System Aspects of Smart Antenna Technology in Cellular Wireless Communications. An overview.

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Abstract: *We surveyed the three main system aspects of smart antenna (SA) technology in wireless communications i.e. SA receiver, wireless network control and planning with SA. A classification of SA receivers and their algorithms is given in order to simplify orientation in a very large amount of structures and algorithms. We discuss system integration of SA receivers taking into consideration expected propagation conditions, user mobility and offered traffic. Several radio network planning and upgrading concepts associated with SA are evaluated. We describe possible radio networks architectures when smart antennas are used at the mobiles, base stations or at both ends. Radio network control functions with SA at the different layers are briefly examined. Existing experimental and commercially available SA and their performance are surveyed.*

1. Introduction

Extensive research activity into the area of SA cellular applications started at the beginning of the nineties. Interest in this technology is increasing since spatial processing is considered as a "last frontier" in the battle for cellular system capacity with a limited amount of the radio spectrum. The smart antenna techniques is one of the few techniques, which are currently proposed for new cellular radio network designs, which will be able dramatically improve system performance. SA can be effectively combined with other techniques such as multi-user detection, polarisation diversity, and channels coding. Air interfaces standards are becoming more "friendly" for SA and future introduction of software radio will make it possible to optimise radio system design for spatial processing and integrate SA into future adaptive modems. There are number of SA commercial products currently available on the market.

The main advantages expected with SA are:
- Higher sensitive reception
- The possibility to implement systems with spatial division multiple access (SDMA)
- Interference cancellation in uplink and downlink functions
- Mitigation effects of multipath fading

On the system level this will lead to the higher capacity, extended range, improved coverage by "in-filling" dead spots, higher quality of services, lower power consumption at the mobile and improved power control (PC).

SA increases system complexity and costs, but at the same time provides an additional degree of freedom for the radio network control and planning.

During the last few decades there has been a lot of attention paid to different combinations of SA optimisation methods and criteria, channel estimation techniques and receiver structures. One of the main problems in this area - SA system integration into existing and future cellular networks has not yet been highlighted.

SA receiver structure and algorithms, network control and planning are the main cellular system components to be considered before SA technology is introduced (Fig.1). To improve radio network performance, SA receiver structure and algorithms should be optimised according to the propagation and interference environment, considering expected traffic and users mobility in the cell. These parameters can be seen as a product of radio network planing. At the same time, SA receiver parameters are important for capacity, coverage and interference planning, they also tightly interact with network control protocols at different layers.

The choice of a SA receiver and algorithm today is highly dependent on the air interface and its parameters. Among the most critical parameters are the multiple access method, the type of duplexing, pilot availability, modulation, diversity, physical channels splitting and frame structure. Beside the compatibility with air interface, the level of integrated circuit (IC) technology is the limiting factor for implementation of some SA algorithms.

SA algorithms should be compatible and optimised with radio network protocols. Link level control protocols have dynamically to maintain the required link quality while carrying out channel and interference

monitoring. Higher layers of protocols have optimally to distribute radio resources with the minimum required signalling while maintaining required links quality. SA should work well together with other techniques such as frequencies, time slot hopping, macro- diversity, fractional loading and support layered cells architecture.

In the network planning the system designer has several options to optimise base stations position and antenna parameters to the offered traffic distribution and propagation environment. Several main strategies are available: to use SA at the base station at the up-link only to increase coverage, to use SA at the up and down – links simultaneously and additionally to coverage improve capacity by tightening channels reuse patterns or achieve same channels reuse inside cell with SDMA thus additionally improving spectrum efficiency. It is possible to use SA at mobiles alone without installing SA at the base stations and achieve about the same improvement in coverage and capacity as with SA at the base stations. SA can also be installed at the both ends to allow several parallel SDMA channels to be established for one between mobile and base station (BS). In this case higher bit rate transmission can be achieved by splitting data streams between parallel channels. Space Time (ST) coding is another method, which exploits transmit diversity techniques with multiple input multiple output (MIMO) channels instead of the use of parallel data transmission.

Network planner should use the advantages of line of sight propagation or can constructively exploit the multipath propagation environment by combining beamforming or/and diversity techniques. Different approaches in the network management are needed for all these techniques.

We survey the SA receiver algorithms and structures in Section 2, network planning in Section 3, and network control in Section 4.
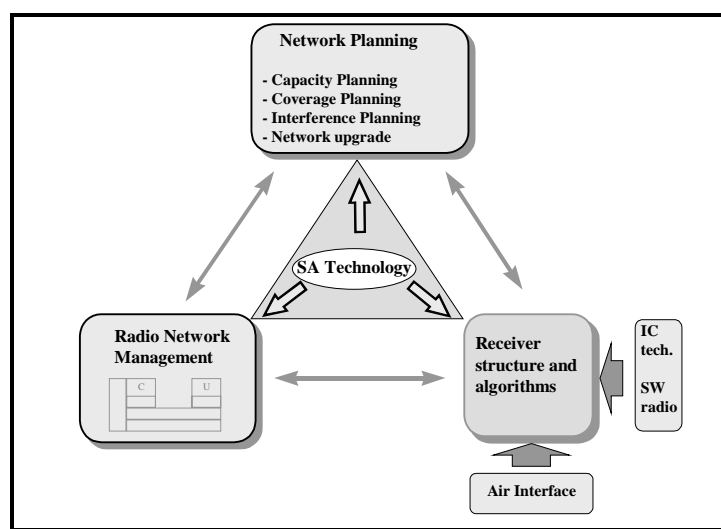

Fig.1. *Impact of spatial processing technology on the main elements of cellular system design. .*

2. SA receiver structure and algorithms

There are many varieties of SA algorithms and structures proposed for the cellular applications in the literature. Below, a classification of SA algorithms and receivers is given in order to provide a comprehensive general picture for orientation in the large number of proposed methods and technical solutions.

SA receivers can be classified as SA with processing in the space domain only and Space-Time (ST) SA receivers with processing in space and time domain simultaneously (Fig. 2). Additional a diversity gain for SA receiver can be obtained by polarisation diversity and macro diversity, which can also be combined with time domain processing. The new technology - ST coding which is currently attracting extensive research activity can also be incorporated in SA. In the CDMA system space domain processing is usually combined with path diversity obtainable with a RAKE receiver.

Many of spatial domain only and ST algorithms include optimisation procedures in their structure. The most popular optimisation criteria are: maximum signal interference to noise ratio (SINR), squared function based criteria such as minimum square error (MSE) and minimum variance (MV), maximum likelihood (ML). The basic assumption of ML methods is that the distribution function of the estimating parameter is Gaussian. A ML ST receiver treats interference as noise temporally and spatially white and Gaussian. As a result, temporal correlation complicates the implementation of equaliser based on the Viterbi algorithm (VA), making this method less attractive in ST SA receivers in the presence of co-channel interference (CCI) with delay spread. MSE optimisation criteria are more attractive for a SA receiver in the presence of correlated CCI and more efficient in an interference than a noise dominated environment. Zero force criteria do not balance out effect of the noise.

2.1. Space-domain only SA processing algorithms and receiver structures.

Space domain processing is an effective way to reduce co-channel interference (CCI) and multiple access interference (MAI) in CDMA system.

According to the side information used for beamforming, they can be classified as beamformers (BF) based on spatial structure e.g. angle of arrival (AoA) of the incoming signal - direction of arrival based beamformer (DOB), BF based on a training signal, which can be considered as a temporal reference BF (TRB), and signal structure based BF (SSBF) which exploit the temporal and/or spectral properties of the received signals. In the mobile scenario DOB requires AoA tracking and TRB uses adaptive algorithms such Least Mean Squares (LMS), Recursive Least Squares (RLS), (Direct Matrix Inversion) DMI.

A beamformer with M antenna elements can create $M-1$ nulls in the direction of the interferes or achieve M-fold diversity gain. The effectiveness of inter-symbol interference (ISI) cancellation in a spatial domain is very limited. SA with space-only domain processing can cancel $(M-1)/2$ symbols with TRB or cancel $M-1$ signals over any delay with DOB. There are always should be a trade-off between an improvement in signal interference to noise (SIR), CCI reduction, spatial diversity gain and ISI cancellation. Since it is possible to cancel ISI by spatial domain-only processing a space-time filter (STF) can be built.

Beamformers can also be classified as data independent and statistically optimum [1]. Data independent DOB steers an antenna beam toward a desired signal direction and/or nulls in the antenna pattern in the direction of interference. BF weights are adjusted according to estimated AoA. The simplest form of data independent BF is conventional BF (CBF), which steers a single beam in the direction of desired signal, assuming the source of the signal has zero spread and no multipath and interference. The optimisation procedure is included in statistically optimum BF algorithms. Statistically optimum BF produces beam pattern based on the data received by the array. In statistically optimum beamformer, the pattern is adapted to minimise cost function, which is associated with the quality of the signal. TRB and SSBF are statistically optimal. Very often statistically optimum BF includes in their structure data independent beamformers. The well-known Generalized Sidelobe Canceller (GSC), MVDR are beamformers, which include this combination. Many of SSBF and blind methods consider temporal properties of signal in their cost function, thus more optimal solution might be achieved.

One of the simplest, but sometimes-effective approaches, is a switched beam SA. In this case SA selects the best one or several fixed beams from the predefined sets of weights.

Beamforming can be implemented at the RF, IF or the base band (BB).

BF performance varies according to propagation, the interference environment and also depends on user mobility. Advantages and drawbacks of DOB and TRB are often different in respect to the ability of CCI cancellation, performance in multipath channel, user mobility, and ISI reduction.

Direction of arrival based BF

In DOB it is assumed that the angular spread of the received signals is relatively small. There are three main types of optimum DOB: BF based in maximisation SINR, maximum likelihood (ML) and minimum mean square error (MMSE) criteria. Another group of DOB is data independent BF. DOB techniques are analytically more tractable but these methods need calibration. Also AoA estimation requires that the number of signals wavefronts including CCI signals should be less than the number of antenna elements M. Loosely speaking, DOB performance depends on the ratio between signal angular spread *(As)* and M. Also the level of CCI suppression very much depends on the angular distribution of the interfering and desired signals. One of the main advantages of DOB is that AoA estimated at the up-link can be directly translated to the down-link in systems with FDD but DOB performance can be seriously degraded in the presence of coherent multipath producing signal cancellation at the array output.

AoA estimation is an important part of DOB. A critical assumption of the most AoA estimation algorithms is that the number of incident signals should be strictly less than the number of antenna elements. This requirement can be relaxed if the properties of incident signals are exploited. An explicit overview of AoA estimation methods can be found in [2,3].

Time reference beamforming (TRB) based on a reference signal

Beamforming based on training signal or time reference beamforming (TRB) is a computationally effective method at the expense of spectrum efficiency. Spatial information such as AoA or array manifold is not necessary. Depending on the particular system and/or scenario used, the reference signal may consists of a priori known signal multiplexed in frequency or in time with a useful signal or a reconstructed signal obtained from the detected symbols. The second approach is more attractive from the tracking requirements but the beamforming and detection are more interdependent. The use of training signals requires prior carrier and signal recovery, which is made difficult by the presence of CCI. In some cellular systems this technique is not applicable due to problems with obtaining a reference.

Iterative adaptive algorithms such LMS, RLS, and DMI algorithm are used for tracking and explicitly discussed in [2,3,4]. TRB overcomes interference by nulling its spatial signatures and shows greater robustness

in the mobile environment where channel characteristics are continuously varying. Coloured training sequences in GSM and an user dedicated pilot in UMTS can be used as a reference signal.
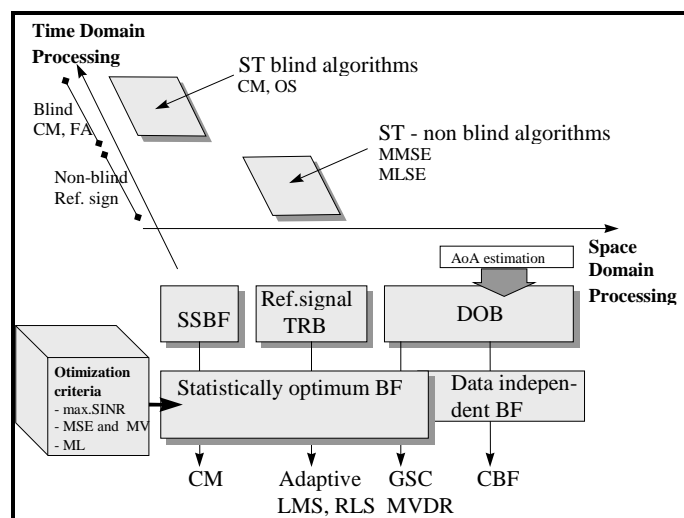

Fig.2. *SA receivers classification*

TRB technique optimally combines multipath components to increase SNR and to reduce the effect of fading.

In a non-coherent multipath both DOB and TRB have the same ability to overcome ISI since two different symbols for the same user will be uncorrelated and will look like noise.

Instead of calibration in DOB, the TRB techniques require accurate synchronisation and to achieve the best performance when the delay spread is low.

Unlike DOB there are no means of obtaining a transmitting weight vector for downlink beamforming with TRB from the information provided at the receiver in FDD.

Signal structure based BF

In signal structure based beamforming (SSBF) adaptive processor exploit temporal and/or spectral structure and properties of the received signal to construct BF. SS BF attempts to restore the signal property, which can be, for example, a constant modulus (CM) for several modulation schemes or finite alphabet (FA) property of digital signals. This BF method is very robust against different propagation conditions but its convergence and capture characteristics can be problematic.

Wideband beamforming

Wideband beamforming realisations and methods of AoA estimation are different from narrowband and discussed in more detailed in [3,5,6]. Among the proposed wideband BF realisations are the switched- beam approach, methods based on AoA estimation with superresolution algorithms, Eigenfilter techniques, which optimise SINR according to the largest eigenvalue of correlation matrix. Eigenfilter methods are more preferable in urban communication channels with highly correlated multipath.

Training signals based BF can also be successfully used in MSE wideband beamforming.

The code-filtering approach proposed [7] for CDMA is a SS BF, which exploits the spectral property of the received wideband signals. Another version of multi-target SSBF [8] combines information of the spreading signal and the CM modulus property of the signal in adaptation of the weight vector.

Wideband Beamforming can be implemented at the symbol or chip level.

2.2. Space-time processing of narrowband signals

Processing in temporal domain adds temporal diversity and ISI reduction to ST processing. ST processing can constructively combine strength of spatial (CCI mitigation) and temporal (temporal diversity) methods. According to the optimisation method, there are two types of non- blind ST receivers: ST-Maximum Likelihood Sequence Estimation (MLSE) and ST- MMSE. A combination of these methods is also proposed.

In ST processing channel estimation techniques are classified into non-blind technique, which use training signals and blind methods. Blind methods can be based on spatial and temporal signal structures. In temporal signal structure such as the constant modulus (CM) envelope of continuous phase modulated signals (CPM), finite the alphabet property (FA) of all digitally modulated signals can be exploit.

ST-processing algorithms can be further extended to ST optimum multiuser (MU) algorithms and further to ST joint MU receiver-transmitter algorithm [9].

ST-MLSE methods

The ST-MLSE is the extension of the scalar MLSE with the Viterbi Algorithm (VA), which includes a ST whitening filter [9,10]. The advantages of ST-MLSE are the possibilities to deal with non-linear modulations and large delay spread but it is difficult to deal with Doppler spread. Implementation of the Viterbi equaliser makes it less attractive in the presence of CCI with delay spread. Theoretically, ST-MLSE outperforms ST-MMSE (if perfect channel estimate is assumed) especially when the ISI is large, however practical implementation is difficult. In the presence of a time varying channel a ST-MLSE receiver must carry joint channel and data estimation (ST-JCDA).

In this type of receiver, the training sequence is used to obtain an initial estimate of the channel and thereafter the channel is tracked by associating channel estimate with each survivor sequence at each state in the search trellis.

Multi-user ST-MLSE (MU-MLSE) will require known channels for all arriving signals to jointly demodulate all the user data sequences.

ST-MMSE methods

ST-MMSE [10,11] does not need CCI statistics and treats Doppler spread more effectively. Several well-studied blind algorithms can be applied. It suppresses CCI effectively and performs adequately against ISI. ST-MMSE is more attractive in the presence of CCI with delay spread and trades CCI and ISI reduction against noise enhancement. MU-MMSE [9,10] needs multiple training sequences for all users with low cross-correlation or blind channel estimate for all users.

A mixed solution has been proposed, which is based on ST filter followed by scalar MLSE where a space space-time filter (STF) suppresses CCI while capturing spatial diversity and scalar MLSE removes residual ISI and captures temporal diversity. Simulation results presented in [10] for a GSM air interface and typical urban (TU) propagation model show that ST- MMSE outperform ST-MLSE for low CIR and the situation is opposite for higher CIR. The mixed solution outperforms ST-MLSE at low CIR.

Wideband space-time processing

ST receiver structure and algorithms for CDMA have several well marked differences. In CDMA network all other users are seen by each other as interference and there are many weaker CCI in the uplink. Multipath gives rise to the MAI due to the losses of codes orthogonality. ISI compensation has less importance in CDMA than interchip interference (ICI). However ISI cancellation may be required for a very high bit rate. Channel estimations can be based on spreading codes and it presumes the introduction of novel techniques.

The most practical implementation of the ST receiver for CDMA is the 2D-RAKE receiver where the MMSE beamformer or beamformer based on code-filtering [7] for each path is followed by a conventional RAKE receiver. The ST-RAKE reduces MAI and thus improves coverage and capacity. Such a receiver structure has an additional degree of freedom and can be optimised to achieve improved coverage or capacity by reducing inter- or intracell CCI by beamforming.

MU-ST-MLSE for CDMA was proposed in [9] but practical implementation is extremely complex. This type of SA receiver has computational complexity linear to the number of users and the same degree of near-far resistance and error rate performance as an optimum MU receiver requires. MU-ST-MLSE requires knowledge of the all users' channels.

As was shown in [14], sophisticated spatial-based blind methods are not efficient for low SNR and this was the reason of more extensive research into the area of switched-beam solutions for a system with an IS-95 air interface. User dedicated pilots at the up- and down-links of the UMTS air interface give an additional advantage for SA technology especially in highly loaded cells.

In CDMA the forward link channel estimation problem is simpler than in TDMA because it is possible to decouple the channel mapping for each path and deal with a lower angle spread. Also in CDMA systems the SA receiver is less sensitive to channel estimation errors [10,11]. However, beam pattern optimization is more complex.

In multi-bit rate CDMA SA the receiver can successfully cancel interference from the limited number of high bit rate users, thus considerably increase system capacity.

2.3. New methods and current trends

Introduced in the last few years, the S-T coding approach splits encoded data into multiple streams. Each stream is modulated and simultaneously transmitted from a different antenna [12,13]. Combinations of ST coding with OFDM, CCI cancellation methods, ML decoding and beamforming are proposed.

Further improvements can be obtained when SA are used at the receiver and the transmitter simultaneously. In this case, the problem of channel estimation is combined with searching for the optimum radio channel in the ST domain.

2.4. Integration of SA receiver into radio networks

Before making decision about type of SA receiver to be used in the cell one should consider a number of cell specific parameters such as propagation, the interference environment, user mobility and radio link quality requirements. Table 1 gives an idea about different types of SA receivers' compatibility for two types of cells. We consider a macrocell with low traffic and more noise than a CCI dominant environment, high users mobility, low angular spread and a microcell with high traffic and CCI, low user's mobility, high angular spread and low delay spread. The level of ISI can be roughly estimated using the ratio between delay spread and transmission rate. Two types of cellular systems, TDMA and CDMA are considered.

In microcell TRB are better fit for a rich multipath environment. SSBF can be used if a proper reference signal is difficult to obtain. Downlink BF is important to increase capacity but there is no way to use uplink information at the downlink in systems with FDD. In this case downlink BF should use more complex methods. In TDD downlink BF is not a problem if channel variation during each time slot is small. In some cases minimum mobile speed can be considered as a limiting factor in TRB [4].

For macrocell the DOB is a feasible solution however, it may be reasonable to make final choice between DOB and TRB based on an *As/M* ratio. Downlink BF can use information at the uplink and some degree of freedom of SA can be spent for ISI cancellation for high bit rate users. In [4] it was shown that there are different requirements for update rates between TRB and DOB. They can be roughly estimated as the ratio between user's distance to the base station and to wavelength. This ratio in a macrocell can be very high. This fact gives a certain advantage for DOB in terms of computation burden.

The TRB training signal method is very effective and relatively simple in CDMA. Eigenfilter and code filtering approaches are feasible for microcells with large angular spread.

In the macrocell superresolution methods of AoA estimation can be applied. TRB and switched methods are applicable.

ST-MMSE can be used in a microcell since it outperforms ST-MLSE for high CCI. ST-MLSE supports high bit rate users but it might be more expensive.

ST-MLSE is more effective in macrocells with a large delay spread of CCI and more likely a considerable ISI. However this type of receiver is more difficult to implement. ST-MMSE can be better choice for fast moving users. A mixed solution based on STF and MLSE can be used since this approach performs better than ST- MLSE at low CIR.

The 2D-RAKE ST receiver, which consists of MMSE TRB is one of the most applicable solution for macro- and microcells. Other ST methods for CDMA require further investigation.

TDMA		
Cell type	**Spatial domain-only processing**	**Space - Time Processing**
Microcell High angular spread (As), High traffic - CCI dominant, low user mobility low delay spread	TRB (Reference signal based) Downlink spatial selective transmission to improve capacity. Downlink BF in TDD can be based on up-link BF.	ST-MMSE ST-MLSE - if ISI more important problem than CCI
Macrocell low angular spread, low traffic, high user mobility	DOB. Performance depends on the ratio *As/M*. For ISI limited transmission some degree of freedom can be spent for ISI cancellation at expense of time diversity or CCI cancellation.	ST-MLSE ST-MMSE for users with high mobility Mixed solution STF/MLSE
CDMA		
Microcell	Eigenfilter approach SSBF code-filtering TRB based on training signal	2D RAKE based on MMSE and RAKE
Macrocell	Some superresolution algorithms can be used for AoA estimation TRB based on training signal Switched beam SA	2D RAKE based on MMSE and RAKE

Table 1. Compatibility of SA receivers structures and algorithms.

3. Radio Network Planning with SA

Different GSM radio network planing concepts with SA were introduced in [15]. High Sensitivity Reception (HSR) utilises the SA at the uplink to increase sensitivity of the system as a function of angular spread. This approach is proposed for coverage planning and requires further evaluation of the up- and down-links budget balances.

Spatial Filtering for Interference Reduction (SFIR) exploits SA at the up and down links simultaneously and in addition to range it increases capacity. In SFIR, SA reduces the level of CCI by spatially selective transmission and makes possible more tight channel reuse and in this way increases capacity.

In the Space Division Multiple Access (SDMA) concept spatial filtering is employed to handle several users at the same frequency and time slots in the same cell. In addition to range and capacity improvements, this approach also has a significant impact on spectrum efficiency. Coverage, capacity and spectrum efficiency improvements for those concepts were analysed in [15]. The SDMA concept has been evaluated in many publications, taking into considerations SA receiver type [16], radio network control algorithms [17] and users mobility [18]. The minimum reuse distance between points in signals constellation in TRB and minimum angular separations for DOB in SDMA have been evaluated in [19] and [20] respectively. It has been shown that the high dynamic range requirements perceived in SDMA put limitations on the receiver. This was the reason of the introduction of power classes concept [15]. The need to upgrade resource management and handover procedures in the existing networks is one of the main problems, which restricted SDMA implementation in GSM systems.

The HSR concept should be considered in network coverage planning. The SFIR concept has an impact on capacity and interference planning. Further network updating from SFIR to SDMA does not simplify network planning and only increases network control complexity. It is possible to go even further and combine SFIR and SDMA operation but system complexity is expected to be very high in this case.

In [4] reuse factor $K=1/3$ for SFIR operation has been proposed with estimated capacity gain about 200%. The required CIR gain for successful SFIR operation is estimated to be in the order of 6dB.

To avoid beams collision in SFIR operation intelligent intracell handover or random frequency hopping should be used. In SFIR operation TRB can exploit cell specific colour codes. In SDMA operation there is need to introduce colour codes for each SDMA traffic channel to identify users. Colour codes in GSM/DCS-1800 is allocated on a cell basis and this should be changed when SDMA is introduced. Theoretically, SDMA operation does not require angular spatial separation since by applying optimum combining a separation in space or polarisation domain, which provides uncorrelated signals, is sufficient.

Spectrum efficiency of sectorisation and SA concepts are evaluated in [15]. It was shown that there is complete computability between sectorisation and SA, it was also mentioned, which pushing sectorisation too far will limit additional gain provided by SA. The choice of 3 or 4 sectors equipped with SA might be considered to be a reasonable compromise.

In [21] several radio network upgrade strategies with SA for urban and rural areas were proposed. Network upgrade with SA was evaluated together with other upgrade technologies, codec rate reduction, cell splitting and sectorisation.

In single carrier CDMA networks only HSR and SDMA concepts can be applicable due to the fact that the reuse factor equals one in such systems.

Possible down link CIR improvements due to the gradual introduction of SA into existing GSM/DCS networks were analysed by simulation [22] and it was shown that even a few BS with SA could considerably improve network quality.

Cumulative CIR distribution in a network with SA in the urban area was analysed in [23,24]. The impact of SA orientation on system performance in an urban microcell was evaluated in [23]. Optimal BS placement with SA in an indoor environment was analysed in [25].

UMTS network planning tool development with SA is the part of the international European project STORMS [26]. The SA simulation method proposed in this project is based on the statistical diagram concept, where SA is considered as omni-directional with statistically added link gain. SA related signalling overhead and economical issues will be further analysed in this project together with network planning and system performance evaluation. Some economical issues related to network planning with SA were discussed in [27].

In network planing, different types of cells may require different SA receivers, when propagation and user mobility are taken into consideration. As it was mentioned above, the SA receiver with DOB is the most feasible solution for macrocells in this case BS positioning should take into consideration the expected angular distribution of the users.

The near-far effect in mixed cells scenario can be alleviated to some extent by SA [28] what is especially important for CDMA network planning.

4. Radio Network Control with SA

SA technology will influence the first three layers of the protocols reference model. The larger capacity we expect to obtain with SA the higher network layer should be upgraded. For example, introduction of the SDMA concept in GSM will require considerable changes in the third layer. Basic implementation will require handover procedure upgrade in CDMA. To obtain fully profit from the SA features in CDMA the resource management procedure has to be modified.

The log-in procedure, handover signalling, link quality monitoring were discussed in detail taking into consideration the GSM protocol [17]. Such issues as frequency hopping, location update and time advancing procedures were evaluated. An interesting parallelism between time advancing, power control (PC) and beamforming was found. A procedure based on switching between omnidirectional and directional beamforming was proposed for initial access. Resource management requires only software upgrade in GSM and as the handover (HO) procedure with SA is one of the most complex in GSM it will require numerous changes. Two solutions were proposed: one is a location-aware handover and another is a transition between channels through broadcast carrier. In the same publications integration of SA related control functions into existing fixed network architectures has been briefly discussed. The service layer will be involved only if information about MS location obtained with SA is to be further utilised in the upper layers.

Avoiding beams collision in SFIR and SDMA can be a part of network control. Colour codes and intracell handover can be used for this purpose. Random frequency hopping can provide spatial "whitening" of CCI to reduce the effect of beam collisions.

There are several complex and important problems in the radio network control with SA, which will require considerable research efforts. Physical link control algorithms performance and compatibility with SA are two of them. Performance and dynamic of PC and SA tracking algorithms, SA algorithm behaviour during acquisition, dynamic range are related to this problem. Another problem is resource management with SA. To solve this problem optimisation of BS assignment, channel allocation, BF and PC algorithms at the up- and down-links are required. An efficient solution can provide large benefits for operators in terms of capacity and revenues. Packet transmission performance can be dramatically improved with SA and two previously introduced problems are inherent in it. All these problems have been partly studied in a number of studies but definitely require further evaluation taking into consideration parameters and protocols of the existing air interfaces.

Performance of the power control (PC) and SA tracking algorithms can be treated jointly or separately. In [4] algorithms based on combination of Kalman Filtering with ML methods were discussed. The performance of two signal-tracking algorithms - LMS and DMI were evaluated with different data to fade rates for IS-54 system in [29].

PC algorithm performance in IS-95 system with SA was studied in [30] by simulation. Different PC step sizes, diversity gain and Doppler shifts were considered in this work. Diversity gain obtained with SA and with other methods like polarisation or macro diversity can considerably improve PC performance. The performance of the AoA tracking algorithm and diversity based on experimental and simulation results were discussed in [31]. The problem of joint optimal spatial processing, PC, BS assignment and resource allocation are among the most interesting and attractive for the research. Several studies have been published in this area.

The problem associated with DOA down-link beamforming and channels allocation in SDMA was evaluated in [32]. The possibilities of CCI reduction by BF optimisation were discussed based on non-linear and linear approaches. It was shown that the linear approach in BF is computationally cheap and well suited for the channel allocation algorithms but non-linear method yields optimum results.

The increasing spectrum efficiency of FDMA system at the down-link with joint beamforming, channel allocation and PC algorithms was studied in [33]. Different down-link generalised BF algorithms were evaluated in scenarios very similar to the SFIR and SDMA. Simulation was used to obtain by simulation outage probability for different downlink beamforming algorithms and capacity improvement concept combinations. Several control algorithms for channel allocation, beamforming and PC have been proposed. System capacity has been evaluated for different ratios between angular spread in radio channel and the number of SA elements. Proposed beamforming algorithms can be effectively used at the up-link of DS-CDMA. The outage probability for the different types of proposed BF algorithms were obtained by simulation. Data obtained from measurements were directly used for simulations. A BF algorithm based on interference nulling gives improvements in outage probability three times larger than BFs, based on simple beamsteering.

A channel assignment strategy in Joint Detection CDMA (JD-CDMA) with SA was discussed in [34]. JD-CDMA burst and frame structures are similar to those in GSM. AoA estimation was directly used to control channel assignment with algorithm based on maximum spatial separation criteria. This procedure was followed by channel estimation. The proposed structure improves channel estimation and joint detection. Considerable system performance improvements were showed in scenarios with poor user spatial separation. In scenarios with good separation, the proposed channel assignment algorithm made it possible to avoid usage of sophisticated channel estimation without any system performance degradation.

Joint optimisation of beamforming, PC and BS assignment algorithms at the up-link of DS-CDMA system were studied in [35]. BF based on CIR maximisation and distributed PC control were considered. CDMA capacity improvement was evaluated by simulations and it was roughly estimated that system capacity can be 4-5 times higher with the proposed algorithm and 4 element SA compered to a system with omni-directional antennas and non-optimised network control. The same problem at the down-link was studied in [36]. It is worth noting that the SA CIR based algorithm is unrealistic for CDMA where all users share the same carrier. In this case other beamforming algorithms should be considered.

Packet radio network performance can be improved by SA due to packet capturing effect and nulling other packets during the same time slot. The throughput and delay performance of ALOHA packet network with SA were analysed in [37] with different SA parameters and the length of randomisation interval within each slot. Furthermore, this method was extended by multi-beam SA to be able to successfully receive several overlapping packets at the same time [38]. Throughput of the radio network with the slotted nonpersistent carrier sense multiple access (CSMA) method and SA was analysed in [39]. The performance of slow frequency FH-CDMA network with SA and packet combining was analysed in the Raleigh fading channel [40]. Random access protocol, slotted ALOHA, is considered, and synchronous memoryless hopping patterns are assumed. In this work it was assumed that SA employs RLS TRB algorithm.

5. Existing SA experimental systems and commercially available products

System level field trials, which involve several GSM/DCS BS with SA, are in the focus of Ericsson-Mannesman co-operation [41,42]. The system will experience a full commercial traffic load in the nearest future. In this experiment SA receivers use eight elements a dual polarised array SA with DOB at the up- and down-links. Improvements in the Carrier to Noise (C/N) ratio in order of 4- 5 dB for up- and down- links were reported. In rural and urban macrocells the SA receiver provides an additional 10 dB and 6 dB (respectively) in CIR. Based on the experiment 100 - 200 % capacity gain is reached and achievable range extension is determined by 4 -5 dB C/N gain what is equivalent to 50 % fewer sites.

Another testbed was built by the Ericsson international team for study of SA receiver performance for D-AMPS[43,44]. Up-link receiver use space and polarisation diversity. The antenna elements has 15 wave length separations. Two types, Maximum Ratio Combining (MRC) receiver and Interference Rejection Combining (IRC) receiver, were studied. Combined space and polarisation approaches provided 3.5dB gain in C/N ratio and additionally 5dB gain with IRC in interference limited scenario. The fixed beam approach was used at the down-link.

A four element adaptive antenna array (TRB) testbed with DMI algorithm was designed by AT&T [45,46] for evaluation of the SA concept in an IS-136 system operating at 850 MHz/1.9 GHz. A 5 dB higher gain was achieved at 10^{-2} BER in a Raleigh fading environment compare with two-element antenna diversity. This corresponds to a 40% increase in range. It was shown that SA could maintain 10^{-2} BER when the interference level is near the level of desired signal with fading rates corresponded to 60 mph. The power control performance was studied with a switched beam SA at the down-link.

NTT DoCoMo is developing a SA experimental system for a third generation UMTS W-CDMA network [47]. The 2D- RAKE receiver includes a MMSE beamformer, which tentatively will exploit user dedicated pilot and recovered data symbols. There are three cell sites in the experimental system and it allows for the evaluation of handover and other network functions. The first experimental results showed a substantial improvement in average BER with SA compare to space diversity.

Participants of the SUNBEAM (former TSUNAMI) ACTS project are using a SA testbed designed by Era Technology Ltd. [48]. AoA is estimated by the MUSIC algorithm and Kalman filtering for tracking. The DECT air interface was selected for trials since it can be easily integrated into SA and allows networking aspect to be neglected. Two independent SDMA channels were supported. The uniform linear array (ULA) consists of 8 elements.

A smart antenna prototype of the SDMA system for GSM/DCS1800 network was developed and tested by Thompson-CSF Communications and CNET [49]. The SA receiver consists of 10 elements and digital BF in the up-link and down-link. In test trials three mobiles communicated in the same FDMA/TDMA channel. The MUSIC algorithm was used for AoA estimation. Such parameters as minimum angular separation, maximum dynamic signal separation, and achievable level of interference rejection were studied.

The Circuit and System Group at Uppsala University and Ericsson Radio Access AB built a 10 element experimental SA [49]. Real traffic data taken from DCS 1800 network were used and spatial multiplexing concept was evaluated. 30 dB in CIR was obtained in a line of sight (LOS) propagation scenario. It was observed that different spatial signatures and low crosscorrelation between training are enough for separation even for signals with the same angular position in the presence of CCI [50]. It was possible to maintain error-free transmission with minimum a 10 degrees angular between desired and interfering signals when CIR = -20 dB.

Designer	Air interface	Antenna *(M)*	SA Receiver algorithm	Remarks	Ref.
SA experimental systems					
Ericsson & Mannesmann Mobilfunk)	GSM/DCS 1800	8	**Up-link:** DOB **Down-link:** DOA switched-beam and adaptive	Several BS equipped with SA integrated into network	[41]
Ericsson Research (SW/US)	IS - 136 (D-AMPS)	spacing up-link 15λ & pol. div.	**Up-link:** MRC and IRC, **Down-link:** fixed beam approach		[43]
AT&T Labs-Research (US)	IS-136	4	**Up-link:** 4 branch adaptive TRB, DMI algorithm **Down-link:** switched beam with or without PC (up to 3 beams)	Up and down links are independent	[45]
NTT DoCoMo (Japan)	UMTS	6	**Up-link:** Decision directed MMSE (tentative data and pilot) 4 finger 2D-RAKE **Down-link:** calibration of weights generated for reverse link	-include 3 cell sites -data transmission up to 2 Mbps	[47]
TSUNAMI (SUNBEAM) Consortium (EU)	DECT -> SDMA ->DCS1800		ULA_MUSIC for DOA estimation Kalman Filtering for tracking	SDMA was Studied based on DECT	[48]
CNET & CSF-THOMPSON (F)	GSM/DCS1 80SDMA	10 circular	**Up-link:** DOA based BF Capon , MUSIC for DOA estim. **Down-link:** DOA based BF		[49]
Uppsala University (SW)	DCS 1800 SDMA	10 circular	**Up-link only:** TRB with SMI	Data traffic from DCS-1800 was used	[50]
Commercially available products					
Metawave (US) Spotlight^TM^2000	AMPS, CDMA	12	**Up- and down links :** 12 switched beam		[51]
Raytheon (US)	Flexible upgraded by SW	8	**Up-link:** DOB based algorithm (?)	SA can be connected to RF input at the BS	[52]
ArrayComm "IntelliCell"(US)	WLL, PHS, GSM	4	**Up-link:** ESPRIT Adaptive interference cancellation	First mass market commercial product	[53]

Table 2. *List of experimental SA systems and commercially available products*

SPOTLIGT ^TM^ Metawave Co. switched beam system with twelve beams at the up- and down- links is among the first commercially available products. SPOTLIGT ^TM^ can be installed in CDMA IS-95 and AMPS networks and according to Metawave a 30% capacity improvements in IS-95 can be obtained [51].

Raytheon E-Systems introduced the "Fully Adaptive Digital Signal Processor System" based on an 8 element SA [52]. It is expected that the SA module can be directly connected to RF input of the existing BS.

ArrayComm offers four element SA for Wireless Local Loop (WLL) and Personal Handyphone System (PHS) which is similar to DECT system in Europe [53]. During field trials that involved GSM protocols interference mitigation of 20 dB was achieved.

Conclusions

We discussed several system issues important for the future radio network design with SA. The authors believe that SA will be widely used in radio networks and will become a vital part of future adaptive modems.

There are several important system issues, which were not discussed in this publication. More detail discussion is needed for SA receiver integration into different types of cell taking into consideration air interface specification. ST processing in CDMA requires more explicit discussion. Another important issue which is not highlighted in this overview, is the implementation of SA receiver algorithms and architectures in IC.

The following conclusions summarise our discussion:
- Proposed SA algorithms are becoming more complex and involve combinations with processing in time domain, multi-user detection, ST coding and multiple antennas at MS.
- There are number of parameters such as the level of CCI reduction, diversity gain, SNR, which can be improved with SA. Some of these parameters can be interdependent and even conflicting. Their importance and

trade-off need to be decided on a cell by cell basis. The following parameters should to be taken into consideration: propagation, interference environment, user's mobility, and requirements for link quality.
- From the implementation point of view, there always should be a reasonable compromise between amount of information about radio channels in different domains to be exploited at the Smart Antenna receiver and the expected level of improvements. The possibility to exploit/obtain more detailed information related to the radio channel is restricted by the signal processing algorithms and hardware, user mobility, data transmission speed and highly dependent on the radio interface type and parameters. In complex (multipath) propagation environments more complex SA algorithms should be used to maintain link quality requirements.
-Wideband spatial processing algorithms require further research to be better understood.
- CDMA network planning concept and site specific network planning tools are needed to be developed.
-      Achievable capacity improvements with SA depend on the penetration level of SA control functions into radio network control. The best performance will be obtained when spatial processing is controlled by network radio resource management.
- Development of jointly optimum resource management and spatial processing algorithms can be an interesting problem for future research and network design.
- Packet switched transmission in cellular network with SA needs further evaluation to take into consideration air interface parameters.
- The majority of the experimental SA includes a space diversity receiver as a reference model, which can be an economical solution. Many of the field trial shows that SA receivers considerably outperform space diversity receivers.
- Experimental and commercially available SAs are mostly based today on very simple algorithms.
- Network coverage and capacity in urban macrocells can be at least doubled with existing SA receivers. To achieve sensible capacity improvements in urban microcell more complex SA algorithms discussed in this paper are required. The possibilities to use complex algorithms are limited by IC technology. It is expected that required IC technology level will be achieved during the next two years. Software radio will add flexibility to SA receiver and network control and perhaps will make them transparent to the air interface.

References:

[1] Barry D. Van Veen and Kevin M. Buckley, " Beamforming: A Versatile Approach to Spatial Filtering", *IEEE ASSP Magazine, April 1988,* pp. 4 - 24.
[2] L. C. Godara, "Application of Antennas Arrays to Mobile Communications. Part II ", *Proceedings of the IEEE,* VOL. 85, NO. 8, August 1997, pp. 1193 - 1245.
[3] Race TSUNAMI Project "Report on Mobile Adaptive Array Processing Algorithms", *Document No.: R2108/UPC/WP3.3/DR/P/031/b1*
[4] Race TSUNAMI Project "Algorithms and Antenna Array Recommendations (Part 1)", *Document No.: AC020/AUC/A1.2/DR/P/005/b1*
[5] S. Rappaport, J.Liberti, "Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications, 1/e", ISBN 0-13-719287-8, *Prentice Hall Professional Technical Reference* , 1999.
[6] P.M. Grant, J.S. Thompson and B. Mulgrew, " Adaptive Arrays for Narrowband CDMA base stations", *Electronics & Communication Engineering Journal,* August 1998, pp. 156 - 166
[7] A. F. Naguib, Adaptive Antennas for CDMA Wireless Networks", *Ph.D. Dissertation*, Stanford University, August 1996, pp. 60 -65.
[8] Z. Rong, T. S. Rapport, P. Petrus, J. H. Reed "Simulation of Multitarget Adaptive Array Algorithms for Wireless CDMA Systems", *Proc. IEEE VTC'97*, Phoenix, AZ, May 1997, pp. 1- 5.
[9] R. Kohno, "Spatial and Temporal Communication Theory Using Adaptive Antenna Array", *IEEE Personal Communications,* February 1998, pp. 28 - 35.
[10] A.J. Paulraj, Boon Chong Ng, "Space-Time Modems for Wireless Personal Communications", *IEEE Personal Communications, February 1998,* pp. 36 - 48.
[11] A. Paulraj, C. B. Papadias, "Space-Time Processing for Wireless Communications", *IEEE Signal Processing Magazine*, November 1997, pp. 49 -83.
[12] N. Seshadri, V.Tarogh, and A. R. Calderbank, "Space-Time Codes for Wireless Communication: Code Construction" *Proc. VTC, Phoenix,* AZ, 1997, pp. 637- 641.
[13] V.Tarogh, "Space-Time Coding for High Data Rate Wireless Communication: Mismatch Analysis", *Proc. ICC,* Montreal, Canada, June 1997, pp. 309 - 313.

[14] P.M. Grant, J.S. Thompson and B. Mulgrew, " Adaptive Antenna Arrays for CDMA Systems", *IEEE Personal Communications*, October 1996, pp. 16 - 25.

[15] R. Rhenshmidth, M. Tangemann, "Performance of Sectorized Spatial Multiplex Systems", *IEEE VTC'96,* Atlanta, April 1996, pp. 426 -430.

[16] J. Fuhl and A. F. Molish, "Capacity Enhancement and BER in a Combined SDMA/TDMA System", *IEEE VTC'96,* Atlanta, April 1996, pp. 1481 - 1485.

[17] "Mobile Cell Control Methods for Adaptive Antennas", *TSUNAMI Project deliverable*, R2108/SEL/WP3-4/DS/I/029/b1, 12 May, 1995.

[18] . Tangemann, "Influence of the User Mobility on the Spatial Multiplex Gain of an Adaptive SDMA System", *Proc. PIMRC '94*, The Hague, The Netherlands, Sept 1994, pp. 745 - 794.

[19] M. Torlak and G. Xu, Minimum Distance of Space-Division- Multiple Access Channel", *Proc. IEEE VTC'97*, Phoenix, AZ, May 1997, pp. 2223 - 2227.

[20] C. Farsakh, J. A. Nossek, "On Spatial Separation Potential of a Uniform linear Antenna Array", *IEEE VTC'96,* Atlanta, April 1996, pp.1477- 1480.

[21] R. Rhenshmidth, M. Tangemann, "Comparison of Upgrade Techniques for Mobile Communication Systems", *Proc. SUPERCOMM/ICC'94*, New Orleans, LA, USA, May 1994.

[22] F. Kronestedt, S. Andersson, " Migration of Adaptive Antennas into Existing Networks", *IEEE VTC'98*, pp. 1670 - 1674.

[23] T. Iwama, "Computer Simulation of Frequency Assignment in Microcellular System using Array Antennas", *IEEE 45th VTC'95,* Chicago, IL*,* 1995, pp. 594 - 598.

[24] M. Frullone *et al.* ,"Usage of Adaptive Antennas to Solve Resource Planning Problems", *Proc. 46th VTC'96*, Atlanta, GA, Apr 1 - May1, 1996, pp. 527 -530.

[25] D. Stamatelos, A. Ephremides, "Spectral Efficiency and Optimal Base Placement for Indoor Wireless Networks", *IEEE Journal on Selected Areas in Communications,* VOL. 14, No4, May 1996, pp. 651 - 661.

[26] "Planning UMTS with adaptive antennas", *STORMS project deliverable*, A016/TDE/TID/DS/L/052/a1, 30.11.97.

[27] "Target Operator Requirements for Adaptive Antennas", *TSUNAMI Project deliverable*, AC020/ORA/A1.1./DR/P/001/b1, 11 December, 1995.

[28] C.V Tsulos, M.A. Beach, S.C. Swales, "Application of Adaptive Antenna Technology to Third Generation Mixed Cell Radio Architectures", *Proc. 44th Vehicular Technology Conference*, June 7 -10, Stockholm, Sweden.

[29] J. H. Winters, "Signal Acquisition and Tracking with Adaptive Arrays in Wireless Systems*", IEEE Trans. on Vehicular Technology*, November 1993, pp. 377 - 384.

[30] A. F. Naguib, "Power Control in Wireless CDMA: Performance with Cell Site Antenna Arrays", *Globecom' 95*, pp. 225 - 229.

[31] S. P. Stapleton, X. Carbo, T. McKeen, "Tracking and Diversity for a Mobile Communications Base Station Array Antenna", *IEEE VTC'96*, Atlanta, GA, April 1996, pp. 1695 - 1699.

[32] C. Farsah, J. A. Nossek, "A Real Time Downlink Channel Allocation Scheme for SDMA Mobile Radio System", *Proc. IEEE PIMRC'96*, pp.1216 - 1220.

[33] P. Zetterberg, "Mobile cellular Communications with Base Station Antenna Arrays: Spectrum Efficiency, Algorithms and Propagation Models", *Ph.D. Dissertation*, Dep. Of Signal, Sensors and Systems, Royal Institute of Technology Stockholm, Sweden, 1997.

[34] A. Papathanassiou, J. J. Blanz, M. Haardt, P. W. Baier, "Spatial Channel Assignment Consideration in a Joint Detection CDMA Mobile Radio System Employing Smart Antennas", *IEEE _* , 1998, pp. 318 - 322.

[35] F. Rashid,L. Tassiulas, K.J. Lui, "Joint Optimal Power Control and Beamforming for Wireless Networks Using Antenna Arrays", *Proc. IEEE Globecom '96*, London, Nov. 1996, pp. I-555-559.

[36] F. Rashid,L. Tassiulas, K.J. Lui, "Transmit Beamformimng and Power Control for Cellular Wireless Systems" , *IEEE Journal on Selected Areas in Communication,* Vol. 16, NO. 8 , October 1998, pp. 1437-49.

[37] J. Ward, T. Compton, "Improving the performance of a Slotted ALOHA Packet Radio Network with an Adaptive Array", *IEEE Trans. on Communications*, VOL. 40, NO. 2, February 1992, pp. 292 - 300.

[38] J. Ward, T. Compton, "High Throughput Slotted ALOHA Packet Radio Networks with Adaptive Array", *IEEE Trans. on Communications*, VOL. 41, NO. 3, March 1993, pp. 460 - 469.

[39] A. Sugihara, K. Enomoto, I. Sasae, " Throughput Prformance of a Slotted Nonpersistent CSMA with an Adaptive Array", *PIMRC'95,* Sep. 1995, , pp. 633 - 637.

[40] J. Y. Kim, J. H. Lee, "Performance Analysis of an FH/SSMA Network with Adaptive Antenna Array and Packet Combining", *IEEE VTC'98*, pp. 2217 - 2221.

[41] S. Anderson, U. Forssen, J. Karlsson ,T. Witzschel, P. Fisher, A. Krug, "Ericsson/Mannesmann GSM Field-Trials with Adaptive Antennas", *Proc . IEEE 47th VTC* , USA, 1997 , pp. 1587 - 1591.

[42] S. Andreson, "Adaptive Antennas for GSM", *Fifth Stanford Workshop on Smart Antennas in Mobile Wireless Communications*, July 23 -24 , 1998.

[43] K. Molnar, "Space-Time Processing in the Evolution of IS-136 System", *Fifth Stanford Workshop on Smart Antennas in Mobile Wireless Communications*, July 23 -24 , 1998.

[44] B. Hagerman, T. Osterman, K.J. Molnar , G. E. Bottomly, "Field Test Performance Results for D- AMPS in PCS Bands with Array Processing", *Proc. IEEE VTC'97*, Phoenix, AZ, May 1997, pp. 1582 - 1586.

[45] J. H. Winters, "Forward Link Smart Antennas and Power Control for IS - 136", *Fifth Stanford Workshop on Smart Antennas in Mobile Wireless Communications*, July 23 -24, 1998.

[46] R. L. Cupo, G. Golden, C.Martin , J. H. Winters, "A Four- Element Adaptive Antenna Array for IS-136 PCS Base Stations", *Proc. IEEE VTC'97*, Phoenix, AZ, May 1997, pp. 1577 - 1581.

[47] F. Adachi, "Application of Adaptive Antenna Arrays to W-CDMA Mobile Radio ", *Fifth Stanford Workshop on Smart Antennas in Mobile Wireless Communications*, July 23 -24 , 1998.

[48] G. Tsulos, M. Beach, J. McGeen, " Wireless Personal Communications for the 21st Century: European Technology Advances in Adaptive Antennas", *IEEE Communicatios Magazine*, September 1997, pp. 102 -109.

[49] J. Monot, J. Thibault, P. Chevalier, F. Pippon, S. Mayrague "Smart Antenna Prototype for the SDMA experimentation in UMTS and GSM/DCS1800 network", *IEEEPIMRC'97 ,Sept. 1-4, Helsinki,* pp. 33- 337.

[50] J. Strandell, M. Wennstrom, A. Rydberg , T. Oberg, O. Gladh, "Experimental Evaluation of an Adaptive Antenna for TDMA Mobile Telephony System", *Personal Indoor and Mobile Radio Communications Conference 1997(PIMRC'97),* Helsinki, September 1-4, 1997

[51] *http://www.metawave.com/Customers/casestudy.htm*

[52] *http://www.raytheon.com/rtis/docs/apd/smtant.htm*

[53] *http://www.arraycomm.com/products/pindex.shtml*