that may be traveling at high speeds b) low latency, e.g. they should transmit packets with minimum delay to adhere to the demanding and differentiated Quality of Service (QoS) requirements of advanced multimedia services. In BWA systems, Multiple Input Multiple Output (MIMO) technology has been proposed for delivering high bit rates using multi-antenna configurations. In a high mobility link, it could be assumed that the receiver has perfect channel knowledge while the transmitter has only knowledge of either the mean or the covariance of the channel coefficients. In [1], the transmitter optimization problem was solved for multiple transmitting and receiving antennas exploiting the channel gain mean and covariance information. It was found that beamforming performs close to the optimal strategy assuming very accurate quality of the channel estimated at the transmitter. Beamforming maximizes the signal energy sent to a desired mobile and it may support multiple mobiles through Spatial Division Multiple Access (SDMA) by minimizing co-channel interference towards neighboring mobiles. In essence, beamforming focuses the transmitted signal energy towards the direction of the intended user, maximizing the user's received SINR and minimize at the same time the interference generated on the rest of the cell. The Orthogonal Frequency Division Access (OFDMA) technique, which has been standardized for mobile BWA systems including IEEE 802.16e/WiMAX and 3GPP LTE [2,3], divides the total frequency band into subchannels. Each subchannel is composed of several subcarriers and each user is allocated a block of subchannels. The main advantage of OFDMA is its robustness against frequency-selective fading by dividing the channel into flat fading subchannels. The combination of beamforming and OFDMA provides exceptional system performance by exploiting multiuser diversity in both frequency and space domains [4]. Distributed Omni Antenna Systems (OASs) have been widely implemented to extend coverage, eliminate dead spots and increase capacity [5].

The contribution of this paper is to present an advanced radio access network with the deployment of a dense network of BSs. The proposed solution, employing multiple antennas at the both ends, enable an advanced BWA network to operate at its full potential towards achieving cost – efficient (the complexity of the transmission is reduced closed to the antennas) and high data rate transmission even in cases of cell edge users. We extend the notion of OASs by assuming multiple distributed Directive Antenna Arrays (DAAs) that are located within a microcell and connected to a central Base Station (BS) via dedicated wires, fiber optics or dedicated Radio Frequency (RF) link. This system has low cost since signal processing is performed at the BS and very minimal hardware (RF power amplifier and RF or optical converter) is required at the DAAs. For such a network we investigate the employment of beamforming and OFDMA techniques to assess the achieved throughput that can be provided. A deployment architecture is assumed according to which a cell may be covered by DAAs located in different places. This structure is compared to an alternative multi-cell system with omnidirectional antennas in reduced coverage, pico-cells, and to traditional cell architecture involving a single high power BS. The results show a performance improvement over the above conventional architectures.

The organization of this paper is the following: In section II the proposed DAA cellular architecture is presented. In section III, a description of the Radio over Fiber (RoF) technology for the deployment of WiMAX networks is provided. Section IV describes the transmission strategy and its simulation assessment is provided in section V. Finally, the related conclusions are given in section VI.

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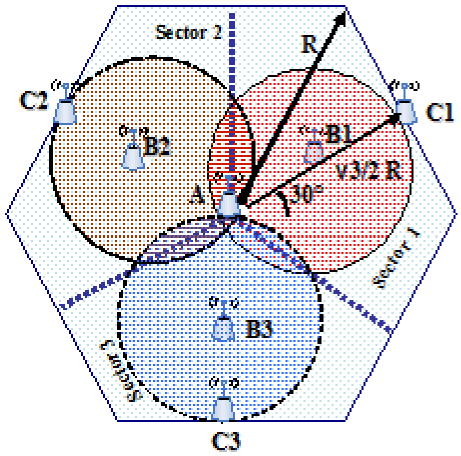

Fig. 1 The positions of Distributed Antenna Arrays in a single cell

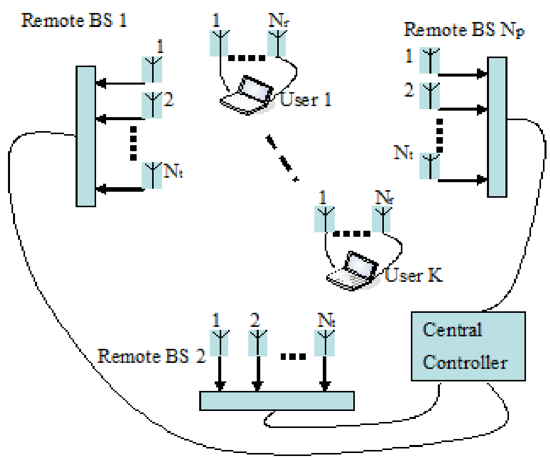

Fig. 2 Cell deployment with remote BS

II. CELLULAR ARCHITECTURE

In literature, distributed OASs are proposed to enhance the cellular capacity[5]. The omni-directional distributed antennas generate co-channel interference within the cell even though they have limited transmit power. In conventional cell configurations, cell splitting by employing three directive antennas and static Frequency Reuse Factor (FRF) of 3 is employed to mitigate co-channel interference and increases the system capacity. The novel concept of the proposed system using DAAs can be described in fig. 1. We developed an RoF system in order to reduce the cost of the remote DAAs. All signal processing (beamforming, scheduling, RF generation and modulation, etc) is made in the Central Controller (CC). The signal to be transmitted by remote BSs is transmitted from the CC to the BS's in the optical band via a fiber optic network. Each remote BS includes only Optical to Electronic (O/E) and Electronic to Optical (E/O) convertes, the antenna array (N_t=4 antenna elements with omnidirectional or 180° sectorized radiation pattern) amplifiers (power at the transmission and low noise at the reception. The considered system is shown in fig. 2. Multiple remote BSs are connected to one CC. There are N_p remote BSs distributed around the cell each with N_t antenna elements. One DAA is employed per sector to achieve performance improvement with minimum complexity and cost. Various candidate positions for DAAs are considered (e.g. for sector 1 we have the positions A, B1, C1) as shown on fig. 1. We will identify the proper location of DAAs in order to enhance the system performance.

III. RADIO OVER FIBER FOR WIMAX NETWORKS

The DAA architecture requires a large number of BSs to cover the service area. Also, low cost BS's are required. The limitations in the infrastructure costs led to the development of centralized systems where signal routing, handover, frequency allocation are carried out at a central Controlling Station (CC) rather than at BS level. Since the optical fiber (fibre) has low loss and ultra-wide bandwidth, the RoF network is used to link the CC with BSs. The resources provided by the CC can be shared among many BSs. The remote BSs perform only simple functions, they have small size and low cost. At frequencies used for WiMAX, directly modulated semiconductor lasers (LD-Laser Diode) and single mode fibre are preferred due to low transmission losses, engineering simplicity, low cost and small size [6]. When Direct Intensity modulation is combined with direct detection using Photo-Diode (PD),it is referred to as Intensity-Modulation Direct-Detection (IMDD). A Semiconductor laser directly converts a small-signal RF modulation into a corresponding small-signal modulation of the intensity of photons emitted. Thus, a single device serves as both the optical source and the RF/optical modulator. The resulting intensity modulated optical signal is transported over the length of the fiber optic to remote a BS. There, the emitted RF signal is recovered by direct detection in a PIN PD. The signal is then amplified and radiated by the antenna.

In [7] the development of RoF technology for the transmission of WiMAX signals in the 3.5 GHz band for several single mode fibres up to 5 Km is studied. Measured spectral mask and maximum allowed Error Vector Magnitude (EVM) for ¾-64 QAM modulation and coding are compliant with the limits defined in the IEEE 802.16 standard. In case of a BS forming a four DA array for implementing beamforming techniques, Wavelength Division Multiplexing (WDM) scheme could be developed. We could transfer the four RF signals from the CC to a remote BS in order to feed the four antenna element via one optical fiber with minimum cost(one fibre than four). The four optical RF wave signals from four LDs could be multiplexed and the composite signal be optically amplified and transported over a single fiber. The remote BS will de-multiplex the RF signals which feed the four DAs. The wavelength multiplexing causes chromatic dispersion. In a fibre, the index of refraction n ($n = c/v_g$, c is the light speed and v_g the group velocity) is function of the wavelength. Therefore, certain wavelengths will propagate faster than others. The delay effects caused by the fibre on the beamforming technique are studied via simulations in [8]. The phase shift differences corresponding to a 2m difference in the fibre lengths give a 10° mis-adjustment in the beam steering. In a high speed user network, the fast radio channel changes introduce greater delays than the delays caused by the fibre. The beamforming technique is not affected by RoF since the phase shift generated by several RoF links in parallel is included in the CSI, which is fed back to the CC.

IV. ADAPTIVE BEAMFORMING AND OFDMA TRANSMISSION

In the IEEE 802.16m standard the Fractional Frequency Reuse (FFR) technique divides the orthogonal frequency resources among neighboring sectors to mitigate co-channel interference. It takes advantage of the fact that in OFDMA, the bandwidth is divided into subchannels and a fraction of all available subchannels is used at each sector. Each subchannel contains a group of subcarriers. There are two subchannel permutation schemes following either diversity or contiguous patterns. The diversity permutation type forms a subchannel with subcarriers pseudorandomly distributed over the available bandwidth to provide frequency diversity while the contiguous permutation scheme groups a block of adjacent subcarriers to form a subchannel in order to provide multi-user diversity gain by choosing the subchannel with the best frequency response. In this paper we will use the contiguous permutation scheme in conjuction with the beamforming and Adaptive Modulation and Coding (AMC) techniques to utilize efficiently the wireless channel characteristics and achieve maximum throughput.

In the proposed strategy, the number of subchannels is selected to be equal to the number of sectors and the subchannels are assumed to be scheduled dynamically according to the channel conditions. If fs with $s \in \{1,2,3\}$ represents the different subchannels in the same frequency channel F, Ns is the number of subcarriers at each subchannel and N the total number of subcarriers, FFR implies that

$$\bigcup_{s=1}^{3} f_s = F \quad (1) \qquad \bigcup_{s=1}^{3} N_s = N \quad (2)$$

Consider the scenario incorporating a single sector s. The transmitter has a DAA with M_t antenna elements and K_s user receivers are assumed to be located in the sector each having M_r antenna elements. Let the matrix $H_k^n = [h_k^n(j,i)]$ of size M_r x M_t represent the channel coefficients between the antenna j of user k and the antenna i of the BS at subcarrier $n \in \{1,2,\cdots N_s\}$. We assume that the channel h_k^n (j,i) is frequency flat (due to OFDM) and quasi-static. Also, we assume that V_s is the beamforming vector applied to M_t antenna elements at the DAA and the noise at the receiver k is zero –mean and white with variance σ_0^2. The receiver employs linear equalization with the Minimum Mean Square Error (MMSE) criterion. The theory of Wiener filters gives the receiver matrix U_k^n applied at the received antenna elements assuming that the transmitted signal is zero-mean with unit variance [9]. The computation of the optimum filter coefficients requires the knowledge of the correlation matrix of the received signal $Y_k = [Y_1^k \; Y_2^k \; \cdots \; Y_{N_r}^k]$ and the desired response x_{0k}.The estimation vector $\hat{x_0}$ is obtained using the theory for linear optimum discete-time Wiener filters[9].

$$\hat{x_{ok}} = F_k^H Y_k \quad (3)$$

The filter weights are

$$F_k = [f_k(i,j)] \quad (4)$$

The coefficients $f_k(i,j)$ are designed to minimize the mean square error

$$d_k = \mathcal{E}\{(x_{0k} - \hat{x}_{0k})^*(x_{0k} - \hat{x}_{0k})\} \quad (5)$$

$$F_k = \mathcal{E}\{Y_k Y_k^H\}^{-1} \mathcal{E}\{Y_k x_0 k^H\} \quad (6)$$

Assuming $\mathcal{E}\{x_{0k}^H x_{0k}\} = 1$ and that the channel matrix $H_k V_k$ is known without any error at the receiver we get

$$U_k^n = H_k^n V_s [H_k^n V_s (H_k^n V_s)^H + \sigma_0^2 I_{N_r x N_r}]^{-1} \quad (7)$$

where $I_{N_r x N_r}$ is the identity matrix of size N_r. The SNR_k^n calculated at the receiver k is

$$SNR_k^n = \frac{\left|(U_k^n)^H H_k^n V_s\right|^2}{\left\|U_k^n\right\|^2 \sigma_0^2} \quad (8)$$

We assume a DAA having multiple antenna elements, with respective spacing among them lower than λ/2 (λ is the wavelength). The beamforming technique is based on the assumption that the Channel State Information (CSI) is available at the transmitter in order to adapt the transmit signal to the channel. Our study is referred to rapidly time-varying channel and accurate CSI is not easy to be obtained. We assume an OFDMA system with imperfect CSI due to high speed users. Aiming to achieve low rate feedback from the users to BS in frequency domain, we utilize the following feedback scheme. N subcarriers are divided into Q clusters of L adjacent subcarriers each, so that

$$N = QL \quad (9)$$

Each mobile k estimates the CSI and calculates the correlation function $R_{k,n}$ for each subcarrier n $n \in \{1, 2, ...N_s\}$ during one downlink subframe (5ms). In high user mobility scenarios, the channel changes rapidly and the feedback information about channel coefficients is outdated. As in [1], our design will benefits from the statistics of the channel coefficients. In the short term, channel coefficients $h(t)$ may have one set of correlation which reflects the geometry of the propagation environment. The covariance matrix of the channel is defined as

$$R_k^n = \varepsilon\{H_k^n (H_k^n)^H\} \quad (10)$$

where the symbol $\varepsilon\{.\}$ means that R_k^n is derived from averaging during the downlink subframe. The representative value of channel state for sector s is obtained by averaging over all subcarriers N_s.

$$R_k^s = \frac{1}{N_s}\sum_{n=1}^{N_s} R_k^n \quad (11)$$

The representative value R_k^s for each subchannel $s \in \{1,2,3\}$ is used in order to reduce further the amount of feedback and therefore the proposed algorithm calculates a common transmission weight vector V_s for all subcarriers. The representative SNR for user k at subchannel s is taken assuming unitary receiver channel matrix (combining without weights the received signals at each antenna element).

$$SNR_k^s = \frac{\left|R_k^s V_s\right|^2}{\sigma_0^2} \quad (12)$$

Note that while the analysis at the receiver is specific to a flat fading channel, it can easily be extended to a frequency – selective channel if the system uses OFDM. The OFDM technique effectively divides a large frequency band into small narrowbands so that the transmitted signals on each narrow band experience flat fading. The design of beamforming is based on providing a minimum QoS assurance (expressed as minimum $SNR_k^s \geq \gamma_k^s$) to each of the receivers by minimizing the transmit power $\|V_s\|_2^2$. We formulate the optimization problem Q as in [4]

Q $\quad \min \|V_s\|_2^2$

Subject to $SNR_k^s \geq \gamma_k^s$

$\forall k \in \{1,2,\cdots K_s\} \qquad \forall s \in \{1,2,3\}$

Out of the large number of feasible vectors V_s that we may compute, we choose the vector which gives the minimum transmit power $\|V_s\|_2^2$. The goal is now to maximize the transmit vector such that the SNR is maximized subject to a constraint on the total transmitted power P_{max}. We introduce weighting vector V_s'=$P_s V_s$. P_s denotes the power boost factor. It can be seen based on (12) that SNR is also multiplied by the factor P_g^{2}. Therefore, the constant P_g is chosen as large as possible. Following that the same number of adjacent subcarriers $\left\lfloor \frac{N_s}{K_s} \right\rfloor$ are randomly allocated to each user k where $\lfloor x \rfloor$ denotes the smallest integer that does not exceed x.

V. SIMULATION RESULTS

A system according to the IEEE 802.16e specification is assumed [10]. A hexagonal cell with three sectors and fractional frequency reuse is considered in the MATLAB environment. The scenario C2 from the WINNER II channel model is used [11]. The frequency band of 3.5 GHz with 10 MHz channel bandwidth was assumed. The number of data subcarriers is 800, the OFDM symbol duration is 102,86 μs and the frame duration is 5 ms. The transmitted power of each Distributed Antenna element was assumed to be equal to 500mW. Each DAA has four antenna elements while each mobile user has four receiver antenna elements and was assumed to move with speed equal to 110 Km/h. Table 1 summarizes our simulation parameters. The physical layer (PHY) data rate is calculated from the table II which gives the type of modulation and coding in relation to the received SNR. Fig. 3 presents the total average throughput per sector for different cell radius values. We assume that twenty users are randomly distributed in each cell. As in fig. 1, the following schemes are set: 1) Three DAAs are placed in the points C1, C2, C3 on the cell edge (DAA-edge scheme) 2) Three DAAs are set at the center of each sector (points B1, B2, B3) (DAA-center scheme) 3) Three OASs are placed at points B1,B2,B3 (OAS-center scheme) and the transmit power of each antenna was assumed to 2 Watts 4) Conventional layout where one BS is located at the center of the cell with one omni antenna and transmit power equal to 2 Watts. It can be seen that the first configuration achieves superior performance due to the fact that the beamforming technique is enabled with four antenna elements (each having 180 degrees radiation pattern while in the second scheme each antenna element has omni-directional radiation pattern). As the cell size increases throughput drops because the users are randomly distributed in a larger area having lower SINR due to the fact that less directive beams may be constructed. For a cell radius equal to 800m we have an improvement of 75% if DAAs are used instead of OASs. Fig. 4 presents the average total throughput per sector as a function of the number of users for different schemes. We observe that PHY data rate decreases as the number of users in the sector increases. Fig. 5 shows that only an improvement about 5% in throughput is achieved if the three DAAs are placed at the cell edge (DAA-edge scheme) instead of placing the three arrays in the center of the cell (one array for each sector).

VI. CONCLUSION

The advantage of the network architecture employing DAAs has been investigated in a mobile BWA system. The results suggest that distributed DAAs improve the overall throughput compared to distributed OASs when adaptive beamforming and OFDMA techniques are used. Based on the results of this paper, we conclude that the cell architecture with DAAs located at the center of the cell (a low cost solution) gives approximately the same performance with the scheme where DAAs are placed at the edge of the cell.

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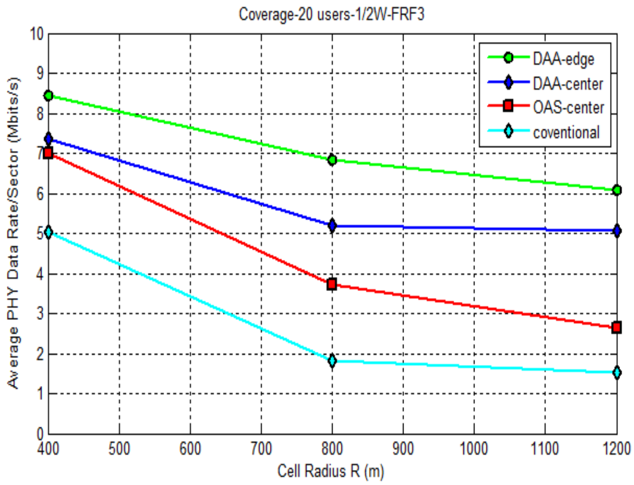

Fig. 3 Coverage for the different schemes with 20 users randomly disttrbuted in the sector

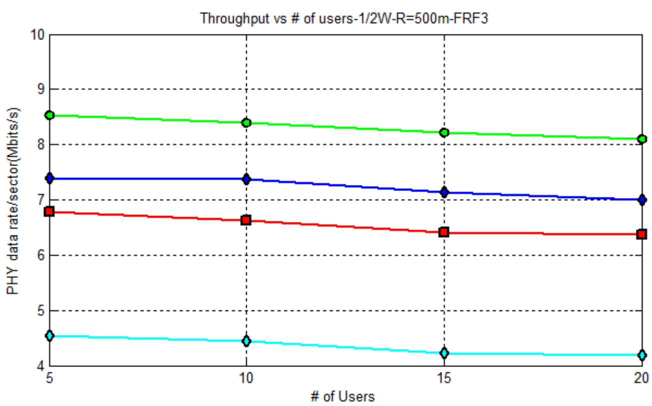

Fig 4 Average PHY data rate throughput per sector versus number of users when one BS is placed in different positions of the sector

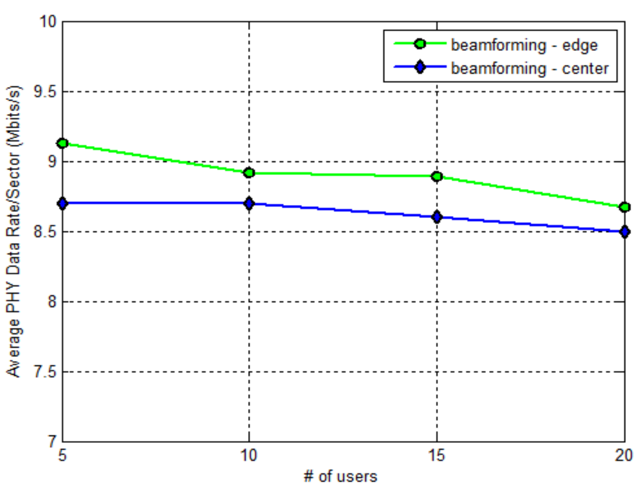

Fig. 5 Average PHY data rate per sector versus number of users for sector edge - center position of BS.

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TABLE 1
SYSTEM MODEL PARAMETERS

Parameter	Value
Site to Site Distance (m)	1000
Cell layout	3 sectors – FRF=3
Frequency Band (GHz)	3.5
Maximum number of remote BS at each sector	4
Number of BS array antenna elements	4
Number of mobile array antenna elements	4
Mobile Velocity (Km/h)	110
Channel Bandwidth (MHz)	10
Frame Duration (ms)	5
OFDM Symbol Duration (μs)	102.86
Number of Data Subcarriers	800
BS Transmit Power (mW)	500
Channel Profile	WINNER II C 2 Metropolitan
Mobile Station Distribution	Uniform, random positioning, 30 users per cell
Traffic Model	Full Buffer

TABLE 2
MCS ACCORDING SNR

Modulation	Coding	SNR (dB)
BPSK	1/2	3
QPSK	1/2	6
QPSK	3/4	8.5
16 QAM	1/2	11.5
16 QAM	3/4	15
64 QAM	2/3	19
64 QAM	3/4	21