1 INTRODUCTION

It is well known that by using the directional properties of adaptive arrays, the interference from multiple users operating on the same channel as the desired user in a time division multiple access (TDMA) cellular network[1], can be reduced significantly [1,2,3]. In these papers the interference from co-channel users in neighboring cells to that of the desired user is considered. It was shown that the reduction in interference results in an increase of the overall system capacity. This is very important, as there is an increasing demand by cellular operators on the capacity of cellular systems.

The capacity of a cellular system can be increased even further by accommodating multiple co-channel users[2] in the same cell [4,5,6], in addition to the co-channel users in the neighboring cells. It was shown in [5] that the capacity of a system can be increased by twelve times (with an array having up to 20 elements) compared to systems with no same cell co-channel users. Three linear arrays in the center of the cell, each covering a 120-degree sector and each sector having a different set of frequencies were proposed. The users in each sector are isolated in angle by reducing the received and transmitted energy towards the co-channel interferers, while maximizing the power towards the desired co-channel users. However, two users with nearly the same angular values relative to the array boresight in a multipath environment with a narrow angular spread[3] and closely spaced antenna elements[4], are difficult to spatially separate from each other and have to be assigned to different channels (different frequency or time slot)[5].

This can be overcome by using an adaptive linear array at every other edge of a hexagonal cell. The concept of placing base stations at the edge of a hexagonal cell is not a new idea [7,8,9]. However, the concept presented in this thesis differs from [7] in that adaptive arrays are used on the base stations instead of 120° overlapping sectorized antennas. It differs from [8,9] in that combined beamforming of the arrays is considered instead of selection diversity. The three arrays form sub-arrays of one large array system (called

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[1] Includes North American IS136 systems as well as GSM systems.
[2] Users in a cellular network are called mobiles.
[3] Angle of arrival spread of the multipath signals at the base station array.
[4] Half wavelength spacing between elements is considered small in multi-input multi-output (MIMO) applications for achieving uncorrelated signals across antenna elements [10].

spatially distributed array system), where the steering vector of the array system is optimized to yield the best signal to interference ratio for all co-channel users in the same-cell.

The array system is able to spatially discriminate between co-channel users in a "two-dimensional plane", since each array has a different view angle towards the incoming multipath signals. A desired user in a narrow angular spread environment that is blocked by an interferer as seen from one array can be spatially isolated from the interferer by another array, as the viewing angle is different. The result is that more co-channel users can operate in the same cell compared to the methods proposed up to now with narrow angular spread propagation environment and closely spaced antenna elements.

Beamforming of the distributed sub-arrays can be undertaken in two ways. Firstly, an optimal (in terms of signal to interference plus noise ratio (SINR)) beam can be formed for each sub-array based on the incoming signals towards the individual sub-arrays. The signals at the output of the sub-arrays can then be either optimally combined or the best signal from the sub-arrays can be selected. Apart from the optimum combining of the sub-array output signals, the sub-arrays have no interaction with each other. An alternative beamforming technique is to form an optimum beam based on the signals arriving at all the sub-array elements. This allows the spatially distributed arrays to operate as one large array with reduced outage probability when compared to beamforming on the individual sub-arrays only.

It will be shown analytically (for a specific distributed array geometry and number of signals) in this thesis that the SINR of independent beamforming is equal to or greater than combined beamforming. The performance advantage by means of simulation results of independent vs. combined beamforming will be presented for TDMA systems on the uplink[6] for various array sizes, fading conditions and angular spreads. The bit error rate performance of an adaptive array in a multipath environment was derived analytically in [11]. This formulation will be extended in this thesis to distributed arrays in a multipath environment.

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[5] It is assumed that the array element separation is in the order of half of the wavelength.

In order to reduce the probability of a deep fade to and from mobiles in a code division multiple access (CDMA) cellular network, mobiles are connected to (or in handoff[7] with) multiple base stations. The number of base stations that the mobile is in handoff with is based on the measured SINR of the base station pilots[8] received by the mobile. On the downlink[9], all base stations that a particular mobile is in handoff with will transmit the same data. Due to uncorrelated fading between base stations, the probability is low that the signal from multiple base stations will be in a fade. Unfortunately, due to the fact that multiple base stations transmits to a particular mobile in handoff, the interference to mobiles in the surrounding cells is increased[10]. As with TDMA systems, increased interference reduce the network capacity. It is therefore important to apply techniques to reduce the interference to mobiles from multiple base stations in handoff. Adaptive arrays can again be used for this purpose [12,13]. Each of the arrays in handoff will independently form a beam with a maximum signal towards the desired mobile and reduced signal towards the other mobiles in the sector covered by the array.

Similarly to combined uplink beamforming of TDMA distributed sub-arrays (as described above), the beamforming of the CDMA arrays in handoff can also be done as one large combined array. The propagation channel between the combined array and the mobile is critical for the operation of combined beamforming. In [14] a method is proposed for adaptively determining the propagation channel on the downlink based on feedback from the mobile. With the assumption that the downlink propagation channel information is available, it will be shown (by means of simulation results) in this thesis that combined beamforming of the downlink arrays in handoff provides a reduced (relative to independent beamforming) probability of outage at the mobiles.

The range of adaptive and phased arrays is a function of the array geometry, location and number of interferers as well as the propagation environment. In the case of the distributed arrays located at the corner of the cell, the range between the sub-arrays and the mobiles

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[6] Uplink is from the mobile to the base station.
[7] Called soft handoff in CDMA systems between cells and softer handoff between sectors of the same base station.
[8] All base stations constantly transmits a signal with a constant power and similar data sequence.
[9] Downlink is from the base station to the mobile.

can be larger than the range between cell center arrays and mobiles. Therefore it is important to investigate the range increase of adaptive and phased arrays relative to an omni antenna. In [2] it was shown that as the array beamwidth becomes narrower than the angular spread, the range increase of a phased array relative to an omni antenna becomes constant as a function of the number of array elements[11]. It was also shown that an adaptive array adapts or matches its beam to the incoming multipath wavefront, and therefore does not have the range limitation of phased arrays. In addition it was shown in [2] that the range limitation of phase arrays disappears in a spread spectrum system if the beam is steered optimally in terms of signal to noise ratio for each RAKE finger[12]. This thesis extends the work of [2] to add the effect of an interfering source in a narrowband system and multiple interferers in a spread spectrum system. An analytical equation is also derived to predict the asymptotic range limitation of phased arrays

1.1 Thesis Outline and Contributions

1.1.1 Thesis Outline

Chapter 2 begins with a general definition of cellular networks with sectorization, frequency reuse patterns of one, three and same cell frequency reuse. This is followed by a description of different beamforming techniques and beamforming configurations. The switched multibeam, phased and adaptive array beamforming is discussed. The uniform linear array and circular array is described. Propagation channel models used in the simulations in later chapters are discussed. The concept of the spatially distributed array is presented. This array geometry is defined and practical implementation considerations for this method are discussed. The signals arriving at the array elements is then defined as well as individual and combined beamforming of the distributed array signals for both narrowband and spread spectrum (CDMA) systems. This is followed by a definition of two methods of estimating the array weight vectors[13]: the direct matrix inversion and least mean squares method. The method of simultaneously estimating the weight vectors for

[10] Interference to mobiles in the same cell as the desired mobile is low due to the use or orthogonal transmit codes.

[11] Limiting the range of a phased array.

[12] The N strongest multipath signals separated by the inverses of the spreading rate is called fingers in a RAKE receiver.

[13] The baseband converted signal of each array element is multiplied by a complex value or weight.

multiple same-cell co-channel users is described. In the last part of the chapter the methods for estimating the performance of the various systems is presented.

In chapter 3 the range increase of adaptive arrays and phased arrays is compared to an omni antenna in a multipath environment in the presence of interfering sources. Firstly, the range increase of a phased array in a non-multipath environment is formulated. The array geometry, multipath model and array element signals for narrowband and spread spectrum systems are briefly summarized. Simulation results of the range increase of phased and adaptive arrays relative to a reference system are presented. The results are shown as a function of angular spread and angular location of a single dominant interferer in the narrowband case and with multiple interferers in the spread spectrum case. An analytical model is developed that predicts the asymptotic range limitation of a phased array in a multipath environment in the presence of a dominant interferer.

The signal to interference plus noise ratio (SINR) performance of a distributed array in the absence of multipath components is investigated in chapter 4. Analytical expressions for the SINR of a distributed array with independent and combined beamforming of the sub-arrays is developed. It is shown analytically that optimum combining of the individual sub-array signals has a SINR equal to the sum of the SINRs of the individual sub-array signals. Thereafter, it is shown for a single interferer and two element sub-arrays that the SINR of a distributed array with optimum combining of the sub-array signals is greater or equal to the SINR with independent combining of the sub-array signals. This result is also shown numerically to be valid for multiple interferers. Next, the SINR of a distributed array with independent and combined beamforming of the sub-arrays is compared to the SINR of conventional arrays at the cell center. The simulation results are for a single cell as well as seven cell network with and without power control.

In chapter 5 an approximate analytical formulation of the bit error rate[14] (BER) of a distributed array in a multipath environment is developed. The method is based on finding the Laplace transform of the probability density function (PDF) of the array output SINR through a generalized eigenvalue solution. The inverse Laplace transform then yields the

[14] The bit error rate is a function of SINR.

required probability density function, which is applied to estimate the BER at the array output. The formulation is first described in detail for a single array and then extended to a distributed array. The BER determined with the analytical model is compared to the BER calculated with a Monte-Carlo[15] simulation for both single and distributed arrays.

The performance of a distributed array with independent and combined beamforming in a multipath environment is compared in chapter 6 by means of Monte-Carlo simulations to the performance of conventional arrays at the cell center. Firstly, the bit error rate (BER) of a single array using the circular vector channel model is compared to the BER with the Rayleigh vector channel model. The BER as a function of the scattering angle[16] and number of elements is presented, followed by the BER of the distributed array as a function of the multipath scattering angle and number of elements. The outage probability[17] of distributed arrays in the presence of fast and slow fading with mobile power control is presented. The outage probability results are shown for a single cell and seven-cell network.

The performance in a CDMA system of combined beamforming of the arrays in sectors experiencing handoff in the downlink is compared to arrays with independent beamforming in chapter 7. The signal model for independent and combined beamforming of the arrays in handoff is defined. This is followed by a description of the mobile power control method used in the simulations. The propagation channel response matrix must be known in order to apply the correct beamforming to the mobiles. Methods that can be used to estimate the propagation channel are described. In order to obtain a first order approximation of the viability of the combined beamforming of the arrays in handoff, simulation results of the SINR of combined vs. independent beamforming with no fading and power control is presented for a single cell followed by a seven cell network. The power control and SINR performance for a single set of mobile locations and fading conditions is presented. This is followed by a comparison of the simulated outage probability of independent and combined beamforming of the arrays in handoff in a nineteen cell network.

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[15] Statistical method to estimate the probability density function.
[16] Also referred to as the angular spread.
[17] Probability that the SINR is below a certain threshold.

1.1.2 Thesis Contributions

The main contribution of this thesis is the analysis of spatially distributed adaptive array systems in TDMA and CDMA cellular communication networks. The focus is on arrays operating in a multipath propagation environment with a narrow angular spread and arrays having closely spaced array elements[18]. Secondary contributions were results of an investigation into the range increase of adaptive and phased arrays relative to an omni antenna in the presence of interference and the development of an analytical model for predicting the phased array range limitation. The range increase of adaptive and phased arrays are important to understand, as the range between mobiles in a spatially distributed array configuration can be significantly larger than in a conventional configuration.

A more detailed breakdown of the contributions is as follows:

1) The effect of interference on the range increase (relative to an omni antenna) of adaptive and phased arrays in a multipath environment for both narrowband and wideband spread spectrum systems is investigated. This work was published in [15]. The investigation builds on material presented in [16], where the effect of interference was not considered. The results in this thesis show that the range increase of both adaptive and phased arrays are affected by the angular spread and the angle of the interferer relative to the boresight of the array. A significant reduction in the range increase of a phased array is visible in a narrow angular spread environment when the multipath angular components of the interferer starts to overlap with the array beamwidth. The adaptive array range increase exceeds that of the phased array for the same conditions (number of elements, angular spread and interferer locations) and for both narrowband and spread spectrum systems.

2) An analytical model is derived for predicting the phased array range increase, including the asymptotic range limitation when the angular spread exceeds the array beamwidth. A simplified model is presented for the probability density function of the angle of arrival of multipath signals for the uniform vector channel model.

3) The concept of the spatially distributed array is presented. Adaptive arrays at the center of the cellsite are limited in their ability to separate co-channel users from each other

when they are closely located in angle relative to each other (as seen by the base station antenna) in a small angular spread (low multipath) environment with closely spaced antenna elements (half wavelength). A concept where multiple arrays are located far apart in the cell (spatially distributed array) is introduced. This array consists of three sub-arrays at alternate corners of the cell, and when applied to TDMA[19] type networks has the ability to receive user signals from multiple viewing angles. It is therefore able to obtain an improved rejection of interfering signals relative to the arrays located at the center of the cell. This concept was published in [17,18], where the reduction of the outage probability of a combined distributed array vs. the conventional array at the cell center in a non-multipath environment was presented.

4) An analytical comparison of the SINR of a desired mobile in the presence of an interfering mobile is made between combined beamforming and independent beamforming of two spatially distributed sub-arrays. The comparison shows that combined beamforming of the sub-arrays produce a higher SINR than independent beamforming of the sub-arrays.

5) The simulated bit error rate (BER) performance of a spatially distributed array with combined beamforming of the sub-arrays is compared to the BER performance of independent beamforming of the sub-arrays as well as to conventional arrays at the center of the cell. Power control of the users, fast and slow fading as well as a multi-tiered network interferers are included in the simulations.

6) An analytical model for estimating the BER performance of spatially distributed arrays in a Rayleigh multipath environment is developed. This model is an extension of a model in [11] for determining the bit error rate performance of a single array in a multipath environment. The BER calculated with the derived analytical model is compared to the BER simulated with a Monte-Carlo method. A spatially distributed array with two element sub-arrays and correlated fading between the array elements for each mobile signal is considered.

7) The concept of combined beamforming of the arrays in handoff in the downlink of a CDMA cellular system is presented. Simulation results for the outage probability

[18] Half wavelength spacing between elements is considered small in multi-input multi-output (MIMO). applications for achieving decorrelated signals at the antenna elements [10].
[19] Examples of TDMA networks are IS-136 and GSM.

performance of combined vs. independent beamforming of the arrays is presented. Power control, fast and slow fading, a seven cell network containing the mobile users and nineteen cells as handoff candidates were considered. The results indicate that the combined beamforming concept produces a lower outage probability due to improved signal reduction of out of cell mobile users.

1.2 Literature Review

1.2.1 Array Range Increase

Studies on the range achievable with an adaptive array have been published in [16,19,20]. In [20] different antenna configurations are compared in terms of received SINR for a wideband CDMA system (interference effects not included). The configurations include number of antenna elements, inter-element spacing and a fixed multibeam antenna. In [20], the relative BER performance at the BTS for WCDMA was calculated for dual sectorized diversity sectorized and fixed beam antennas. Interference was modeled as white noise and as colored noise. In [16], the range increase of adaptive vs. phased arrays was studied in a multipath environment for both narrowband and wideband (spread spectrum) systems.

1.2.2 GSM Systems

An eight element adaptive array system for GSM1800 was presented in [21]. The system estimates the direction of arrival (DOA) of the desired and interfering signals using the training sequence in the GSM protocol. The DOAs are then used to determine suitable weight vectors. A beam is steered towards the desired signal multipath components, and all other directions are nulled (thereby placing broad nulls on the interferers).

In [5,22] the capacity increase of GSM systems with multiple co-channel mobiles in the same cell was investigated. Adaptive arrays were used to separate the mobiles signals using spaced division multiple access. In order to reduce interference, mobiles were classified into angular and power groups. Based on this, the frequencies in the cell were allocated to the mobiles. Transmission on the downlink was done using direction of arrival measurements on the uplink. It was shown that between two and twelve times capacity increase is obtainable with up to twenty element arrays.

1.2.3 IS 136/IS54 and PCS Systems

A four element real time adaptive array lab performance is given in [23] for IS136. The Synchronization and CDVCC sequences in the slot are used to determine and update the weights based on an enhanced direct matrix inversion algorithm. A SINR gain of 6dB for a BER[20] of 1e-3 was achieved.

In [24] the dynamic BER performance of adaptive arrays in IS-54 systems is investigated. The least mean squared (LMS) and direct matrix inversion (DMI) methods of weight acquisition and tracking using the synchronization sequence in the slot as desired signal to determine the weight vectors. Various mobile speeds are compared based on the BER performance of the system. It was found that the DMI algorithm gave the best results, with only 0.2dB degradation from ideal SINR performance at a BER of 1e-2 for a mobile with speed up to 60mph.

In [4] a novel approach was described for separating multiple same-cell co-channel signals. The method utilizes the temporal structure of digital signals to determine simultaneously the array response vector and symbol sequence. Two methods were described: The iterative least squares with projection and a method based on the alternating projection combining least squares with enumeration. It was found that signals can be estimated well even if they are located close in angle to each other.

1.2.4 Analytical BER Performance Estimation of Arrays

In [11], analytical expressions were derived for the CDF and BER of adaptive arrays with uncorrelated and correlated fading across the elements in a multipath environment. The closed form expressions were derived in terms of the eigenvalues of the interference co-variance matrix. It was stated that the eigenvalues can be determined analytically for a single interferer, but have to be determined with a Monte-Carlo method for more than one interferer and for correlated fading across the elements. In the case of correlated fading, the eigenvalues have to be determined for each SINR value.

[20] In this thesis BER is the raw BER without coding gain.

Closed form solutions for the CDF and BER of an array with optimum combining with a single interfering signal in a multipath environment is given in [2]. Numerical CDF and BER results determined with Monte-Carlo simulations for two or more interferers were also presented for various array sizes. The correlation between antenna elements of the received multipath components of a single signal as a function of the element spacing and angle spread was described in [25]. It was shown that there is low correlation between elements when either the angular spread is wide (e.g. 30 degrees) or the element spacing is large in terms of wavelengths (e.g. 5 wavelengths or 5λ).

1.2.5 CDMA Systems

It is shown in [13] that the capacity of a CDMA system can be doubled by using an eight element array (spaced half a wavelength apart) at the BTS. On the uplink, the signals from the antenna elements are downconverted, sampled and then a fast Fourier transform (FFT) is applied to the signals. The net effect of that is the same as beamforming with a butler matrix. The FFT essentially forms 8 virtual beams for an eight element array. The strongest virtual beam is then processed by a RAKE receiver. In the downlink, a beam is transmitted in the direction corresponding to the beam in the uplink with the strongest signal.

In [26] the constant modulus algorithm was applied to antenna elements spaced far apart (several wavelength). The SNR performance was compared to switched diversity.

The performance of the uplink and downlink of CDMA systems with adaptive arrays at the base stations and mobiles in a multipath environment was investigated in [12,27,28,29,30,31]. In [12], the uplink outage probability and Erlang capacity was presented. The model included a rake receiver at the output of each array element. Results were obtained with Monte-Carlo simulations for various number of antenna elements. The downlink was described in [30], where an adaptive beam was formed towards each mobile. The required downlink transmit array vector was estimated with the feedback method [14], where training sequences are periodically transmitted from the base station to the mobile on the downlink. From the received signal information, which the mobiles feedback to the base-station, the transmission response vector can be calculated. A Monte-Carlo simulation method was used to determine the outage probability as function of the cell loading. It was found that for a five element array and an outage probability of 0.01, the capacity increases from 32 mobiles per cell to 123 mobiles.

In [32], various beamforming (or spatial filtering) algorithms applied to CDMA systems were compared in terms of SINR, converging rates, capacity enhancements and computational complexity. The algorithms are conventional (SMI, LMS, RLS and DDLMS) as well as channel estimates (code filtering, autocorrelation matrix, shifted autocorrelation matrix, etc). The 2D SMI algorithm achieved the largest capacity for the 2D RAKE algorithms. However, the 2D RAKE receiver algorithms converged slower than the conventional 1D algorithms.

1.2.6 Macroscopic/Microscopic Diversity

1.2.6.1 Sectorized Antennas

The outage probability of micro-diversity (antennas relatively close together in a typical cellsite) vs. macro-diversity (antennas far apart) was determined in [33] as a function of antenna spacing and two and four port combining. It was shown that macro-diversity is an effective fading countermeasure in micro-cellular environments.

In [34] the capacity increase in a cellular system with macro-diversity applied to the entire cell was studied. A macroscopic diversity architecture was proposed where remote antennas consist of a sectorized 120° antenna and electric-optic converter and the signals are relayed to a central unit (where the demodulation is done) with fiber optic cables. Under specific assumptions, at 90 % area coverage a 9.5dB coverage gain was achieved for selection macro-diversity and 11.3 dB for simulcasting. The selection macro-diversity downlink capacity gain is 6.4 Erlangs per cell at 10% blocking margin.

The uplink bit error probability in a CDMA system with macro diversity is calculated in [35,36] for sectorized antennas. It was shown that macroscopic diversity improves the performance of a CDMA system significantly. In [7] an architecture was introduced with overlapping three sector 120 degree sectorized antennas at every other corner of a hexagonal cell. The signals from each set of three sectorized antennas pointing to the center of the cell, are combined on the uplink. On the downlink all three antennas transmits simultaneously. It was shown that this configuration can achieve the same downlink C/I for a reuse of three compared to a conventional omni system with a reuse of seven. On the uplink, the C/I ratio is better than 5dB compared to the conventional sectorized system with a reuse of three.

The uplink outage probability for the architecture with overlapping sectorized antennas at the cell edges (macro diversity) are compared to the conventional network architecture with sectorized antennas at the cell center in [37]. Maximum ratio combining vs. selection diversity of the macro diversity antennas (cell edge antennas) was investigated. The analysis included log normal slow fading (but excludes fast fading effects) and power control by the nearest base station in a 37 cell network for a network reuse factor of three. This analysis [37] was extended to the downlink in [38], where simulcast from the edge antennas was considered for networks with reuse factors of 3 as well as 4. Power control in the downlink and uplink of simulcast networks was presented in [39].

1.2.6.2 Arrays

In [8,9] a composite micro and macro diversity system was described. Each array element signals are combined with either selection or maximum ratio combining to combat fast fading (called micro diversity). The maximum output of a number of arrays separated far in distance are then selected (selection macro diversity). Closed form solutions for the average bit error rate vs. SINR were derived. The effect of interference from surrounding cells was not directly considered in the analysis. The conclusion was that composite diversity offers substantial improvement over micro-diversity alone.

Closed form first order expressions for the uplink and downlink capacity increases of a CDMA system with an adaptive array was presented in [40,41]. The effect of multipath (one and three path) and soft-handoff gain was taken into account. The effect of shadowing was taken into consideration by assuming that a certain margin is required for a specific link reliability.

In [42] analytical expressions were derived for a CDMA system for the uplink SINR at antenna diversity elements and in the downlink at the mobile in the presence of Rayleigh fading and log-normal shadowing. The interference from multiple base stations and multiple same cell and adjacent cell mobiles were included. One of the major assumptions that was made is that the fading across receive antenna elements is uncorrelated, in other words that the angular spread is large and the elements are spaced far apart.

1.2.7 Downlink Propagation Channel Matrix Determination

In order to transmit a maximum signal to the desired mobile while minimizing the interference to the other mobiles, the propagation channel response vector is required. This cannot be determined reliably from the uplink information, as the uplink and downlink do not operate on the same frequency and are therefore not coherent. A method of measuring the propagation channel matrix for all mobiles was given in [14,43]. The method is based on transmitting probing signals from each element of the array and measuring the relative amplitude and phase at each mobile. The measurements are sent back to the BTS array on the uplink. This simulated CDMA capacity improvement of base station arrays in [27] assumed that the propagation channel matrix can be determined according to the above feedback method. However, the method in [14] requires a large amount of feedback data to the BTS. In order to reduce the amount of feedback data, an alternate method was proposed by [44]. This method is well suited for CDMA systems. The received signal at each mobile is correlated with its Walsh code to obtain a signal pertaining to the specific mobile. Nonlinear processing is applied to the signal to extract the hard limited information bits. A scalar error between hard limited signal and a known (or reference) signal is determined. If this error is above a certain value, it will be fed back to the BTS. This error is then used at the BTS to recursively update the transmit weight matrix in order to minimize the errors fed back from the mobiles.

1.2.8 Propagation Channel Models and Measurements

Multibeam, phased and adaptive arrays require propagation models which includes time delay spread and angle of arrival. These types of propagation channel models are referred to as vector channel models. An overview of vector channel models was presented in [45,46].

Several papers gave results of measured angular and delay spread as a function of the propagation environment. In [47] the measured angular and delay spread in a dense urban environment were 8° and 115ns respectively. In suburban environments the measured angular and delay spread were 3° and 109ns respectively. In [22, p. 204] the measured angular spread in an urban environment was between 3° and 6° and in a sub-urban environment between 1° and 6° for mobile to base station distances between 1km and 2km. The measured path angular spread in an urban environment as reported in [48] was between 5° and 10°.