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An Overview of System Aspects of Smart Antenna Technology in Cellular Wireless Communications

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ABSTRACT:

A survey has been observed on the three main system aspects of smart antenna (SMART ANTENNA) technology in wireless communications i.e. SMART ANTENNA receiver, wireless network control and planning with Smart Antenna. A classification of SMART ANTENNA 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 SMART ANTENNA receivers taking into consideration expected propagation conditions, user mobility and offered traffic. Several radio network planning and upgrading concepts associated with SMART ANTENNA 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 SMART ANTENNA at the different layers are briefly examined. Existing experimental and commercially available SMART ANTENNA and their performance are surveyed.

Keywords: Smart Antenna, attenuation, optimismar, Viterbi, duplexing, orthogonality, sectorism art, infilling, protocol

1. INTRODUCTION

Extensive research activity into the area of SMART ANTENNA 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. SMART ANTENNA can be effectively combined with other techniques such as multi-user detection, Polari smart attenuation diversity, and channels coding. Air interfaces standards are becoming more "friendly" for SMART ANTENNA and future introduction of software radio will make it possible to optimise radio system design for spatial processing and integrate SMART ANTENNA into future adaptive modems. There are number of SMART ANTENNA commercial products currently available on the market.

The main advantages expected with SMART ANTENNA are:

- 1 .Higher sensitive reception
- 2 .The possibility to implement systems with spatial division multiple access (SDMA)
3. Interference cancellation in uplink and downlink functions
4. Mitigation effects of multipath fading

On the system level this will lead to the higher capacity, extended range, improved coverage by "infilling"

Dead spots, higher quality of services, lower power consumption at the mobile and improved power control (PC). SMART ANTENNA increases system complexity and costs, but at the smart antennae 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 SMART ANTENNA optimisation methods and criteria, channel estimation techniques and receiver structures. One of the main problems in this area - SMART ANTENNA system integration into existing and future cellular networks has not yet been highlighted. To improve radio network performance, SMART ANTENNA receiver structure and algorithms should be optimised according to the propagation and interference environment, considering expected traffic and user's mobility in the cell. These parameters can be seen as a product of radio network planning. At the smart antennae time, SMART ANTENNA 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 SMART ANTENNA receiver and algorithm today is highly dependent on the air interface and its parameters. Among the most critical parameters is 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 SMART ANTENNA Algorithms.

SMART ANTENNA 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. SMART ANTENNA 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 SMART ANTENNA at the base station at the up-link only to increase coverage, to use SMART ANTENNA at the up and down -links simultaneously and additionally to coverage improve capacity by tightening channels reuse patterns or achieve smart antennae channels reuse inside cell with SDMA thus additionally improving spectrum efficiency. It is possible to use SMART ANTENNA at mobiles alone without installing SMART ANTENNA at the base stations and achieve about the smart antennae improvement in coverage and capacity as with SMART ANTENNA at the base stations. SMART ANTENNA 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 beam forming or/and diversity techniques.

2. SMART ANTENNA receiver structure and algorithms.

There are many varieties of SMART ANTENNA algorithms and structures proposed for the cellular applications in the literature. Below, a classification of SMART ANTENNA 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. SMART ANTENNA receivers can be classified as SMART ANTENNA with processing in the space domain only and Space-Time (ST) SMART ANTENNA receivers with processing in space and time domain simultaneously (Fig. 2). Additional a diversity gain for SMART ANTENNA 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 SMART ANTENNA. 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 SMART ANTENNA receivers in the presence of co-channel interference (CCI) with delay spread.

MSE optimismart attenuation criteria are more attractive for a SMART ANTENNA receiver in the presence of correlated CCI and more efficient in interference than a noise dominated environment. Zero force criteria do not balance out effect of the noise.

2.1. Space-domain only SMART ANTENNA 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 beam forming, they can be classified as beam formers (BF) based on spatial structure e.g. angle of arrival (AoA) of the incoming signal - direction of arrival based beam former (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 beam former 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. SMART ANTENNA 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. Beam formers 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 optimism art attenuation 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 beam former, 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 beam formers. The well-known Generalized Side lobe Canceller (GSC), MVDR are beam formers, 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 SMART ANTENNA. In this case SMART ANTENNA selects the best one or several fixed beams from the predefined sets of weights. Beam forming 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.

2.11 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 maxim smart attenuation 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 wave fronts 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 (A_s) 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].

2.12 .Time reference beam forming (TRB) based on a reference signal

Beam forming based on training signal or time reference beam forming (TRB) is a computationally effective method at the expense of spectrum efficiency. Spatial information such as AoA or array manifold is not necessary antenna. Depending on the particular system and/or scenario used, the reference signal may consist 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 beam forming 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 as 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. 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 smart antenna ability to overcome ISI since two different symbols for the smart antenna user will be uncorrelated and will look like noise. Instead of calibration in DOB, the TRB techniques require accurate synchronization 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 beam forming with TRB from the information provided at the receiver in FDD.

2.13 .Signal structure based BF

In signal structure based beam forming (SSBF) adaptive processor exploits 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.

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

2.21 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]. 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 [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-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 compensates attenuation has less importance in CDMA than intersymbol interference (ISI). 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 beam former or beam former 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 beam forming. MU-ST-MLSE for CDMA was proposed in [9] but practical implementation is extremely complex.

This type of SMART ANTENNA receiver has computational complexity linear to the number of users and the smart antennae 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 SMART ANTENNA 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 th

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 beam forming are proposed.

Further improvements can be obtained when SMART ANTENNA 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 SMART ANTENNA receiver into radio networks

Before making decision about type of SMART ANTENNA 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 SMART ANTENNA receivers' compatibility for two types of cells. We consider a macrocell with low traffic and more noise than a CCI dominant environment, high user's 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.

For macrocell the DOB is a feasible solution however, it may be reasonable to make final choice between DOB and TRB based on an A_s/M ratio. Downlink BF can use information at the uplink and some degree of freedom of SMART ANTENNA 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. Eigen filter and code filtering approaches are feasible for microcells with large angular spread.

In the macrocell super resolution 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

3. Radio Network Planning with SMART ANTENNA

Different GSM radio network planning concepts with SMART ANTENNA were introduced in [15]. High Sensitivity Reception (HSR) utilises the SMART ANTENNA 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 downlinks budget balances. Spatial Filtering for Interference Reduction (SFIR) exploits SMART ANTENNA at the up and down links simultaneously and in addition to range it increases capacity. In SFIR, SMART ANTENNA reduces the level of CCI by spatially selective transmission and makes possible tighter 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 smart antenname frequency and time slots in the smart antenname 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 SMART ANTENNA 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 intra cell 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 are 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 polar smart attenuation domain, which provides uncorrelated signals, is sufficient. Spectrum efficiency of sector smart attenuation and SMART ANTENNA concepts are evaluated in [15]. It was shown that there is complete computability between sector smart attenuation and SMART ANTENNA, it was also mentioned, which pushing sector smart attenuation too far will limit additional gain provided by SMART ANTENNA. The choice of 3 or 4 sectors equipped with SMART ANTENNA might be considered to be a reasonable compromise. In [21] several radio network upgrade strategies with SMART ANTENNA for urban and rural areas were proposed. Network upgrade with SMART ANTENNA was evaluated together with other upgrade technologies, codec rate reduction, cell splitting and sector smart attenuation. 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 SMART ANTENNA into existing GSM/DCS networks were analysed by simulation [22] and it was shown that even a few BS with SMART ANTENNA could considerably improve network quality. Cumulative CIR distribution in a network with SMART ANTENNA in the urban area was analysed in [23,24]. The impact of SMART ANTENNA orientation on system performance in an urban microcell was evaluated in [23]. Optimal BS placement with SMART ANTENNA in an indoor environment was analysed in [25]. UMTS network planning tool development with SMART ANTENNA is the part of the international European project STORMS [26].

The SMART ANTENNA simulation method proposed in this project is based on the statistical diagram concept, where SMART ANTENNA is considered as omni-directional with statistically added link gain. SMART ANTENNA 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 SMART ANTENNA were discussed in [27]. In network planning, different types of cells may require different SMART ANTENNA receivers, when propagation and user mobility are taken into consideration. As it was mentioned above, the SMART ANTENNA 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 SMART ANTENNA [28] what is especially important for CDMA network planning.

4. Radio Network Control with SMART ANTENNA.

SMART ANTENNA technology will influence the first three layers of the protocols reference model. The larger capacity we expect to obtain with SMART ANTENNA 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 SMART ANTENNA 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 beam forming was found. A procedure based on switching between Omni directional and directional beam forming was proposed for initial access. Resource management requires only software upgrade in GSM and as the handover (HO) procedure with SMART ANTENNA 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 smart antennae publications integration of SMART ANTENNA 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 SMART ANTENNA 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 intra cell 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 SMART ANTENNA, which will require considerable research efforts. Physical link control algorithms performance and compatibility with SMART ANTENNA are two of them. Performance and dynamic of PC and SMART ANTENNA tracking algorithms, SMART ANTENNA algorithm behaviour during acquisition, dynamic range are related to this problem. Another problem is resource management with SMART ANTENNA. To solve this problem optimum attenuation of BS assignment, channel allocation, BF and PC algorithms at the up- and downlinks 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 SMART ANTENNA 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 SMART ANTENNA 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 SMART ANTENNA was studied in [30] by simulation. Different PC step sizes, diversity gain and Doppler shifts were considered in this work. Diversity gain obtained with SMART ANTENNA 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 beam forming and channels allocation in SDMA was evaluated in [32]. The possibilities of CCI reduction by BF optimum attenuation 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 beam forming, 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 beam forming algorithms and capacity improvement concept combinations. Several control algorithms for channel allocation, beam forming and PC have been proposed. System capacity has been evaluated for different ratios between angular spread in radio channel and the number of SMART ANTENNA elements. Proposed beam forming algorithms can be effectively used at the up-link of DS-SS-SSMA. 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 beam steering.

A channel assignment strategy in Joint Detection CDMA (JD-CDMA) with SMART ANTENNA 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 smart antennae of sophisticated channel estimation without any system performance degradation.

Joint optimization of beam forming, PC and BS assignment algorithms at the up-link of DS-CDMA system were studied in [35]. BF based on CIR maximization 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 SMART ANTENNA compared to a system with omni directional antennas and non-optimised network control. The smart antenna problem at the down-link was studied in [36].

It is worth noting that the SMART ANTENNA CIR based algorithm is unrealistic for CDMA where all users share the smart antenna carrier. In this case other beam forming algorithms should be considered. Packet radio network performance can be improved by SMART ANTENNA due to packet capturing effect and nulling other packets during the smart antenna time slot. The throughput and delay performance of ALOHA packet network with SMART ANTENNA were analysed in [37] with different SMART ANTENNA parameters and the length of random smart antenna interval within each slot. Furthermore, this method was extended by multi-beam SMART ANTENNA to be able to successfully receive several overlapping packets at the smart antenna time [38]. Throughput of the radio network with the slotted non persistent carrier sense multiple access (CSMA) method and SMART ANTENNA was analysed in [39]. The performance of slow frequency FH-CDMA network with SMART ANTENNA and packet combining was analysed in the Rayleigh fading channel [40]. Random access protocol, slotted ALOHA, is considered, and synchronous memory less hopping patterns is assumed. In this work it was assumed that SMART ANTENNA employs RLS TRB algorithm.

5. Existing SMART ANTENNA experimental systems and commercially available products.

System level field trials, which involve several GSM/DCS BS with SMART ANTENNA, 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 SMART ANTENNA receivers use eight elements a dual polarised array SMART ANTENNA 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 SMART ANTENNA 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 SMART ANTENNA receiver performance for D-AMPS[43,44]. Up-link receiver use space and polar smart antenna 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 polar smart antenna 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) test bed with DMI algorithm was designed by AT&T [45,46] for evaluation of the SMART ANTENNA 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 Rayleigh fading environment compare with two-element antenna diversity. This corresponds to a 40% increase in range. It was shown that SMART ANTENNA 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 SMART ANTENNA at the down-link. NTT Do Co Mo is developing a SMART ANTENNA experimental system for a third generation UMTS W-CDMA network [47]. The 2D- RAKE receiver includes a MMSE beam former, 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 SMART ANTENNA compare to space diversity.

Participants of the SUNBEAM (former TSUNAMI) ACTS project are using a SMART ANTENNA test bed 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 SMART ANTENNA 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 SMART ANTENNA receiver consists of 10 elements and digital BF in the up-link and down-link. In test trials three mobiles communicated in the smart antenname 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 Up smart antennal a University and Ericsson Radio Access AB built a 10 element experimental SMART ANTENNA [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 cross correlation between training are enough for separation even for signals with the smart antenname 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.

CONCLUSIONS

We discussed several system issues important for the future radio network design with SMART ANTENNA. The authors believe that SMART ANTENNA 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 SMART ANTENNA 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 SMART ANTENNA receiver algorithms and architectures in IC.

The following conclusions summarise our discussion:

- Proposed SMART ANTENNA 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 SMART ANTENNA. 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 SMART ANTENNA 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 SMART ANTENNA depend on the penetration level of SMART ANTENNA 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 SMART ANTENNA needs further evaluation to take into consideration air interface parameters.
- The majority of the experimental SMART ANTENNA includes a space diversity receiver as a reference model, which can be an economical solution. Many of the field trial shows that SMART ANTENNA receivers considerably outperform space diversity receivers.
- Experimental and commercially available SMART ANTENNAS are mostly based today on very simple algorithms.
- Network coverage and capacity in urban macrocells can be at least doubled with existing SMART ANTENNA receivers. To achieve sensible capacity improvements in urban microcell more complex SMART ANTENNA 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 SMART ANTENNA receiver and network control and perhaps will make them transparent to the air interface.

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