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

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***Abstract*—In this paper, 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's. 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's are evaluated. We describe possible radio networks architectures when SA's are used at the mobiles, base stations, or at both ends. Radio network control functions with SA's at different layers are briefly examined. Existing experimental and commercially available SA's and their performance are surveyed.**

***Index Terms*—Adaptive antenna arrays, beamforming technique, cellular networks, cellular radionetwork control protocols, network management, network performance, network planning, phased-array antenna, radio–air interfaces, SDMA, smart antennas, spatial filtering.**

I. INTRODUCTION

EXTENSIVE research activity into the area of smart-antenna (SA) cellular applications started at the beginning of the 1990's. 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 SA techniques are one of the few techniques that are currently proposed for new cellular radio network designs, which will be able to dramatically improve system performance. SA's can be effectively combined with other techniques such as multiuser (MU) detection, polarization diversity, and channels coding. Air interfaces standards are becoming more "friendly" for SA's and future introduction of software radio will make it possible to optimize radio system design for spatial processing and integrate SA's into future adaptive modems. There are number of available SA commercial products currently on the market.

The main advantages expected with SA's are as follows:

- higher sensitive reception;
- possibility to implement systems with spatial-division multiple access (SDMA);
- interference cancellation in uplink and downlink functions;
- mitigation effects of multipath fading.

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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).

An 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 optimization 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.

The 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, the SA receiver structure and algorithms should be optimized 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, and they also tightly interact with network control protocols at different layers.

The choice of an 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. Besides the compatibility with air interface, the level of integrated circuit (IC) technology can be a limiting factor for implementation of some SA algorithms.

SA algorithms should be compatible and optimized with radio network protocols. Link-level control protocols have to maintain the required link quality dynamically while carrying out channel and interference monitoring. Higher layers of protocols have optimally to distribute radio resources with the minimum required signaling while maintaining required links quality. SA's should work well together with other techniques such as frequency hopping, macro-diversity, fractional loading, and support-layered cells architecture.

In the network planning, the system designer has several options to optimize base-stations position and antenna parameters to the offered traffic distribution and propagation environment. Several main strategies are available: to use SA's at the base station (BS) at the uplink only to increase coverage, to use SA's at the up- and downlinks simultaneously, and additionally, to coverage improve capacity by tightening channels reuse patterns or

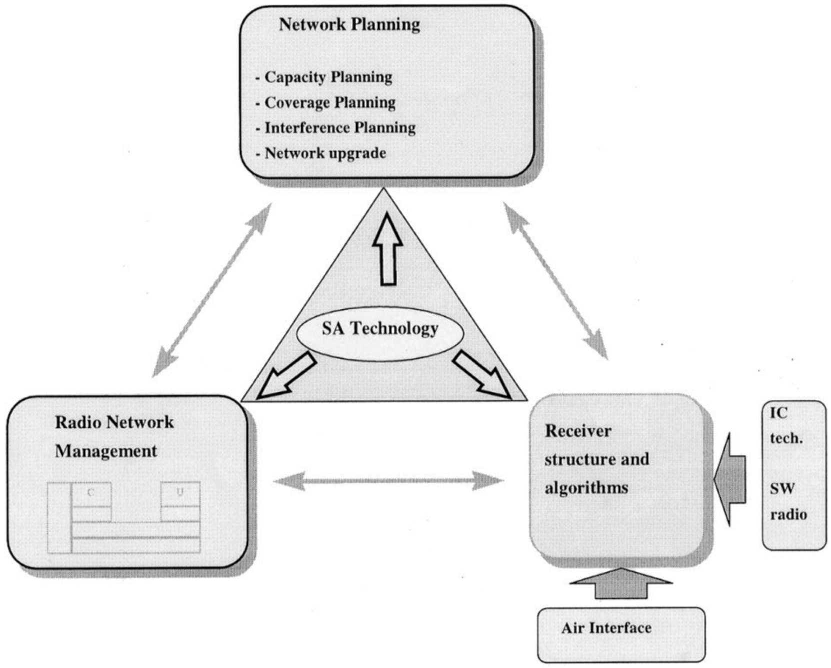

Fig. 1. Impact of spatial processing technology on the main elements of cellular system design.

achieve same channels reuse inside a cell with SDMA, thus, additionally improving spectrum efficiency. It is possible to use SA's at mobiles alone without installing SA's at the BS's and achieve about the same improvement in coverage and capacity as with SA's at the BS's. SA's can also be installed at both ends to allow several parallel SDMA channels to be established for one between the mobile and 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) channel.

Network planner should use the advantages of line-of-sight propagation or/and 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 II, network planning in Section III, and network control in Section IV.

II. 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's with processing in the spatial domain only and ST SA receivers with processing in spatial and temporal domain simultaneously. Additionally, a diversity gain for an SA receiver can be obtained by polarization diversity and macro diversity, which can also be combined with spatial and temporal processing. The new technology–ST coding, which is currently attracting extensive research activity, can also be incorporated in SA's. In the CDMA system, space-domain processing is usually combined with path diversity obtainable with a RAKE receiver.

Many of the spatial-domain-only and ST algorithms include optimization procedures in their structure. The most popular optimization criteria are: 1) maximum signal-to-interference-plus-noise ratio (SINR) and 2) squared function based criteria such as minimum square error (MSE), minimum variance (MV), and maximum likelihood (ML). The basic assumption of ML methods is that the distribution function of the estimating parameter is Gaussian. An ML ST receiver treats interference as noise temporally and spatially white and Gaussian. As a result, temporal correlation complicates the implementation of an equalizer 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 optimization criteria are more attractive for an 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 the effect of the noise.

A. *Spatial Domain—Only SA Receivers and Algorithms*

Spatial-domain processing is an effective way to reduce CCI in narrow-band systems and multiple-access interference (MAI) in CDMA systems.

According to the side information used for beamforming, they can be classified as beamformers (BF's) based on a spatial structure, e.g., angle of arrival (AoA) of the incoming signal direction of an arrival-based beamformer (DOB), BF based on a training signal, which can be considered as a temporal reference beamformer (TRB), and signal-structure-based beamformer (SSBF), which exploit the temporal and/or spectral properties of the received signals. In the mobile scenario, a DOB requires AoA tracking and a TRB uses adaptive algorithms such least mean squares (LMS), recursive least squares (RLS) or direct matrix inversion (DMI) algorithm.

A BF with M antenna elements can create $M-1$ nulls in the direction of the interference source or achieve M-fold diversity gain. The effectiveness of intersymbol interference (ISI) cancellation in a spatial domain is very limited. An SA with spatial-only domain processing can cancel $(M-1)/2$ symbols with a TRB or cancel $M-1$ signals over any delay with the DOB. There always should be a tradeoff between an improvement in signal-to-noise ratio (SNR), CCI reduction, spatial diversity gain, and ISI cancellation. Since it is possible to cancel ISI by spatial-domain-only processing, a ST filter can be built.

BF's 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 generate nulls in the antenna pattern in the direction of interference. The simplest form of a data-independent BF is the conventional beamformer (CBF), which steers a single beam in the direction of the desired signal, assuming the source of the signal has zero spread and no multipath and interference. The optimization procedure is included in statistically optimum BF algorithms. A statistically optimum BF produces a beam pattern based on the data received by the array. In a statistically optimum BF, the pattern is adapted to minimize cost function, which is associated with the quality of the signal. The TRB and SSBF are statistically optimal. Very often, statistically optimum BF's include in their structure data-independent BF's. The well-known generalized sidelobe canceller (GSC) minimum variance distortionless response (MVDR) are BF's, which include this combination. Many of SSBF blind beamforming methods consider temporal properties of signal in their cost function.

One of the simplest, but sometimes effective, solutions is the switched-beam SA when the SA selects the best one of several fixed beams from the predefined sets of weights.

BF performance varies according to propagation, the interference environment, and also depends on the user's 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.

1) Direction of Arrival-Based Beamforming: In the DOB, it is assumed that the angular spread of the received signals is relatively small. There are three main types of optimum DOB's: BF's based on SINR maximization, ML, and minimum mean square error (MMSE) criteria. Another group of DOB's is data-independent BF's. 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. Loosely speaking, DOB performance depends on the ratio between signal angular spread and M. The level of CCI suppression very much depends on the angular distribution of the interfering and desired signals. One of the main advantages of the DOB is that AoA estimated at the uplink can be directly translated to the downlink in systems with frequency division duplexing (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's. 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) Temporal Reference-Based Beamforming: Beamforming based on training signal or time reference beamforming is a computationally effective method at the expense of spectrum efficiency. Spatial information such as an AoA or array manifold are not necessary. Depending on the particular system and/or scenario used, the reference signal may consists of an *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.

The adaptive algorithms LMS and RLS, or the DMI algorithm are used for tracking, and are explicitly discussed in [2]–[4]. The TRB overcomes interference by nulling its spatial signatures and shows greater robustness in the mobile environment where channel characteristics are continuously varying. Colored training sequences in global system for mobile communications (GSM) and a user-dedicated pilot in universal mobile telecommunication system (UMTS) can be used as reference signal.

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

In a noncoherent multipath, both the 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 the DOB, the TRB techniques require accurate synchronization and to achieve the best performance when the delay spread is low.

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

3) Signal-structure-Based Beamforming: In signal-structure-based beamforming, adaptive processors exploit temporal and/or spectral structures and properties of the received signal to construct a BF. Many SSBF's attempt to restore the signal property, which can be, for example, a constant modulus (CM) for several modulation schemes or finite alphabet property of digital signals. This blind BF method is very robust against different propagation conditions, but its convergence and capture characteristics can be problematic.

4) Beamforming in CDMA Systems: The BF in CDMA can be implemented as a narrow-band BF assuming narrow-band propagation model or as a wide-band BF that can be considered as an ST filter. ST filtering in CDMA will be discussed later.

The BF structure and method of AoA estimation for CDMA systems can be different from narrow band [3], [5], [6]. Among the proposed BF's are the switched-beam approach, methods based on AoA estimation with superresolution algorithms, and eigenfilter techniques, which optimize SINR according to the largest eigenvalue of correlation matrix. Eigenfilter methods are more preferable in urban communication channels with highly correlated multipath.

Training-signal-based beamforming techniques can be successfully used in CDMA systems where a pilot symbol is available.

The code-filtering approach proposed [7] for CDMA is an SSBF technique, which exploits the spectral property of the received wide-band signals. Another version of a multitarget SSBF [8] combines information of the spreading signal and the CM property of the signal in adaptation of the weight vector.

A CDMA BF can be implemented before (chip-level BF) or after despreader (symbol-level BF). If a spatial filter followed after a despreader, the M despreaders will be required.

B. ST Processing

Processing in the 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 optimization method, there are two types of nonblind ST receivers: ST maximum likelihood sequence estimation (MLSE) and ST MMSE. A combination of these methods is also proposed.

Techniques of ST channel estimation are classified into nonblind techniques, which use training signals, and blind methods. Blind methods can be based on spatial and temporal signal structures. Signal structures, such as CM envelope of continuous phase modulated signals, and finite the alphabet property of all digitally modulated signals can be exploit.

ST processing algorithms can be further extended to ST optimum MU algorithms and further to ST joint MU receiver–transmitter algorithms [9].

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

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.

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

2) 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 an ST filter followed by scalar MLSE where a space ST filter 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 propagation model show that ST MMSE outperforms ST MLSE for low carrier-to-interference ratio (CIR) and the situation is opposite for higher CIR. The mixed solution outperforms ST MLSE at low CIR.

3) ST Processing in CDMA Systems: The ST receiver structure and algorithms for CDMA have several well-marked differences. In a 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.

Wide-band ST filter usually includes a tap delay line (TDL) structure at each branch of broad-band array. The TDL allows each element to have a frequency response, which varies with frequency. An MMSE chip equalizer can null out $M-1$ users and effective in the systems with small processing gain when interference is spatially and temporally colored. Good performance can be achieved with matched filter approach when MAI is spatially and temporally white in systems with large processing gain.

The most practical implementation of the ST receiver for CDMA is the suboptimal two–dimensional (2-D) RAKE receiver where the MMSE BF or BF 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 optimized to achieve improved coverage or capacity by reducing intercell 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 uplinks and downlinks 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.

TABLE I
APPLICABILITY OF SA RECEIVERS STRUCTURES AND ALGORITHMS IN MACROCELL AND MICROCELL

Cell type	Spatial domain-only processing	Space - Time Processing
TDMA		
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 Large processing gain – matched filter approach
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 Large processing gain – matched filter approach

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

C. SA in MIMO Systems

Enormous capacity of MIMO channel can be achieved with ST coding or/and layered ST system architecture [12], [13]. These techniques are based on the combinations of transmit diversity techniques, new coding methods, beamforming, and interference cancellation. Combinations of ST coding with orthogonal frequency-division duplexing (OFDM), CCI cancellation methods, ML decoding, and beamforming are proposed.

Further improvements can be obtained when SA are used at the receivers and the transmitters of an MIMO system simultaneously. In this case, the problem of channel estimation is combined with the optimum partitioning of the MIMO channel in the ST domain.

D. Integration of SA Receiver into Radio Networks

Before making decision about the 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 I gives an idea about the applicability of different types of SA receivers 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, i.e., time-division multiple access (TDMA) and CDMA, are considered.

In a microcell, TRB's are better fit for a rich multipath environment. An SSBF can be used if a proper reference signal is difficult to obtain. The 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, a downlink BF should use more complex methods. In time-division duplexing (TDD), the 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 the TRB [4].

For a macrocell, the DOB is a feasible solution; however, it may be reasonable to make a final choice between the DOB and TRB based on an angular spread to the M ratio. A downlink BF can use information at the uplink and some degree of freedom of an 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 the TRB and DOB. They can be roughly estimated as the ratio between the user's distance to the BS and wavelength. This ratio in a macrocell can be very high and it gives a certain advantage for the 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 a large angular spread.

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

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

The 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. The ST MMSE can be a better choice for fast moving users. A mixed solution based on the STF and MLSE can be used since this approach performs better than the ST MLSE at low CIR.

The 2-D RAKE ST receiver, which consists of an MMSE TRB, is one of the most applicable solution for macrocells and microcells. If MAI can be considered as spatially and temporally white in systems with large processing gain, the matched filter approach can be the most reasonable choice for the CDMA network.

III. Radio Network Planning with SA

Different GSM radio network planing concepts with an SA were introduced in [15]. High sensitivity reception (HSR) utilizes the SA at the uplink to increase sensitivity of the system. This approach is proposed for coverage planning and requires further evaluation of the uplinks' and downlinks' budget balances.

Spatial filtering for interference reduction (SFIR) simultaneously exploits the SA at the uplinks and downlinks and, in addition to range, it increases capacity. In SFIR, the SA reduces the level of CCI by spatially selective transmission, 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 analyzed in [15]. The SDMA concept has been evaluated in many publications, taking into considerations SA receiver types [16], radio network control algorithms [17], and users' mobility [18]. The minimum reuse distance between points in signals constellation in a TRB and minimum angular separations for the 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 for the introduction of the power classes concept [15]. The need to upgrade resource management and handover (HO) 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 influence 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 the SFIR operation has been proposed with estimated capacity gain of about 200%. The required CIR gain for successful SFIR operation is estimated to be in the order of 6 dB.

To avoid beams collision in SFIR operation, intelligent intracell HO or random frequency hopping should be used. In SFIR operation, the TRB can exploit cell-specific color codes. In SDMA operation, there is a need to introduce color codes for each SDMA traffic channel to identify users. Color 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 polarization domain, which provides uncorrelated signals, is sufficient.

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

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

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 downlink CIR improvements due to the gradual introduction of the SA into existing GSM/DCS networks were analyzed by simulation [22], and it was shown that even a few BS's with an SA could considerably improve network quality.

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

UMTS network planning tool development with an 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 the SA is considered as omnidirectional with a statistically added link gain. SA-related signaling overhead and economical issues will be further analyzed in this project together with network planning and system performance evaluation. Some economical issues related to network planning with an 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 was mentioned above, the SA receiver with a 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 the SA [28], which is especially important for CDMA network planning.

IV. 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 the 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 HO procedure upgrade in CDMA. To obtain a full profit from the SA features in CDMA, the resource management procedure has to be modified.

The log-in procedure, HO signaling, and 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, 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 HO procedure with an SA is one of the most complex in GSM, it will require numerous changes. Two solutions were proposed: one is a location-aware HO, and another is a transition between channels through a 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 the mobile station (MS) location obtained with the SA is to be further utilized in the upper layers.

Avoiding beams collision in SFIR and SDMA can be a part of network control. Color codes and intracell HO 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 an SA, which will require considerable research efforts. Physical link control algorithms performance and compatibility with the SA are two of them. Performance and dynamic of the PC and SA tracking algorithms, SA algorithm behavior during acquisition, and dynamic range are related to these problems. Another problem is resource management with the SA. To solve this problem, optimization of BS assignment, channel allocation, BF's, and PC algorithms at the uplinks 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 an SA, and two previously introduced problems are inherent in it. All these problems have been partly studied in a number of works, but definitely require further evaluation, taking into consideration parameters and protocols of the existing air interfaces.

Performance of the PC and SA tracking algorithms can be treated jointly or separately. In [4], tracking algorithms based on a 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 the IS-54 system in [29]. PC algorithm performance in the IS-95 system with an SA was studied in [30] by simulation. Different PC step sizes, diversity gain, and Doppler shifts were considered in this paper. Diversity gain obtained with an SA and with other methods like polarization or macro diversity can considerably improve PC performance. The performance of SA tracking algorithm and diversity was 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 downlink beamforming and channels allocation in SDMA was evaluated in [32]. The possibilities of CCI reduction by BF optimization were discussed based on nonlinear and linear approaches. It was shown that the linear approach in a BF is computationally cheap and well suited for the channel allocation algorithms, but a nonlinear method yields optimum results.

The increasing spectrum efficiency of a frequency-division duplexing (FDMA) system at the downlink with joint beamforming, channel allocation, and PC algorithms was studied in [33]. Different downlink generalized BF algorithms were evaluated in scenarios very similar to the SFIR and SDMA. Simulation was used to obtain outage probability for different downlink beamforming algorithms and capacity improvement concept combinations. Several algorithms for channel allocation, beamforming, and PC have been proposed. System capacity has been evaluated for different ratios between angular spread in the radio channel and the number of SA elements. Proposed beamforming algorithms can be effectively used at the uplink of direct-sequence CDMA (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 BF's, based on simple beamsteering.

A channel assignment strategy in joint detection CDMA (JD CDMA) with an 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 an algorithm based on the 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 optimization of beamforming, PC, and BS assignment algorithms at the uplink of a DS-CDMA system were studied in [35]. BF's 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 four-element SA compared to a system with omnidirectional antennas and nonoptimized network control. The same problem at the downlink was studied in [36].

Packet radio network performance can be improved by an SA due to a packet capturing effect and nulling other packets during the same time slot. The throughput and delay performance of the ALOHA packet network with an SA were analyzed in [37] with different SA parameters and the length of randomization interval within each slot. Furthermore, this method was extended by a multibeam 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 analyzed in [39]. The performance of a slow frequency-hopping CDMA (FH-CDMA) network with an SA and packet combining was analyzed in the Raleigh fading channel [40]. A random access protocol, i.e., slotted ALOHA, is considered, and synchronous memoryless hopping patterns are assumed. In this paper, it was assumed that the SA employs a RLS TRB algorithm.

V. Existing SA Experimental Systems and Commercially Available Products

System-level field trials, which involve several GSM/DCS BS with an SA, are in the focus of Ericsson–Mannesman cooperation [41], [42]. The system will experience a full commercial traffic load in the near future. In this experiment, SA receivers

TABLE II
LIST OF EXPERIMENTAL SA SYSTEMS AND COMMERCIALLY AVAILABLE PRODUCTS

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:** DOB 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 ->DCS1800		ULA with MUSIC for AoA estimation Tracking with Kalman filtering	SDMA was Studied, based on DECT	[48]
CNET & CSF-THOMPSON (F)	GSM/ DCS1800	10 circular	**Up-link:** DOB based BF Capon , MUSIC for AoA estimation **Down-link:** DOB	SDMA	[49]
Uppsala University (SW)	DCS 1800	10 circular	**Up-link only:** TRB with DMI algorithms	Data traffic from DCS-1800 was used	[50]
Commercially available products					
Metawave (US) Spotlight™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 directly at the RF input at the BS	[52]
ArrayComm "IntelliCell"™ (US)	WLL, PHS, GSM	4	**Up-link:** ESPRIT algorithm Adaptive interference cancellation	First mass market commercial product	[53]

use eight elements, a dual-polarized array SA with DOB at the uplinks and downlinks. Improvements in the carrier-to-noise (C/N) ratio in the order of 4–5 dB for uplinks and downlinks were reported. In rural and urban macrocells, the SA receiver provides an additional 10 and 6 dB, respectively, in the CIR. Based on the experiment, 100%–200% capacity gain is reached, and achievable range extension is determined by 4–5-dB C/N gain, which is equivalent to 50% fewer sites.

Another test bed was built by the international team of Ericsson, Stockholm, Sweden/Research Triangle Park, NC, for study of SA receiver performance for digital-advanced mobile phone service (D AMPS) [43], [44]. The uplink receiver uses space and polarization diversity. The antenna elements has 15 wavelength separations. Two types, i.e., a maximum ratio-combining (MRC) receiver and interference rejection-combining (IRC) receiver, were studied. Combined space and polarization approaches provided 3.5-dB gain in the C/N ratio and, additionally, 5-dB gain with IRC in an interference-limited scenario. The fixed-beam approach was used at the downlink.

A four-element adaptive antenna array (i.e., TRB) test bed with a DMI algorithm was designed by AT&T, Holmdel, NJ [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} bit error rate (BER) in a Raleigh fading environment compare with two-element antenna diversity. This corresponds to a 40% increase in range. It was shown that the SA could maintain 10^{-2} BER when the interference level is near the level of the desired signal with fading rates corresponded to 60 mi/h. The PC performance was studied with a switched-beam SA at the downlink.

NTT DoCoMo, Yokosuka-shi, Japan, is developing an SA experimental system for a third-generation UMTS wide-band CDMA (W-CDMA) network [47]. The 2-D RAKE receiver includes an MMSE BF, 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 HO and other network functions. The first experimental results showed a substantial improvement in average BER with the SA compared to spatial diversity.

Participants of the SUNBEAM (formerly, TSUNAMI) ACTS Project are using an SA test bed designed by Era Technology Ltd., Leatherhead, Surrey, U.K. [48]. AoA is estimated by the MUSIC algorithm and uses Kalman filtering for tracking. The digital enhanced cordless technologies (DECT's) air interface was selected for trials since it can be easily integrated into an SA and allows networking aspect to be neglected. Two independent SDMA channels were supported. The uniform linear array (ULA) consists of eight elements.

An SA prototype of the SDMA system for a GSM/DCS1800 network was developed and tested by Thompson-CSF Communications, Cennevilliers, France, and CNET/France Telecom, Issy les Moulineaux, France [49]. The SA receiver consists of ten elements and a digital BF in the uplink and downlink. 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, Uppsala University, Uppsala, Sweden, and Ericsson Radio Access AB, Stockholm, Sweden, built a ten-element experimental SA [49]. Real traffic data taken from a DCS 1800 network were used, and a 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 same angular position in the presence of CCI [50]. It was possible to maintain error-free transmission with minimum of a 10° angular between desired and interfering signals when $\mathrm{CIR} = -20$ dB.

The SPOTLIGT Metawave Company, Redmond, WA, switched-beam system with 12 beams at the uplinks and downlinks is among the first commercially available products. SPOTLIGT can be installed in CDMA IS-95 and AMPS networks and, according to Metawave, a 30% capacity improvements in IS-95 can be obtained.[1]

Raytheon E-Systems, Fall Church, VA, introduced the “Fully Adaptive Digital Signal Processor System” based on an eight-element SA.[2] It is expected that the SA module can be directly connected to the RF input of the existing BS.

ArrayComm, San Jose, CA, offers a four-element SA for a wireless local loop (WLL) and personal handyphone system (PHS), which is similar to the DECT system in Europe.[3] During field trials that involved GSM protocols, interference mitigation of 20 dB was achieved.

A list of experimental SA systems and commercial products are presented in Table II.

VI. Conclusions

We discussed several system issues that are important for the future radio network design with an SA. The authors believe that SA’s 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 paper. More detailed discussion is needed for SA receiver integration into different types of cells, taking into consideration the air interface specification. ST processing in CDMA requires more explicit discussion. Another important issue, which is not highlighted in this paper, is the implementation of SA receiver algorithms and architectures. Also, different transmit diversity techniques require more detailed discussion.

[1][Online.] Available: http://www.metawave.com/Customers/casestudy.htm

[2][Online]. Available: http://www.raytheon.com/rtis/docs/apd/smtant.htm

[3][Online]. Available: http://www.arraycom.com/products/pindex.shtml

The following conclusions summarize our discussion.

- Proposed SA algorithms are becoming more complex and involve combinations with processing in time domain, multiuser detection, ST coding, and multiple antennas at MS.
- There are number of parameters such as the level of CCI reduction, diversity gain, and SNR, which can be improved with an SA. Some of these parameters can be interdependent and even conflicting. Their importance and tradeoff 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 should always be a reasonable compromise between the amount of information about radio channels in different domains to be exploited at the SA 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, and data transmission speed, and is 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.
- Considerable improvements in the radio network performance with an SA can be achieved by combining different spatial-domain processing techniques like beamforming, spatial diversity, sectorization with temporal-domain processing, and other diversity techniques. Correct and feasible combination can perhaps provide more improvements in system performance than implementation of very complex and sophisticated SA algorithms.
- A network planning concept with SA and site specific network planning tools are needed to be developed.
- Achievable capacity improvements with the SA depend on the penetration level of SA control functions into radio network control. The best performance will be obtained with an integrated approach to radio resource management and spatial processing. Jointly optimum resource management and spatial processing algorithms can be an interesting problem for future research and network design.
- The majority of the experimental SA’s include a spatial diversity receiver as a reference model, which can be an economical solution. Many of the field trials show that SA receivers considerably outperform space diversity receivers.
- Today, experimental and commercially available SA’s are mostly based on very simple algorithms.
- Network coverage and capacity in urban macrocells can at least be doubled with existing SA receivers. To achieve sensible capacity improvements in an urban microcell, more complex SA algorithms, discussed in this paper, are required.
- A software radio will add flexibility to the SA receiver and network control, and perhaps will make them transparent to the air interface.

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