System Aspects of Smart Antennas Technology in Cellular Wireless Communications.

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Abstract: *System aspects of smart antenna (SA) technology in wireless communications such as SA receiver structure and algorithms, wireless network control and network planning are discussed. A classification of SA receivers and their algorithms is given in order to simplify orientation in very large amount of the proposed types. Several radio network planning and upgrading concepts with SA are evaluated. Idea about radio network control functions with SA at the different layers is given.*

1. Introduction

Spatial processing is considered as a “last frontier” in evolution of cellular wireless systems. Air interfaces standards become more “friendly” for SA technology. Expected improvements in microelectronics technology during the next several years, higher processing speed, more effective architecture, possibility to built software radio, give hopes that SA technology will be widely used in the near future. There several SA commercial products currently available on the market.

The main advantages expected with SA are:

- Higher sensitive reception
- Interference cancellation at up-link and down-link
- Mitigation effects of multipath fading

On the system level higher capacity, extended range, improved coverage by “in-filling” dead spots, higher quality of services, lower power consumption at the mobile, improved power control (PC), new services can be expected.

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

During last decade a lot of attention in SA research was paid for different combinations of SA optimisation methods and criteria, channel estimation techniques and receiver structures. One of the main problems in this area - system integration into existing and future cellular networks was not highlighted yet.

SA receiver structure and algorithms, network control and planning are the main cellular system components to be considered (Fig.1). To improve radio network performance with SA, receiver structure and algorithms should be optimised according to the propagation and interference environment, considering expected traffic and users mobility. These parameters can be seen as a product of radio network planing. At the same time, performance and parameters of SA receiver are important for network planning and should be considered in network control. Air interface parameters are very important for SA receiver. Among the most critical parameters are multiple access method, duplexing, reference signal availability, diversity, physical channels structure, modulation format.

2. SA receiver structure and algorithms

SA receivers can be classified as SA receivers with processing in space- only domain and space-time (ST) SA receivers with processing in space and time domain simultaneously. Additional diversity gain for SA receivers can be obtained by using additional polarisation diversity and macro diversity. ST coding approach based on transmit diversity is currently attract extensive research activity. In CDMA systems space domain processing is usually combined with path diversity obtained with RAKE receiver.

Majority of spatial domain only and ST algorithms include optimisation procedure in their structures. The most popular optimisation criteria in spatial domain processing are: direct optimisation to achieve maximum signal interference to noise ratio (SINR), squared function based criteria - minimum mean squared error (MMSE), maximum likelihood (ML) criteria.

ST receivers can use MMSE criteria or maximum likelihood sequence estimation (MLSE). ST multi-user (MU) receivers are proposed. ST MU-MLSE receiver considered as an optimum receiver in the presence of co-channel interference (CCI).

2.1. Spatial domain processing.

Spatial domain-only processing is an effective way to reduce CCI and multiple access interference (MAI) in CDMA system. Beamformer (BF) with *M* antenna elements can create *M-1* nulls in the direction of interferes or achieve *M*-fold diversity gain. Ability of inter-symbol interference (ISI) cancellation in spatial domain is very limited. Beamformer can cancel ISI coming from M-1 direction.

Amount of antenna elements defines the spatial selectivity of BF.

Beamformer can be built at the RF, IF or at the baseband.

According to the side information available for BF , they can be classified as BF based on spatial structure e.g. (AoA) of the incoming signal - direction of arrival based beamformer (DOB), BF based on training signals, which can be also considered as temporal reference BF (TRB), and signal structure based BF (SSBF) which exploit received signals temporal and/or spectral properties. In mobile scenario DOB requires AoA tracking and TRB requires adaptive algorithms such as well-known LMS, RLS, DMI.

Beamformers also can be also classified as data independent and statistically optimum [1]. Data independent DOB steers antenna beam toward desired signal direction and/or nulls of antenna pattern in the directions of interference. The simplest form of data independent BF is conventional BF (CBF), which steers single beam in the direction of desired signal, assuming source of signal with zero spread and absence of multipath and interference. Optimisation procedures based on the criteria discussed before is included in statistically optimum BF algorithms. Very often statistically optimum BF consists of also data independent beamformer. Well known Genralized Sidelobe Canceller (GSC), MVDR are the beamformers, which include this combination.

One of the simplest, but sometime effective solution, is a switched beam approach when SA selects the best one or several fixed beams.

DOB requires estimation of AoA and precise knowledge about array manifold and calibration. This technique is more analytically tractable but could not perform well in multipath. AoA estimation step may require Egendecomposition and one or more multidimensional non-linear optimisation. It also requires that number of signal wavefronts include CCI will be less than number of antenna elements. Explicit overview of AoA estimation methods can be found in [2].

One of the important advantages of DOB is that the information about AoA at the uplink can be directly translated for the downlink beamforming in the systems with frequency division duplexing (FDD).

In TRB knowledge of array manifold is not necessary and it requires training signals assigned for the each user. Instead of calibration in DOB, the TRB techniques require accurate synchronisation and achieve best performance when delay spread is low. Unlike DOB there are no means of obtaining a transmitting weight vector with TRB from the information provided at the receiver in FDD.

TRB requires prior carrier and symbol recovery. Training signals consumes spectrum efficiency and can be not available in some types of air interfaces.

Reference signal may consist of a priori known signal multiplexed in frequency or in time with useful signal or a reconstructed signal obtained from the detected symbols. The second approach is more attractive from tracking point but the beamforming and detection is more interdependent.

TRB overcomes interference by nulling its spatial signatures and shows greater robustness in the mobile environments where channel characteristics are continuously varying.

Time reference also can be used for optimum combining [14]. In this case antenna element spacing can be very large to achieve better diversity gain and antenna diagram can be meaningless.

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

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

Wideband beamforming

Wideband beamforming realisations and methods of AoA estimation are different from narrowband and discussed more detailed in [3,5,6]. Among the proposed wideband BF are switched- beam approach, methods based on AoA estimation with superresolution algorithms, Eigenfilter techniques.

Training signal based BF also can be successfully used in MMSE wideband beamforming.

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

2.2. Space-time processing

Processing in temporal domain add temporal diversity and ISI reduction to spatial processing. ST processing can constructively combine strength of spatial (CCI mitigation) and temporal (temporal diversity) methods.

In ST processing channel estimation techniques are classified into non-blind techniques, which use training signals and blind methods. Blind methods can be based on spatial and temporal signal structures. Such temporal signal structure as CM , FA property of all digitally modulated signals can be exploit.

ST-MLSE method

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

ST-MMSE method

ST-MMSE [10,11] does not need CCI statistics and treats Doppler spread more effectively. Several well-studied blind algorithms can be applicable. 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 was proposed and it is based on ST filter followed by scalar MLSE where space space-time filter (STF) suppresses CCI while capturing spatial diversity and scalar MLSE removes residual ISI and captures temporal diversity.

Wideband space-time processing

The most practical implementation of ST receiver in CDMA is 2D-RAKE receiver where MMSE beamformer or beamformer based on code-filtering [7] for each path is followed by conventional RAKE receiver. ST-RAKE reduces MAI and thus improves coverage and capacity. Such a receiver structure has an additional degree of freedom and can be optimised to achieve improved coverage or capacity by reducing inter- or intracell CCI by beamforming. MU-ST-MLSE for CDMA was proposed in [9] but practical implementation can be extremely complex.

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 lower angle spread. Also in CDMA systems the SA receiver is less sensitive to channel estimation errors [10,11]. However, beam pattern optimisation is more complex.

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

Further improvements in spatial and ST processing can be obtained when SA are simultaneously used at the receiver and the transmitter. In this case, the problem of channel estimation is combined with search of the optimum radio channels in ST domains.

3. Radio Network Planning with SA

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

Spatial filtering for interference reduction (SFIR) exploits SA at the up and down links simultaneously and in addition to range it increases capacity. In SFIR SA reduces the level of CCI by spatially selective transmission and makes possible tighter channel reuse this way increases capacity.

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

HSR concept should be considered in the network coverage planning. SFIR concept impacts capacity and interference planning. Further network update from SFIR to SDMA does not alert network planning and only increases network control complexity. It possible to go even further and combine SFIR and SDMA operation but system complexity expected to be very high in this case.

It was proposed [4] reuse factor $K=1/3$ for SFIR operation and estimated capacity gain in order of 200%. The required CIR gain for successful SFIR operation estimated to be in order of 6dB.

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

Spectrum efficiency of sectorisation and SA concepts is evaluated in [15]. It was shown that there is a full computability between sectorisation and SA. It pointed out that pushing sectorisation to far will limit additional gain provided by SA. The choice of 3 or 4 sectors equipped with SA might be considered as a reasonable compromise.

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

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

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

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

CDMA network simulation tool with SA was introduced in [12]. This tool includes deterministic propagation model and can be used in network planning. With this tool it is possible to study performance of radio network control algorithms (handover, admission control, resource management) with SA.

Some economical issues related to the network planning with SA were discussed in [27].

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

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

4. Radio Network Control with SA

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

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

Several concepts of broadcast channels control with SA are proposed. In [13] it was introduced a revolving beam concept for GSM/DCS. In [41] control of CDMA pilot channel by SA is discussed.

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

There are several complex and important problems in the radio network control with SA, which will require considerable research efforts. Physical link control algorithms performance and compatibility with SA is the one of them. Performance and dynamic of PC and SA tracking algorithms, SA algorithms behaviour during acquisition , dynamic range are related to this problem. Another problem is resource management with SA. To solve this problem optimisation of BS assignment, channel allocation, BF and PC algorithms at the up- and downlink are required and should be done in dynamic fashion. Efficient solution of this problem can provide considerable benefits for operators.

Performance of the power control (PC) and SA tracking algorithms were studied in the number of publications. In [4] algorithms based on combination of Kalman filtering with ML methods were discussed. Performance of two signal tracking algorithms - LMS and DMI were evaluated with different data to fade rates for IS-54 system in [29]. PC algorithm performance in IS-95 system with SA was studied in [30] by simulation. Different PC step sizes, diversity gain and Doppler shifts were considered in this work. Diversity gain obtained with SA and with other methods like polarisation or macro diversity can considerably improve PC performance.

Performance of AoA tracking algorithm and diversity was discussed in [31].

Problem of joint optimal spatial processing, PC, BS assignment and resource allocation are among the most interesting and attractive for the research. Several works have been published in this area.

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

Spectrum efficiency improvements in GSM like system at the down-link were studied in [33] with algorithms based on the joint beamforming, channels allocation and PC. Different down-link generalised BF algorithms were evaluated in scenarios which very much resemble SFIR and SDMA concepts. Values of outage probability were obtained. Several algorithms for channel allocation, beamforming and PC were proposed. System capacity was also evaluated for the different ratios between angular spread in radio channel and amount of SA elements. Proposed beamforming algorithms can be effectively used at the up-link of DS-CDMA. BF algorithm based on interference nulling gave improvements in outage probability three times larger than BF based on simple beamsteering.

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

Joint optimisation of beamforming, PC and BS assignment algorithms at the up-link of DS-CDMA system were studied in [35]. BF based on CIR maximisation and distributed PC control were considered. CDMA system capacity improvement was evaluated by simulations and it was roughly estimated that system it can be 4-5 times higher with proposed algorithm and 4 elements SA The same problem at the down-link was studied in [36].

SA can improve packet radio network performance due to the packet capturing effect and nulling other packets during the same time slot. The throughput and delay performance of ALOHA packet network with SA was analysed in [37] with different SA and lengths of the randomisation intervals within each slot. Furthermore, this method was extended to multi-beam SA case to be able successfully receive several overlapping packets at the same time [38].

Throughput of the radio networks with slotted non-persistent carrier sense multiple access (CSMA) method and SA with TRB was analysed in [39]. Performance of slow frequency FH-CDMA network with SA (RLS adaptive TRB algorithm) and packet combining was analysed in Raleigh fading channel [40]. Random access protocol based on slotted ALOHA is considered, and synchronous memoryless hopping patterns was assumed.

There are number of experimental systems with SA, which include several BS. Ericsson carrying out SA system integration studies into GSM/DCS network [42,43] and NTT DoCoMo is studying SA in W-CDMA network [44].

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