

NEXWAY White Paper: Reconfigurable Antenna for Future Wireless Communication Systems

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Abstract— This paper deals with the processing techniques that are known as reconfigurable antennas: these methods are foreseen to be a booster for the future high rate wireless communications, also for the capacity gain which is afforded. Main antenna processing techniques are reviewed and described, aiming to highlight performance / complexity trade-offs and how they could implement in the future systems. The coexistence of all these different technologies in a wireless environment requires high efficiency and flexibility of the transreceiver. Future transreceiver implementation based on the Software Defined Radio technology are also described.

Index Terms— Radio Channel, Smart Antennas, Adaptive Beamforming, Estimation of the Direction of Arrival, Antenna Diversity, Spatial Filtering, MIMO Techniques, Space-Time Coding, Space Time Coded Modulation, Space Time Block Codes, BLAST, Iterative MUD, Software Radio Terminal, Hardware Architecture, Remote Terminal Configuration

I. INTRODUCTION

Future high data rate wireless access claims for a dramatic transmission rate increase, with the same bandwidth occupation. This challenging goal can be achieved by multiple antennas systems: theoretical studies show that the bandwidth efficiency/hertz/s can be increased linearly according to the transmitting /receiving antennas number.

From a propagation point of view, MIMO (Multiple-Input Multiple-Output) antenna systems can also be used to reduce the channel impairments and the multipath effects: thanks to the spatial diversity, signals affected by independent fading can be jointly combined in order to reduce the probability of deep attenuation.

As a result, adaptive/reconfigurable antenna array systems are currently thoroughly studied: as it is known, in the adaptive array the main lobe can be steered to the desired signal, also aiming to cancel the interference signals coming from the other directions plus the noise. On the antenna array output, adaptive digital signal processing algorithms and evaluation algorithms of the direction of arrival can provide the required performance for the desired signal in terms of BER or SNR.

Beyond this traditional approach, the Space-Time (ST) processing can be used to further improve the system capacity, the coverage and the receiving quality; moreover,

it can be applied to the emerging technologies: advanced transmitting and receiving techniques, like multiple antennas or advanced receivers can be used to reduce the interference.

Space-time coding schemes offer spatial (space) and temporal (time) diversity, and they are designed to exploit the increased potential capacity of multi-antenna systems. Therefore, they offer increased bandwidth efficiency proportional to the number of antenna. These techniques can be successfully coupled with OFDM systems and advanced WCDMA receivers.

For what concerns the multiuser MIMO systems, some recent studies showed that it is possible to exploit a rich scattering wireless channel to separate users and, as a consequence, reduce the MAI. Moreover, a multiuser scheme with one antenna per user and an antenna array at the BS can be regarded as a MIMO single user system; therefore, we can state that near capacity-limit performance are achievable using both MUD and spatial diversity, even for heavily loaded systems.

The coexistence of all these different technologies in a wireless environment requires high efficiency and flexibility of transmitter and receiver (transreceiver). The solution is to realize the future transreceiver with the Software Radio (or Software Defined Radio) technology, also for multiple antenna arrays. This guarantee a complete reconfigurability of all the system. This specific research activity focuses on the design of a HW architecture able to perform the cited functions and on the definition of a radio definition macro-language which is able to represent remotely all the signal processing functions required in the terminal.

II. RADIO CHANNEL CHARACTERIZATION

The propagation of radio signals through a physical channel is vulnerable to free space propagation loss (path loss) and fluctuations in signal level called fading [1], [2], [3]. Fading includes long-term and short-term variations. Long-term variations are caused by shadowing effects due to energy absorbing objects along the propagation path. The short-term varying fading corresponds to rapid fluctuations of the received signal caused by relative movements of the

transmitter and the receiver with respect to surrounding scatterers. This multipath propagation results in spreading of the signal in three different dimensions - delay (or time) spread, Doppler (or frequency) spread, and angular spread. Spread in the delay domain appears in frequency selective channels and causes inter-symbol interference (ISI) at a receiver. A frequency selective channel can be characterized by the coherence bandwidth, the maximum frequency separation for which the frequency-domain channel responses at two separate frequencies remain strongly correlated. Relative motion between the transmitter and receiver causes the Doppler spread, i.e., a pure tone is spread over a finite frequency band. Approximately inversely proportional to the Doppler spread, the coherence time represents a time separation for which the channel impulse responses at two time instances remain strongly correlated.

Angular spread is caused by a spatially-selective channel and refers to the distribution of angle-of-arrival (AOA) of the multipaths at the receiver, and the angle-of-departure (AOD) at the transmitter.

For a deeper insight on the radio propagation aspects and statistical modelling of multidimensional fading channels the reader is referred to [1] → [17].

III. SPATIAL FILTERING

Spatial filtering or beamforming can be applied to benefit from the angular spread and commonly different spatial signatures of the desired and interfering signals. Spatial filtering is achieved by the complex coefficient weighting and combining of signals induced on different spatially correlated antennas to form a single output of an array. For the given set of complex antenna weights, the direction in which the array has the maximum gain is typically called the beam pointing direction. The main advantage of applying beamforming in reception comes from the reduced co-channel interference CCI (filtering the desired from interfering users), ISI suppression (nulling the delayed signals arriving from directions other than the strongest one), and angular diversity (forming multiple beams and coherently combining the spatially filtered multipath components from different dominant scatterers). Similarly, in transmission, the energy can be spatially steered towards the desired user while minimizing the interference towards other users and the spatial pre-equalization can be applied so that signals coherently combine without ISI at a MS. Angular diversity gain becomes rather limited in the case of small angular spread where adjacent beams typically have received signal levels more than 10 dB weaker than the strongest beam. For accurate spatial filtering in reception and transmission, AOA and AOD estimation are required respectively for calculating the set of complex antenna weights. Therefore, transmit beamforming inherently falls into the group of closed loop transmission schemes. In reciprocal channels, where AOA and AOD coincide, the estimated weights during the reception period are reused

during the transmission period. A TDD system with a duplexing period smaller than the coherence time is a typical example where channel reciprocity holds. In nonreciprocal channels, a feedback channel is required for calculating optimal antenna weights for transmission. Furthermore, the antenna weights can be either fixed or calculated in an adaptive fashion according to some optimization criterion, i.e., maximization of the signal-to-interference-plus-noise-ratio (SINR). Adaptive beamforming and AOA (AOD) estimation are commonly regarded as traditional array or space-only processing techniques. Temporal or time-only processing techniques employ adaptive equalizers to offer time domain CCI suppression and reduced ISI by complex coefficient weighting and combining of the temporally sampled signals. Space-time processing or smart antenna technology is loosely defined as any combination of space-only and time-only processing. It allows the advantages to be simultaneously exploited in both dimensions improving the different aspects in the performance of a radio communication system including system capacity, coverage, reduction in hand-off rate, quality of service in terms of throughput and probability of outage etc. For a comprehensive overview of the ST processing area see [4], [10], [18] → [29]. As for the system capacity, a two-fold increase by employing ST processing is possible; an indirect increase through increase in the link capacity and a direct increase by allowing users in a given cell to share the same time/frequency and code resources based of their physical location or spatial separation. The latter benefit known as spatial-division multiple-access (SDMA) has attracted considerable attention in the recent past as it can be further coupled with any of the existing multiple-access methods [10], [30] → [33].

IV. SMART ANTENNAS

In the SDMA (Space Division Multiple Access) the radiation pattern of the antenna system at the base station should be dynamically modified by steering the main beam toward the desired user and placing the nulls in the pattern corresponding to the interference directions (null steering method).

In personal communication systems, this approach can be implemented by using adaptive antenna array to shape the radiation pattern.

The antenna array provides a greater receiving gain than an omnidirectional antenna, allowing to transmit with a lower power level and to reduce electromagnetic pollution levels. The SDMA techniques can increase the overall number of users which access the system: in fact, the Spatial orthogonality allows to separate the signals from different users even if they are overlapped in the frequency/time domain (FDMA/TDMA techniques) increasing the spectral efficiency.

In the case of CDMA access where all the users share the same channel and each user has a different pseudonoise

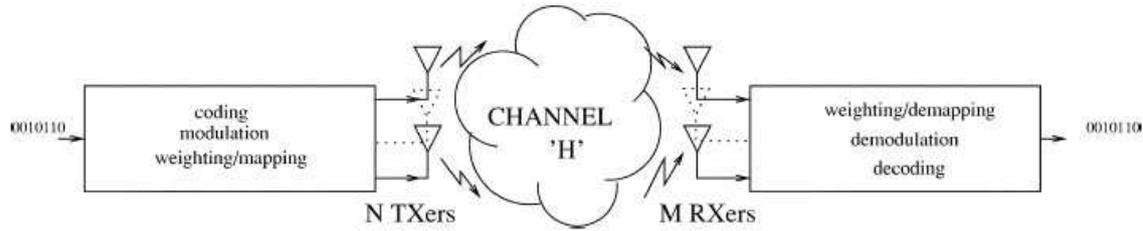


Fig. 1. MIMO wireless transmission system generic scheme. The transmitter and receiver are equipped with multiple antenna elements. Coding, modulation, and mapping of the signals onto the antennas may be realized jointly or separately.

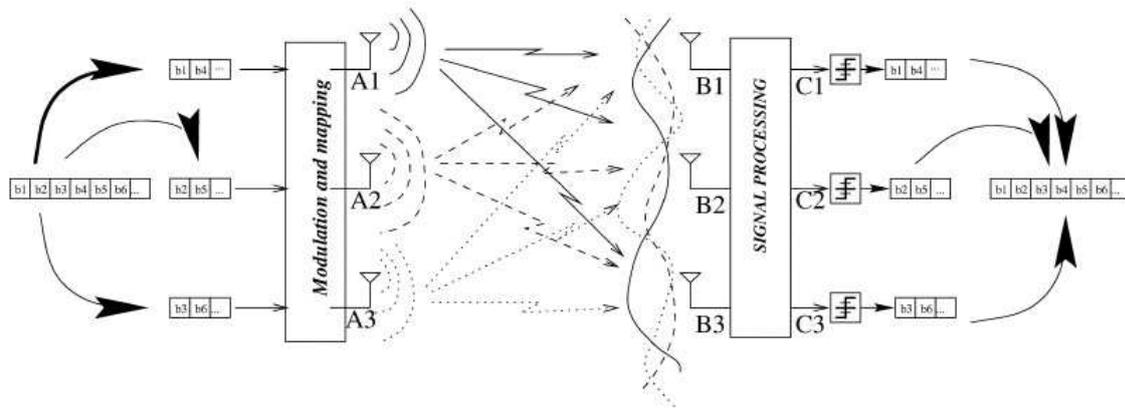


Fig. 2. Basic spatial multiplexing scheme.

code, the use of smart antennas improves the signal-to-interference ratios allowing to reduce the MAI.

A. Adaptive Beamforming

In a space diversity system the weighed sum of the received signals is combined at the output of beamformer to steer a beam toward the user signal and adjust the nulls to reject interference.

Different kinds of algorithms are possible with a different degree of complexity:

- Based on Direction of Arrival (DOA) estimation: if the direction of the desired user is known, the beamformer tries to minimize the output power constrained to maintain a distortionless response in the direction of interest (Minimum Variance Distortionless Response-MVDR). This method strongly depends on the spatial information knowledge (e.g. MUSIC,ESPRIT), is computationally expensive, and the number of users is limited by the number of antenna elements.
- Based on training sequence: the beamformer employs a training sequence to minimize the difference between the training sequence and its output in the mean-square sense (MMSE). The use of a training sequence reduces the system capacity.
- Blind methods (Constant Modulus-CMA): it works on the assumption that the interference and multipath

cause distortion on the amplitude of array output which has a constant modulus. It is only effective for constant modulated envelope signals such as GMSK and QPSK.

B. Estimation of the Direction of Arrival

The Direction of Arrival (DOA) correct estimation is particularly useful when the transmission is meant to be received only by the desired user, reducing the interference and allowing a lower level of electromagnetic pollution, or when the position of a mobile user is to be determined for emergency services. Conventional DOA methods use the eigenvectors decomposition and are based on the assumption that the number of antenna elements is greater than the number of impinging signals (users and replicas). Therefore, these algorithms are not suitable in multiuser environment with multipath channel.

In multiuser systems where each user is identified by an unique code, an optimized approach requires a DOA estimator (MUSIC or Iterative-MUSIC) which is implemented for each replica of each user [34]: in this case only one peak of MUSIC spectrum is estimated at a time, providing a high reliability in DOA estimate values with no influence from the effect of multiple paths at a cost of a complexity increases.

V. ANTENNA DIVERSITY

Antenna diversity includes spatial, polarization, and angular diversity. For spatial diversity, antennas in the array need to be separated by more than the coherence distance to obtain a low fading correlation (correlation factor must be ≤ 0.7). With the mobile station (MS) generally placed low below rooftops and surrounded by scatterers, the angular spread is typically uniformly distributed and so that an antenna spacing equal to $\lambda/4$ (where λ is the wavelength) results to be enough. This relation also holds for base stations (BSs) in indoor and microcell environments where antennas are usually mounted at the same height as the surrounding objects. For outdoor and macrocell environments, BSs are typically deployed in isolated spots high above rooftops. Therefore, the angular spread may be only a few degrees in rural areas and somewhat higher in urban areas. A horizontal separation of 10-20 \circ between antenna elements is commonly needed to secure low spatial correlation.

Due to the different size, weight, and power constraint, spatial diversity is more suitable for BSs than for an MS and as such have been commercially used for many years in conjunction with selection combining, maximum ratio combining, or equal gain combining as a receive diversity method in the up-link. The knowledge of the complex channel phase (equal gain combining) and/or amplitude (maximum ratio combining/selection combining) is typically needed to utilize receive diversity.

Transmit Diversity has recently received considerable attention as a cost effective way to employ spatial diversity in the downlink of cellular systems. The Transmit Diversity methods can be characterized as either closed loop or open loop depending on whether the transmitter is provided with some prior knowledge of the channel.

Polarization diversity uses the horizontal and vertical polarization of electromagnetic waves to theoretically double the antenna diversity order without the need for adding new antenna elements [35]. In practice, polarization diversity is better suited for indoor and microcell environments since for high BS antennas, the horizontal polarization can be typically 6-8 dB weaker than the vertical polarization resulting in reduced effective diversity gain. In indoor/short-range communications, the use of non-isotropic antennas can lead performance degradation due to the asymmetric orientation between Tx and Rx antenna. This problem can be easily faced by using polarization transmit diversity [36].

VI. MIMO TECHNIQUES

Multiple antennas at the transmitter and receiver provide diversity in a fading environment. By employing multiple antennas, multiple spatial channels are created, so that it will be unlikely that all the channel will fade simultaneously. If the statistical decorrelation among antenna elements is realized, the multiple transmit and receive antennas can create independent parallel channels.

In rich scattering environments the system capacity can be increased exploiting decorrelation of transmitted signals by using the space-time coded modulation (STCM) and MIMO processing.

Generally speaking, in the STCM approach data is encoded by a space-time channel encoder and the output is split into N streams to be simultaneously transmitted using N transmit antennas. The received signal at each antenna is a linear superposition of the transmitted signals perturbed by flat fading channel and noise. This coding across spatial channels is based on Trellis Coded Modulation (TCM) concepts in order to define symbols to antennas mapping methods. The space-time decoding process at the receiver requires trellis decoding and may have high complexity.

A. Space-Time Coding

In order to exploit the potentially large link capacities of MIMO fading channels, a considerable amount of research has been focused on ST processing for arrays of uncorrelated antennas at both ends of a wireless link. Such ST signalling designs evolved along three main paths characterized by the assumptions of CSI knowledge.

- The first approach comprises the non-coherent, so called differential, or unitary ST coding schemes where neither receiver nor transmitter has Channel State information (CSI) knowledge [37] \rightarrow [44].
- The second method path targeted the signalling schemes that benefit from the channel reciprocity, or the existence of an unlimited capacity feedback channel, where CSI is available at both transceiver ends [45] \rightarrow [48].
- The third technique deals with the design of coherent ST coding schemes optimized on the assumption of no available CSI at a transmitter and estimated CSI at the receiver. The latter allows adaptive implementations where the limited CSI is fed to the transmitter through a typically low capacity feedback channel.

The schemes employing the optimal MLD at a receiver are commonly qualified as the optimal ST coding schemes to distinguish from the sub-optimal ST coding schemes featuring different reduced complexity sub-optimal linear and decision feedback receiver interfaces. Two main categories of optimal ST coding schemes are the STCM and the space-time block codes (STBC).

Originally inspired by the lower bound on MIMO channel capacity, the layered ST coding architectures employing different sub-optimal receivers are an important alternative to the previous transmit diversity schemes.

B. Space Time Coded Modulation

The different proposals for STCMs in the literature, originally designed for simultaneous diversity and coding gains, are mainly based on single antenna coded modulations, i.e., Trellis Coded Modulation (TrCM), multiple TrCM,

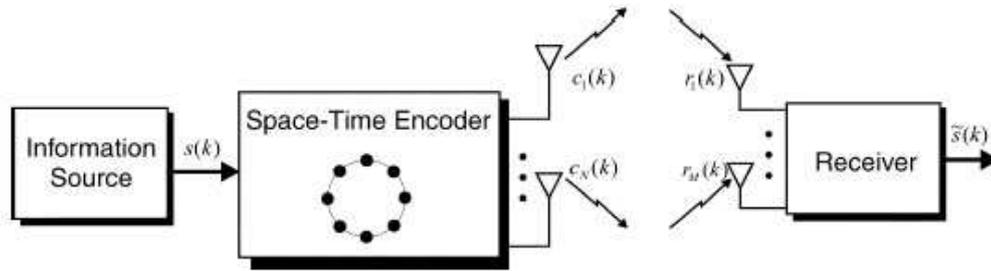


Fig. 3. Space-Time coding generic scheme.

multi-level coded modulation and Bit Interleaved Coded Modulation (BICM).

Owing to its integrated trellis coding and higher order modulation design with the redundancy expansion in both signal and antenna space, space-time trellis codes (STTrCs) [49], also referred to as ST TrCM, can be seen as a generalization of the TrCM to multi-antenna systems. STTrCs evolved from the combined transmit Delay Diversity (DD) and receive Maximum-Likelihood Detection (MLD), originally introduced for two transmit antennas in [50], [51] and further generalized to an arbitrary number of transmit antennas in [52], [53].

The optimization of STTrCs over quasi-static fading channels for the case of a large number of receive antennas or for low SNR values was based just on the trace criterion in [54]. The systematic STTrC design for an arbitrary number of transmit antennas was further studied in [55] based on the rank and determinant criteria. The low constraint-length STTrC optimization for fast fading channels based on the distance and product criterion was considered in [56] → [60].

The extension of multiple TrCM to MIMO systems was further studied in [61]. The extension of multi-level coded modulation to MIMO systems applying sub-optimal multistage decoding was considered in [62]. The multi-antenna BICM was devised in [63], [64] and with iterative MIMO equalization and decoding in [65], [66], [67]. Multiantenna block coded modulation was considered in [68]. The performance evaluation of STTrCs with different types of equalizers at a receiver for the SC based systems over frequency selective fading channels was investigated in [69] → [73] including iterative MIMO equalization and STTrC decoding in [74], [75]. The optimal STTrC design in the presence of ISI at the receiver was addressed in [76], [77], [78]. The impact of CSI errors to the performance of STTrCs was inspected in [79] and iterative CSI estimation and STC decoding in [80] → [83]. The analysis of the probability of an erroneous un-coded modulated transmission over MIMO channels with maximum-likelihood detection and imperfect CSI at the receiver was presented in [84].

C. Space Time Block Codes

Owing to the linear matrix pre-coding at the transmitter that reduces the optimal MLD at the receiver to simple linear combining, STBCs [85] → [88] represent an attractive open loop transmit diversity scheme that satisfies the rank criterion for full transmit diversity over quasi-static fading channels but offers no coding gain over uncoded system with the same diversity order.

A simple transmit diversity scheme for two transmit antennas originally introduced in [89] and in a slightly modified form standardized for third generation cellular systems [90], motivated authors in [85], [86] to generalize such a signalling approach to an arbitrary number of transmit antennas.

The STBCs in combination with maximum ratio combining receive diversity, as common to the majority of transmit diversity schemes, transforms a MIMO fading channel into a SISO channel with characteristics desirably close to Gaussian. Numerous papers have studied the performance and optimization of different single antenna coded modulations employed over such an equivalent SISO channel [91] → [105]. The underlying mathematical framework of orthogonal designs poses restrictions in terms of maximum achievable rates when complex signal constellations are used. The schemes for more than two transmit antennas have a drawback of decreased rate as compared to single transmit antenna systems. In order to preserve the rate in such a case, the diversity order must be compromised with the code orthogonality, i.e., the level of self-interference induced [106], [107].

The adaptation of STBCs to Single Carrier (SC) systems in frequency selective fading channels was studied in [108] → [112]. The channel estimation for STBCs was studied in [113].

D. Layered Space Time-Coding

The complexity of MLD decoding increases exponentially with the transmission rate K (bps/Hz) and the number of transmit antennas N . Despite the recent efforts to reduce such complexity by sub-optimal combining [114], [115], the optimal ST coding designs for full rate MIMO

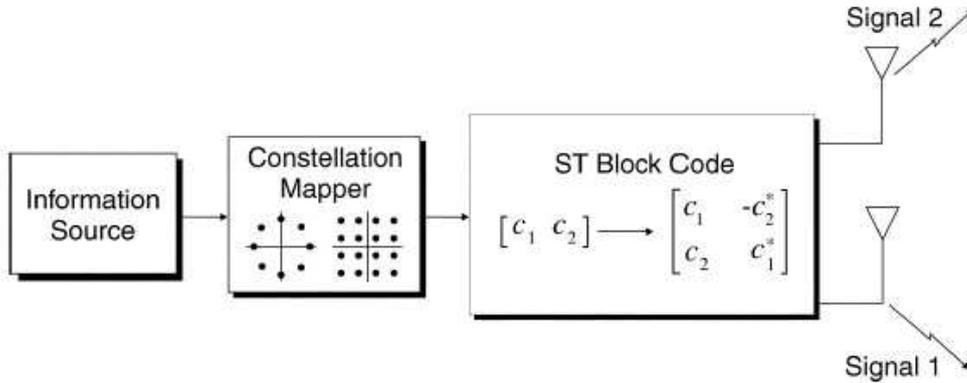


Fig. 4. Space-Time block coding transmitter scheme.

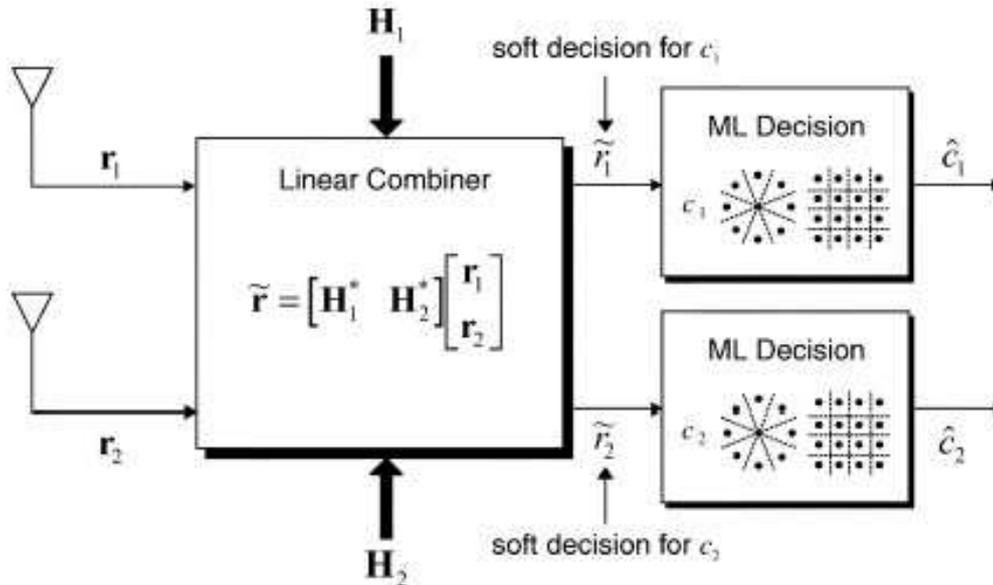


Fig. 5. Space-Time block coding receiver scheme.

transmission, commonly conditioned by $K = N$, are mainly constrained to two transmit antennas.

Inspired by the lower bound on MIMO channel capacity, authors in [116] proposed the Bell Labs Layered Space-Time (BLAST) architecture as a reduced complexity, pragmatic method for achieving high bandwidth efficiencies in systems with a large number of transmit and receive antennas. The Bell Laboratories Layered Space-Time (BLAST) approach achieves spectral efficiencies as high as 40 bits/sec/Hz in short-range, rich scattering wireless environment for a fixed total transmit power. The introduction of BLAST motivated the deep interest for design of different layered space-time (LST) coding architectures that combine spatial multiplexing at the transmitter with different sub-optimal linear and non-linear ST detectors at the receiver to assemble classical single antenna channel codes to MIMO systems.

In spatial multiplexing a single data bit stream is demultiplexed through serial-to-parallel conversion into N data sub-streams, commonly denoted as data layers that are independently interleaved, modulated and transmitted simultaneously from N uncorrelated transmit antennas. In the case of horizontally-LST coding each layer is transmitted only from its own corresponding antenna. The preferred approach from [116], introduced as diagonally-LST coding, assumed an additional cyclic permutation of layers among the transmit antennas. The sub-optimal non-linear detection proposed in [116] assumes successive zero forcing (ZF) or minimum mean square error (MMSE) based interference suppression of layers that are not yet detected combined with decision directed interference cancellation of those layers previously detected.

For SC based systems operating in frequency selective fading channels, temporal equalization can be added to

linear or decision feedback interfaces to combat ISI at the receiver. Different non-linear receivers for LST codes were further studied in [117] → [128]. Spatial multiplexing systems with linear receiver interfaces were examined in [129], [130] and with reduced complexity MLD in [131], [132]. Some of the above papers also include PEP analysis for sub-optimal linear and non-linear detection.

The LST codes can be implemented as horizontally-coded or vertically-coded distinguished by the position of the serial-to-parallel converter before or after a channel encoder, respectively [133] → [136].

The horizontally-coded LST code therefore employs a separate encoder for each of N data layers while in the case of vertically-coded LST code outputs of a single encoder are de-multiplexed to N data layers. The hybrid horizontal-vertical coding that commonly results in a reduced transmission rate was also considered in [133]. A non-linear detector processes the received signal along both the spatial and temporal domain in a manner determined by the employed type of encoding and layering.

The horizontally-coded horizontally-LST coding offers improved decoded based decision directed interference cancellation since in each step of detection, in between the interference suppression and the interference cancellation, decoding of a given layer can take place to reduce error propagation.

For the vertically-coded horizontally-LST codes and vertically-coded diagonally-LST codes decoding can start only after all the layers have been detected. Therefore, interference cancellation is based on row decisions though schemes are expected to benefit from the averaged SINR over successive layers, i.e., spatial interleaving. Vertical-BLAST (VBLAST) relies on spatial multiplexing at the transmit multiple antennas and spatial filtering at the receive multiple antennas. The basic idea is to transmit different signals simultaneously on different antennas and this spatial diversity relies on a rich scattering matrix channel. V-Blast rather than jointly decoding the signals from all the transmit antenna realizes a beamforming in multipath and first decodes the strongest signal, then cancels the effect of this transmit signal from each of the received signals and then proceeds to decode the strongest second signal of the remaining transmit signals. It is evident the analogy with the multiuser sequentially interference cancellation. The drawback of this method can be envisaged in the order for the sequential estimation and cancellation, from the strongest signal to the weakest one, and in the propagation of errors from one step of detection to the next [137].

To retrieve full receiver diversity and further improve the performance for different types of coding and layering the iterative detection and decoding is commonly applied [138], [139], [140]. After the first stage of detection and decoding that comprises both the interference suppression and decision directed interference cancellation, the successive stages employ only the interference cancellation. Hard

or soft decisions from the previous stages are used to cancel the interfering layers enabling the full number of receive antennas to be utilized for diversity reception.

A generalization of LST coding introduced as ZF array processing in [141] and maximum SNR array processing in [142] proposed a pair-wise partitioning of antennas at the transmitter for combined MIMO signal processing and ST decoding at the receiver. Unlike LST codes where spatially multiplexed signals with equal average transmitted power were detected in order of decreased post-detection SNR, i.e., post-ordered detection, the order of detection in [141] and [142] followed the adhoc unequal geometrical or arithmetical power allocation among different pairs of transmitting signals respectively, i.e., pre-ordered detection.

As a conclusion, ST coded modulation and STBC were essentially characterized as optimal with respect to the link reliability while the LST code was identified as optimal with respect to the channel capacity.

E. T-BLAST Architecture

In order to mitigate the degrading effects of CAI, a robust multi-transmit multi-receive system using the combination of Turbo decoding principles and V-BLAST was analyzed in literature [143], [144], called TBLAST. In this section, the use of the simplified iterative interference receiver as in [143], and its performance in the specific context of the IEEE 802.11b standard is underlined. The IEEE 802.11b standard adopts high data rate with bit rates up to 11 Mbps. For achieving data rate greater than 2 Mbps, the IEEE 802.11b standard specifies the Complementary Code Keying (CCK) modulation scheme. The IEEE 802.11b complementary spreading codes have code length 8 and a chip rate of 11 Mchip/s. The 8 complex chips comprise a single symbol. By making the symbol rate 1.375 Msps, the 11 Mbps waveform ends up occupying the same approximate bandwidth as that for the 2 Mbps 802.11b QPSK waveform. Other IEEE 802.11b requirements are:

- o It operates in 2.4GHz-2.4835GHz frequency band
- o Direct Sequence Spread Spectrum (DSSS)
- o Three non-overlapping 22 MHz channels

In the T-BLAST architecture a single data stream is demultiplexed into M substreams, where M is the number of transmitting antennas, and each substream is then encoded into symbols and fed to its respective transmitter. Transmitters 1- M operate in co-channel way at symbol rate with synchronized symbol timing.

It is assumed that the same constellation is used for each substream and that transmissions are organized into bursts of L symbols. The power radiated by each transmitter is proportional to $1/M$, so that the total radiated power is constant and independent of M . A straightforward way to implement coding for V-BLAST is to use the Horizontal Coding architecture.

Each layer is encoded separately. In the horizontal encoder operation each layer uses a Parallel Concatenated

Convolutionally Code (PCCC) Turbo code, but other error correcting codes can also be adopted.

The optimal receiver processing for a coded BLAST system requires a global ML (Maximum Likelihood) solution, which jointly considers the detection (demodulation), deinterleaving and decoding of error correcting codes. However, due to the high complexity of such an approach many suboptimal techniques have been considered, including linear processing techniques such as Zero-Forcing (ZF) or Minimum Mean Square Error (MMSE) method, and non-linear methods such as Ordered Successive Interference Cancellation (OSIC) [144].

The performance of these suboptimal detection methods may be improved through iterative detection and decoding, which utilize the decoding results for a second step of processing.

VII. ITERATIVE MUD FOR WIRELESS MULTIUSER MIMO NETWORKS

The main performance losses for a wireless coded CDMA system are caused by the Multiple Access Interference (MAI) and by the poor capacity of error correction of the turbo codes on the slowly fading channels [145] [146].

For what concerns multiple access systems, practical CDMA communications rely on the utilization of error control coding and interleaving so that, recently, more and more attention has been addressed to the coded systems. Optimal joint decoding/detection is an excellent solution to this problem, as shown in [147]. However, this scheme results in a prohibitive computational complexity for the actual implementations. In contrast, suboptimal solutions, which separate the operations of symbol detection and channel decoding, appears more attractive for the practical applications.

Since the proposal of turbo codes [148], the "Turbo-Principle", i.e., the soft information iterative exchange between receiver constituent blocks, has been foreseen as a possible booster for the Multuser Detection (MUD) schemes: in particular, the attention has been devoted to Parallel Interference Cancellation (PIC) receivers because of their relatively reduced complexity compared to the linear detectors and small delay with respect to serial cancellation.

For what concerns wireless channel drawbacks, a particular attention has to be devoted to the rich-scattering block fading environments, e.g., the indoor communications, and to the detection strategies which are suitable for those systems: in particular, the performance degradation due to the MAI and to the lack of a general coordination between the users, is remarkable in those fading environments.

Antenna diversity at the receiver has been proposed as a low-cost solution to the fading impairments [149] [150]. Furthermore, spatial diversity at the Base-Station (BS) provides an increased signal-to-noise ratio, which

helps to remove more accurately MAI thanks to a better initial estimate of the received signal [151].

Moreover, the recent studies on Multiple Input Multiple Output (MIMO) systems [152] [153] [154] showed that it is possible to exploit a rich scattering wireless channel to separate users and, as a consequence, reduce the MAI.

According to [154] a multiuser CDMA scheme with one antenna per user and antenna array at the BS can be regarded as a MIMO single user system; therefore, we can state that near-capacity-limit performance are achievable using both MUD and spatial diversity [153] [154].

In this section we will describe the utilization of a low complexity iterative receiver, such as the PIC, together with receive diversity permits to completely eliminate MAI even for heavily loaded systems in highly correlated fading channels [156]: particularly, the MUD receiver which has been considered is based on the generalization of a Turbo-PIC detector to a multiple antenna diversity system. It is important to point out that, in the considered working conditions, a general strategy against wireless multiple access drawbacks fails and suitable specific approaches have to be defined.

It is worth stressing that a proper diversity schemes naturally leads to user separation, boosts the convergence of cancellation algorithm and affords remarkable performance to the turbo MUD receivers.

Aiming to keep the required complexity low with no performance loss, the performance results, of a Total PIC (TPIC) and a Modified Weighted PIC (MWPIC) has been compared [156]. The TPIC is a classical one-stage cancellator where all the cancellation weights have been set equal to 1 for all the users. Conversely, the MWPIC device has been introduced to achieve the best performance thanks to the space processing introduction. Antenna diversity helps to obtain a better initial estimate of the received signal; hence, the reconstructed signals can be considered more reliable and cancelled with a higher weight. The weights which are assigned to the cancellation stages are pre-calculated.

The MWPIC outperforms the TPIC in BER performance and has a lower complexity because it needs just one iteration to reach the SU bound.

VIII. SOFTWARE RADIO CONCEPTS

The number of different wireless access techniques for mobile terminals is remarkably increased during the last years. The coexistence of different services and access technologies in the same geographical area promoted the multi-standard terminal concept that has its most complex and challenging aspect in the physical layer software re-configurability.

The flexibility of a terminal in Software Radio technology, consists in the capacity to operate in multi-standard environment, without being forced to replicate hardware

resources. In addition to that it is also ready for modifications in the signal processing structure in order to correct bugs in existing standard implementations and eventually to transform itself into completely new radio devices.

The software defined radio is still a complex problem for a number of technological reasons [158]. The transformation process toward a fully programmable radio terminal is obtained through two main steps [159]:

- the boundary between the analog and the digital section will move closer toward the antenna,
- a duplicated switched dedicated hardware will be replaced by general purpose DSP engines.

Present transmitters and receivers developed in SR technology are based on a traditional implementation of super-heterodyne scheme (see figure 6). In this scheme the RF and IF stages are totally analog while the digital components are used for base band processing and are usually implemented in ASIC technology.

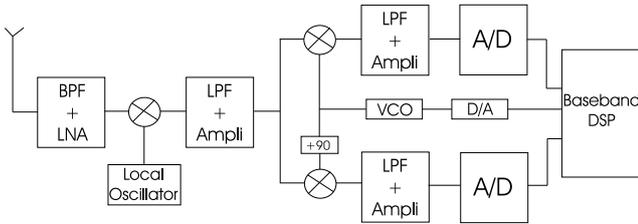


Fig. 6. Super-heterodyne scheme.

Ideally, the structure of a SR terminal (shown in figure 7) has a minimal analog component represented by the antenna, the pass band filter and the LNA [160]. The A/D conversion is performed directly at the RF and the successive signal processing is operated in the digital domain.



Fig. 7. Ideal scheme of SR.

A relevant element to the development of SR terminals is the remote configuration capability. It represents a complex trade-off between two elements: the level of details in the description of radio components and the level of abstraction required for a hardware independent remote reconfiguration. We will present a SW/HW architecture for SR terminals along with the essential elements of a descriptive language used for the remote configuration process.

A. SDR Terminal: Hardware Architecture

The future mobile terminals are designed to support high bit rate traffic and they will be probably equipped with high computational capacities[161], [162].

Third and fourth generation mobile terminals will use more than one microprocessor to increase the global computational capacity of the device.

Inside this device an Operating System (OS) performs all the control functions required by the terminal. In a SR mobile terminal, the OS can be also used to generate the firmware to be inserted into the reconfigurable strata of the hardware.

The SR terminal is subdivided into an analog section and a baseband processing digital section[165], [166]. The first one includes the antenna, the RF-to-IF conversion stages and the Analog-to-Digital converters. A feasible architecture of the baseband digital signal processing section is represented in figure 8. It is constituted by the following

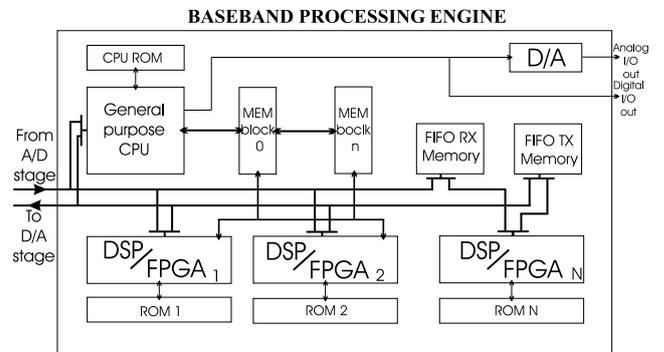


Fig. 8. Main constitutive elements of the baseband architecture for the SR device.

blocks:

- a General Purpose microprocessor;
- multiple DSP/FPGA blocks, depending on the required functional target of the devices;
- FIFO memories for both the RX and TX branches;
- ROM/FLASH memories, for storing the resident parts of the OS;

The FIFO memories in the receiver branch (FIFO RX MEMORY) are used to store symbols from A/D stage while the FIFOs in the transmitter branch (FIFO TX MEMORY) store the data generated by the *baseband processing engine* directed to the DAC device. The ROM banks are used to store the Operating System (OS) and the firmware which will be loaded into the DSPs and FPGAs. The reconfigurable hardware, the FIFO Memories and the general purpose CPU are interconnected by an high speed bus.

B. SDR Terminal: Software Architecture

The device operating in SR technology acts as a node in the hosting network architecture both for control functions (*control plane*) and for the communication functions (*traffic plane*)(see figure 9).

The relevant entities of a Software Radio network architecture are the *Configuration Manager* and the *SR mobile terminal*.

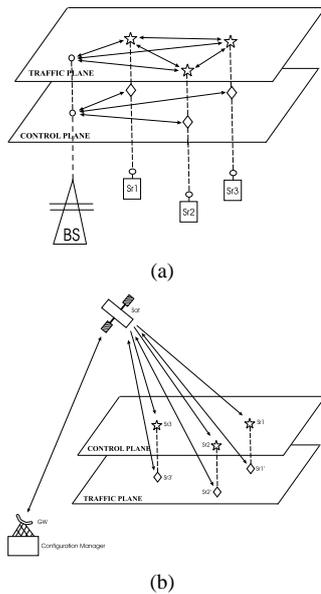


Fig. 9. a) terrestrial architecture; b) satellite architecture;

The Configuration Manager is the one that gives instructions to the SR wireless terminals about its configuration; it can be located in the base station (figure 9a)) of a terrestrial network or in the earth gateway for a satellite network (figure 9b)). In the former there is a direct line of communication between the SR-terminal and the Base-Station; in the latter the Earth-Gateway must establish a communication channel with the SR-terminal making of use a satellite network.

The SR terminal is a hand-held device with high computational capacity able to translate the setup information sent by the Configuration Manager into assembler instructions for the chosen DSP/FPGA.

The physical layer of the SR mobile terminal is split into two sub-layers: the reconfigurable hardware (realized in DSP or FPGA technology) and the microcode (the firmware) which implements the target communication protocol.

The SR terminal operates on two main states: "operative" and a "setup" mode. The OS assists the device in its normal functions during the operative mode and performs the hardware reconfiguration during the setup mode.

IX. SPECTRUM AND SPACE

The absolute need for radio channel capacity in the next generation wireless systems drives the search for smart and sophisticate techniques to maximize the efficiency of channel exploitation.

The most promising techniques are based on a adaptive, flexible use of both spatial and spectral dimensions, by conjugating on the same access stratum:

- multiple access schemes (MC-CDMA, MC-TDMA),

- multi-carrier modulations (OFDM),
- multiple independent radio channels (MIMO),
- beam-forming and angular partition of the radio coverage.

Weiss and Jondral in [173] showed that large chunks of potential spectral resources are used only sporadically. A capacity borrowing mechanism, called *Spectrum pooling*, enables secondary utilization of already licensed frequency bands without sacrificing the transmission quality of the actual license owner or requiring any new hardware in the original licensed system. To implement this option a SDR-based, reconfigurable physical layer is considered on the terminal to obtain a complete software control of channel sub-carriers.

OFDM-MIMO techniques obtain significant improvements on channel capacity and resource flexibility. In [176] a software radio implementation of OFDM-MIMO system for broadband communications realized at Georgia Tech is presented. Several open issues still have to be solved in order to obtain feasible architectures for SDR terminals, the computational complexity required by channel estimation and channel coding being the most limiting factor for the engineering of such terminals.

Also in the Vicom project framework, dealing with advanced transmission techniques for virtual immersive communications, a Software Radio implementation of a MIMO/OFDM system is at design stage. In Figure 10 is shown the testbed architecture for a 2:1 OFDM/MIMO system operating in the 2.4 GHz. The transmitter section is dominated by a fully reconfigurable DSP platform where all the baseband signal processing functions are executed before DAC and frequency conversion stages. The receiving terminal is equipped with a single antenna and a baseband dual-DSP board where demodulation, detection, and channel decoding are implemented in software.

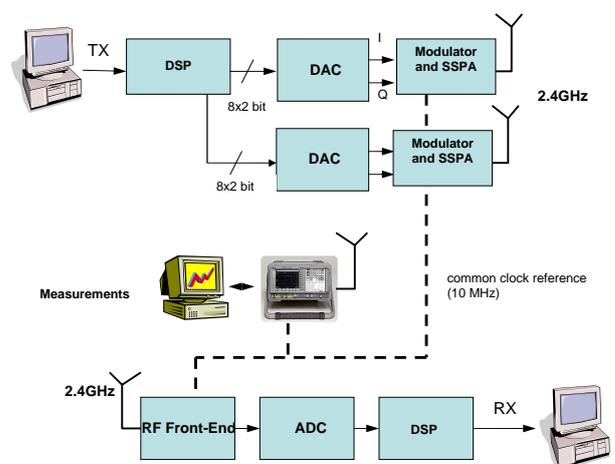


Fig. 10. VICOM Project: SDR implementation of OFDM/MIMO terminal

X. CROSS LAYER APPROACHES

Any innovation adopted at physical layer will not obtain the maximum performance if it does not interact with the upper MAC layer. This concept, opposed to the historical separation of functions between layers, has demonstrated significant results in terms of efficiency in the use of the communication resources.

The so-called *cross-layer* approach, depicted in figure 11, is the mutual exchange of information between physical and upper layers and is naturally enabled by Software Radio [174], [179], [178].

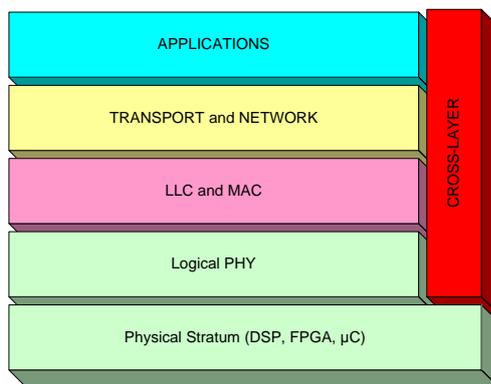


Fig. 11. The cross-layer concept

Several objectives have been proposed for cross-layer design. Some research has addressed improving power management, proposing strategies based on modifying different layers of the communications system and showing that adapting transmission to channel fading significantly improves link efficiency [177].

Another approach is to adapt the radio transmission parameters (frame length, error control, equalization, power) to minimize power consumption for varying channel conditions [178]. Also source coding can benefit from the knowledge of transmission parameters in order to save power and reduce interference in CDMA systems [180].

Cross-layer design, whichever is its target, requires a physical layer in communication with LLC and MAC not only giving information about the physical status of the channel, but also accepting real-time reconfigurations of transmission parameters. Also in this case the Software Radio acts as the enabling technology, providing a full logical control over the signal processing functions located at physical layer.

XI. REMOTE TERMINAL CONFIGURATION

The software definition of physical layer enables another attractive property to SDR wireless terminal: the remote configurability, i.e. the ability for a wireless device to have the communication layers re-defined automatically by the network operator.

This key feature is of particular importance for the following points:

HW upgrading: the wireless terminal, especially cell-phones, can increase the set of functions lately inserted in the communication standard, limiting the aging of the real hardware;

bug-fixing: this element, alone, justify the technological effort. The costs of recalling a terminal for malfunctions are huge, but the market requires a constant flow of innovation for services and terminal features. New devices are often put into the market without a suitable testing and result in a significant cost to the manufacturer.

global roaming: remote configured universal terminals can "learn" transmission modes by the host network, eventually choosing the optimum communication standard with respect to required quality, traffic, type of service, billing, channel condition or a combination of this parameters.

The key process for remote configuration of a wireless terminal is the *radio software download* [175]. By radio software download is intended the transfer of software via:

- a remote server via the actual radio interface through the supporting core network (over-the-air), or
- a local server that employs different mechanisms but does not involve the over-the-air interface.

The software download process is constituted by three main phases:

- pre-download,
- download and
- post-download.

During the pre-download phase, the terminal discovers the need for a radio software reconfiguration. It then triggers a download event (coming from the terminal itself, the network or an application). The main download parameters are initialized and a mutual authentication between the terminal and the remote peer occurs. When the remote peer, upon verification of the terminal credentials, authorizes the download process, the two entities exchange capability information and the mutual agreement to proceed. The remote peer initialize also the protection mechanism against intentional modifications of the transmitted data.

The actual download takes place. The data is transmitted with an acknowledged protocol and checked for integrity at the downloading terminal.

When a copy of the radio software is present in the terminal, the post-download steps occur. The first of these steps involves the temporary installation of the downloaded data. The radio profile obtained by the network could be incompatible with the hardware of the terminal, although it passed the integrity check. A set of functionality tests are operated by the terminal, then a final acceptance is asked to the user before proceeding with the final activation phase. The radio profile data is finally installed on the device which is then restarted. If the restart with the new radio

software is successful, the temporary memory used during the installation phase is cleared and the device enters the operating state.

The radio download data is intended platform dependent. With the recent advances in the computational capabilities of microprocessors a novel approach becomes also possible: the use of an abstract radio layer definition language instead of a platform specific one. In [181] the remote physical layer definition is operated through a high level descriptive language, called *RADL* (Radio Access Definition Language). The level of abstraction of *RADL* permits a compact representation of known communication standards, but is also able to define new signal processing functions independently from the underlying hardware platform.

The software modules involved during a *RADL* reconfiguration process are shown in figure 12:

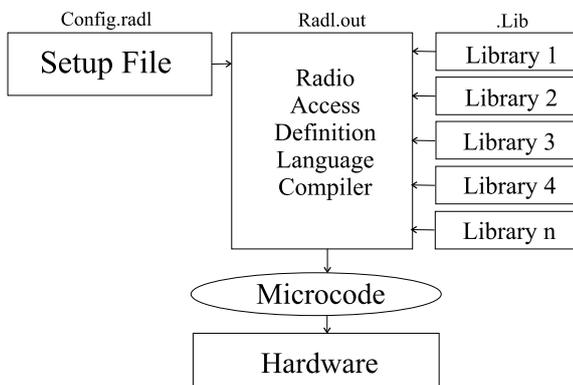


Fig. 12. Software modules involved in the reconfiguration process of the SR terminal.

A setup file, called *config.radl*, is downloaded from the *Configuration Manager* of the network.

The *RADL* compiler, uses some libraries available on the wireless SR terminal to implement the required functions into a machine dependent program. The *Configuration Manager*, aware of the libraries available in the terminal during the configuration process, generates the setup file accordingly.

The libraries in the mobile terminal can implement a wide range of signal processing functions, from simple operations to complex sections of existing communication standards (i.e. GSM and 3GPP framing, modulation and coding). As an example, functions like digital filtering, coding and decoding, modulation, pulse shaping, carrier recovery, timing acquisition are defined by a set of parameters provided by the *Configuration Manager* and implemented locally by the SR terminal using its libraries.

There is also the opportunity to replace partially or totally the terminal libraries; this allows upgrades of existing communication protocols but also the definition of new standards. The direct definition of a new library is written in a specific section in the *config.radl*; the *RADL* Compiler

interprets this section and builds the code corresponding to the new library, making it available for future applications.

The complete communication standard implemented in the SR terminal is described, in the configuration file, as a single block with a set of inputs and outputs and several system-wise parameters.

This top-level block is composed by other blocks interconnected to create the specific system to be developed. The *RADL* compiler translates this block structure into a code executable by the device hardware.

XII. RESEARCH VISIONS, PERSPECTIVE

MIMO technology significantly enhances system performance increasing bit rates or improving diversity order.

Information theory reveals the great capacity gains that can be provided by applying MIMO techniques. Whether this is fully or at least partially achievable depends on a sensible design of transmit and receive signal processing algorithms, in practice.

Different problems have to be yet addressed:

The layered space-time architecture requires synchronized symbol timing and the exact knowledge of the channel to achieve the promised high spectral efficiency

Multiple antenna deployments requires multiple RF chains typically very expensive. Optimal antenna subset selection can be a promising solution.

Further steps in MIMO modellization, aiming at characterizing directional broadband channel, are strongly needed and pursued by many research groups.

Moreover, the application of low-complexity methods for coupling MIMO and several techniques such as OFDM, MC-CDMA and UWB will be a key feature of the next research trend.

The digital signal processing applied to radio signals allows the implementation of complex reception schemes, where the spatial, temporal and spectrum dimensions are combined together to accomplish the two main objectives cited before.

XIII. ROAD MAP

Most of technological efforts in the wireless communication area are devoted to increase the rational use of resources and devices with two main objectives:

- to increase of efficiency, measured in terms of radio coverage, number of served users, power consumption, spectrum usage, biological impact, short time-to-market and fast network (re)-planning,
- to provide a good degree of service innovation as well as preparing the devices for next generation systems, possibly with a contained investment.

Following these guidelines, technologies such as reconfigurable antennas, MIMO reception schemes, ACM and software radio provide the necessary support for the next generation devices. These key elements, however,

must be enabled by a suited underlying signal processing technology, based on high degrees of reconfigurability and processing power. This justifies the current growing interest on FPGAs, considered as the most promising signal processing technology allowing the "softwarization" of CPU and DSP.

The success of MIMO algorithm integration into commercial standards such as 3G, WLAN, and beyond (4G, short range communications, etc.) will rely on a fine compromise between rate maximization (Layered type) and diversity (space-time coding) solutions, also including the ability to adapt to the time changing nature of the wireless channel using some form of feedback.

Finally, upcoming trials and performance measurements in specific deployment conditions will be required in order to evaluate precisely the overall benefits of MIMO systems in real-world wireless scenarios (for the actual and the future services).

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