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# Beamforming in 3G and 4G Mobile Communications: The Switched-Beam Approach

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## 1. Introduction

The technology and deployment of modern mobile communications systems, should adapt to the continuous and rapid growth of wireless data traffic. Besides the increase in bandwidth, the addition of cell sites and sectors, and the enhancement of air interface capabilities, smart antennas play also a substantial role in the improvement of wireless systems' performance. When we refer to smart antennas, we mean structures of multiple antenna elements at the transmitting and/or the receiving side of the radio link, whose signals are properly processed, in order to better exploit the mobile radio channel and enhance the communications performance. During the last decade there has been intensive research on Multiple Input-Multiple Output (MIMO) systems, which are antenna formations that involve processing at both sides of the link (Jensen & Wallace, 2004).

Depending on the signal processing methods and the adaptive schemes used, smart antenna techniques can be separated into three broad categories: a) Diversity, b) Spatial Multiplexing (SM), and c) Beamforming. Roughly speaking, beamforming aims at improving Signal to Interference plus Noise Ratio (SINR), diversity aims at reducing the variations in the SINR experienced by the receiver, while SM aims at sharing SINR in high SINR scenarios (3G-Americas, 2009).

Transmit and receive diversity are used in order to mitigate the problem of multipath fading, enhancing the reliability of a wireless link. In SM, which is the most popular transmission scheme of MIMO systems, multiple data streams are transmitted in parallel, increasing the data transmission rate. Beamforming uses an antenna array<sup>1</sup> to transmit/receive energy in a specific direction, increasing the cellular capacity and coverage. Although it is an early smart antenna technology, beamforming is still supported by the latest 3GPP releases (3rd Generation Partnership Project - [www.3gpp.org](http://www.3gpp.org)), namely the LTE (Long Term Evolution) and LTE advanced. Operators though seem reluctant to incorporate smart beamforming techniques into base stations, mainly due to the cost and complexity of such implementations. The current research concerning 4G mobile systems is mostly concentrated on MIMO processing and space-time coding algorithms. However, antenna arrays and beamforming have still the potential to contribute in the enhancement of modern cellular systems.

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<sup>1</sup> Antenna array is called the aggregation of radiating elements in a certain electrical and geometrical arrangement (Balanis, 2005).

Beamforming systems are generally classified as either Switched-Beam Systems (SBS) or Adaptive Array Systems (AAS). A SBS relies on a fixed BeamForming Network (BFN) that produces a set of predefined beams. Probably the most popular solution for fixed BFN is a Butler Matrix (BM) (Butler & Lowe, 1961). A BM in its standard form is a  $M \times M$  network, which consists of hybrid couplers, phase shifters and crossovers.  $M$  is the number of input/output ports that give a set of  $M$  different beams. In (Kaifas & Sahalos, 2006), the reader can find a comprehensive review of the BM functionality and its implementation issues.

A SBS needs a Switching Network (SN) in order to select the appropriate beam to receive the signal from a particular Mobile Station (MS). As it is shown in Fig. 1a, the maximum of the selected beam might not point at the desired direction. Moreover, typically a beam serves more than one MS. On the contrary, an AAS has the possibility to form a special beam for each user Fig. 1b. This is accomplished by a series of adaptive array processors that apply weight vectors to the received and transmitted signals, in order to control the relative phase between the antenna elements and their amplitude distribution. In this way specific beam patterns can be produced, directing the main lobe towards the desired MS and nulls towards the interfering signals. Thus, Direction of Arrival (DoA) estimation of signals impinging on an antenna array is a very important issue for cellular communications.

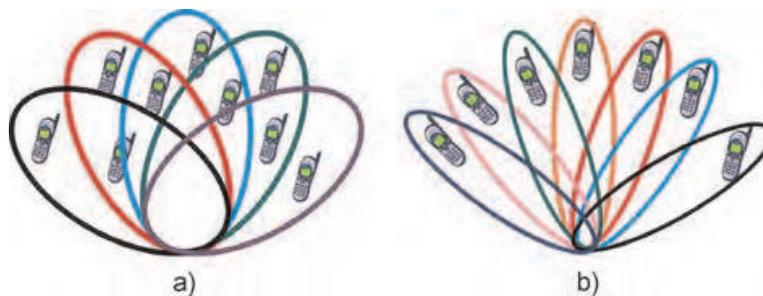


Fig. 1. Beam coverage of a) switched-beam system and b) adaptive array system.

Adaptive beamforming presupposes that the Base Station (BS) updates the localization of the MS. However, accurate localization is not an easy task, since a big number of simultaneous mobile users can overload the process. Therefore, although many popular DoA estimation methods and adaptive beamforming algorithms have been developed (Godara, 2004), no particular standardization has been established. The implementation of an adaptive system is much more complex than a switched-beam one. On the other hand, ideal adaptive beam pointing minimizes the interference between users and exploits much better the available power resources. In any case there are advantages and disadvantages which have to be considered (Baumgartner, 2003; Baumgartner & Bonek, 2006; Osseiran et al., 2001; Pedersen et al., 2003).

In order to exploit the simplicity of SBS, and promote effective smart antenna beamforming, the authors in (Gotsis et al., 2009) developed a Neural Network (NN) DoA estimation methodology, which has been especially designed for an SBS and applied to a Direct Sequence Code Division Multiple Access (DS-CDMA) scheme. As a succession of the above paper, an improved BM based beamforming network has been presented in (Gotsis et al., 2010). The proposed structure provides enhanced beamforming flexibility compared to a typical BM and also has the possibility to efficiently work in conjunction with the NN-DoA estimation technique.

The main scope of this chapter is the completion and extension of the work presented in the above references. A basic subject is the introduction of 'DoA-based Switching (DoAS)'

and its incorporation into a 3G mobile communications framework, like the Universal Mobile Telecommunications System (UMTS). DoAS is evaluated and compared to the so called in this work 'Typical Switching (TS)'. The term 'TS' refers to the typical operation of a SBS, which is determined by the highest uplink SINR or by the highest mean received power.

In (3G-Americas, 2009; 2010) one can find various propositions for 4G systems that combine MIMO techniques and fixed beamforming (using BM) into a single structure. Generally, BM still attracts the interest of researchers (Chia-Chan et al., 2010; Peng et al., 2009). Therefore, the 3G case is followed by a discussion of how the switched-beam approach using BM could be useful in the context of next generation systems.

## 2. The improved switched-beam system

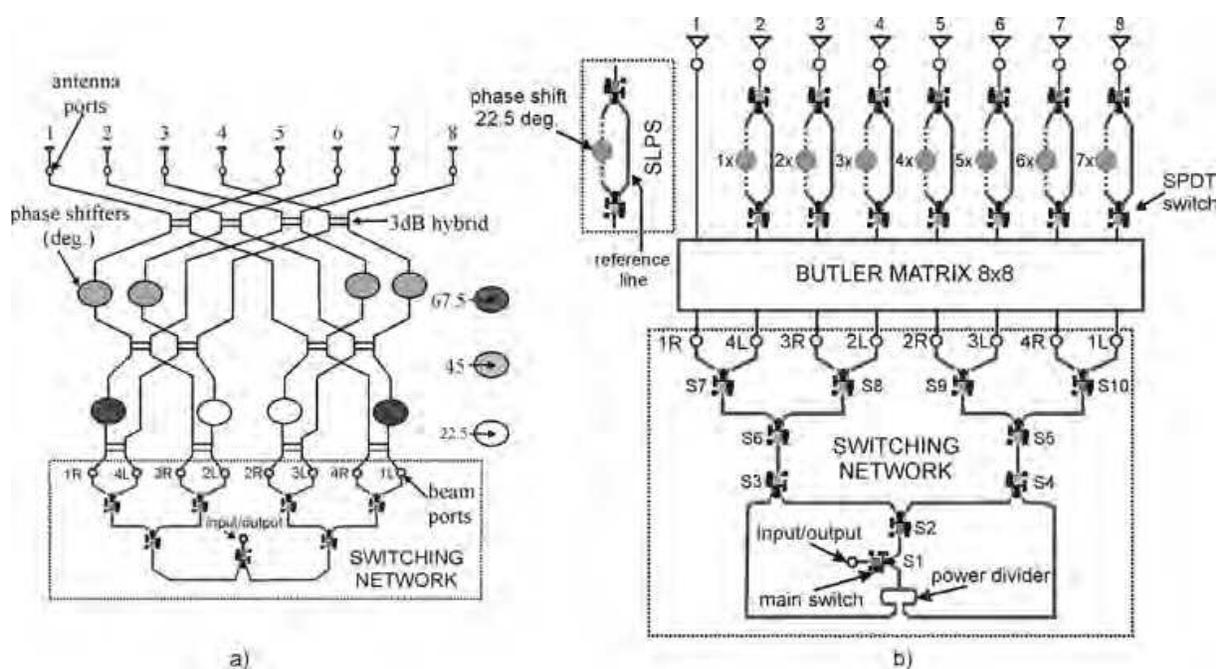


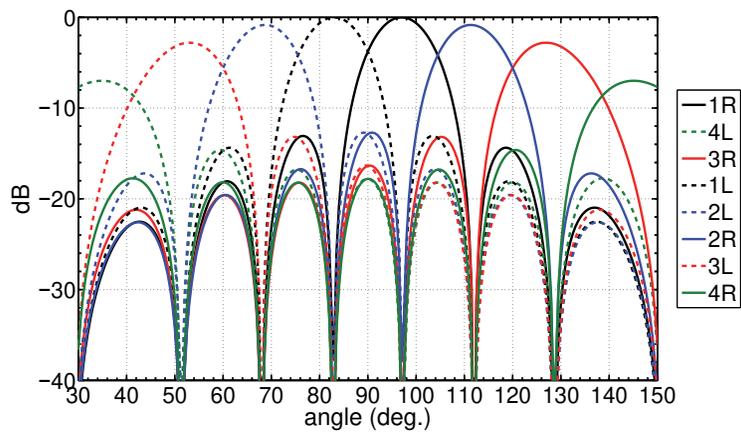
Fig. 2. a) Typical schematic of a Butler Matrix (BM)  $8 \times 8$  and its SN. b) Schematic of a beamforming network with a typical BM  $8 \times 8$  enhanced by the appropriate SN and a group of SLPS.

### 2.1 The beamforming network

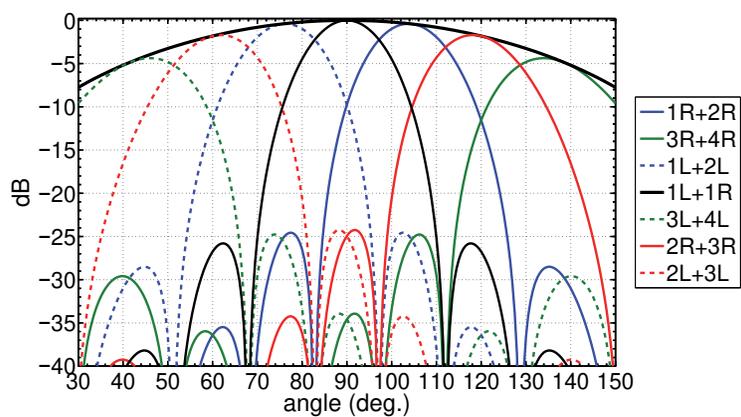
A concentrated illustration of the beamforming network proposed in (Gotsis et al., 2010), is depicted in Fig. 2b. In Fig. 2a, a typical schematic of a BM  $8 \times 8$  and its SN is shown. The BFN is constituted of three main blocks: a) a BM  $8 \times 8$ , b) a switching network and c) a block of Switched Line Phase Shifters (SLPS). Regarding the BM, taking into account the radiation pattern characteristics, the degrees of freedom offered and the complexity of the implementation, the  $8 \times 8$  dimensions are the most appropriate to cover an angular sector of  $120^\circ$ .

#### 2.1.1 Single and combined BM port excitation

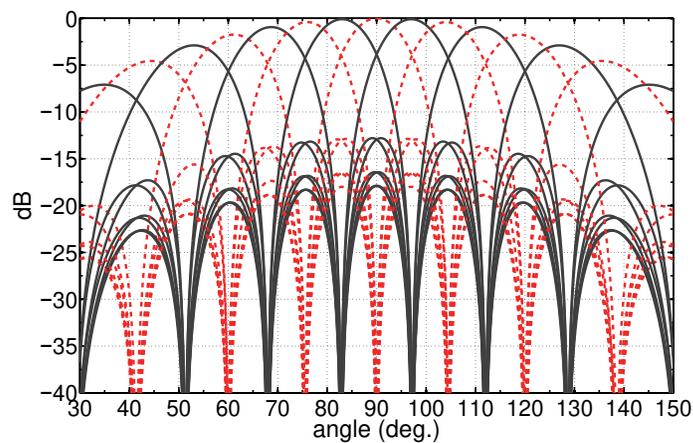
The SN consists of a circuit of Single Pole Double Throw (SPDT) switches (Pozar, 1990) in dendroid structure and a 3dB power divider. A digital word determines the switches' state ('0'



(a)



(b)



(c)

Fig. 3. Radiation patterns produced by the proposed SBS: a) eight orthogonal beams from the single (1:0) beam port excitation, b) seven beams from the combined (1:1) port excitation plus a sector beam from a single antenna element, and c) enhanced grid of 15 beams resulting from the addition of the SLPS at the output of the BM  $8 \times 8$ . The dotted lines correspond to the added beams.

or '1') and thus, the signal's route through the network. The first bit of the word corresponds to the state of the main switch (S1), which gives two options. The first option is the typical single port excitation (1:0) of the BM, that leads to the uniform illumination of the antenna elements. The result is a grid of eight orthogonal beams, as shown in Fig. 3a. The beams are called orthogonal in the sense that at one beam's maximum, all the other beam patterns have a minimum. There are four beams at the right (R) and four at the left (L) of the broadside. The beam ports take their name after the position of the corresponding beam in relation to the broadside. The second option is the combined equal excitation (1:1) of the BM ports that correspond to pairs of adjacent in space orthogonal beams. This results to the cosine illumination of the antenna elements and a grid of seven beams, as shown in Fig. 3b. In the same diagram the sector beam of a single antenna element (a rectangular microstrip patch) is also illustrated. The reader observes that 1:1 provides beams with lower Side Lobe Level (SLL), higher Crossover Level (CL) and wider Half-Power BeamWidth (HPBW) than the 1:0 case. This is due to the cosine versus the uniform illumination of the antenna elements, that confirms the following rule of thumb: "in linear antenna array synthesis the array with the smoothest amplitude distribution has the smallest side lobes and the larger HPBW (and vice versa)" (Balanis, 2005). Details about the characteristics of the discussed radiation patterns in (Gotsis et al., 2009).

### 2.1.2 Extra beams from single port excitation

Extra beams in a BM can be produced if a block of SLPS is added at its output (see Fig. 2). The SLPS do not modify the layout of the typical BM. They just interconnect the last row of the hybrids and the antenna ports of the BM. A SLPS is a simple structure, which uses two SPDT switches to drive the signal between the one of two microstrip lines of different length (Pozer, 1990). The length difference determines the phase difference between the two paths. The one path (solid reference line) of the proposed structure, is the path of the typical BM that gives the orthogonal beams. The length of the other line (dotted in Fig. 2b), has been chosen so that an extra phase  $\Delta\phi = (n - 1) \cdot 22.5^\circ$  is added at the  $n^{th}$  antenna element<sup>2</sup>. Thus, the progressive phase difference produced by the excitation of each beam port is increased by  $22.5^\circ$ . For example the beam port 1R produces either the predefined phase difference  $\beta = 22.5^\circ$  or  $\beta = 45^\circ$ . The new phase difference corresponds to a new beam that lies between 1R and 2R. All possible single port excitations create an enhanced grid of 15 beams. This grid is constituted from the standard eight orthogonal beams, plus the seven beams (also orthogonal between them) that come from the use of the added SLPS (Fig. 3c). Table 1 summarizes the features of the resulting pattern.

Compared to Fig. 3a the CL is much higher. Even between the edge beams, the CL is higher than -3dB. Between the rest of the beams the CL ranges from -1.9dB to -0.9dB, whereas in the typical eight beams pattern ranges from -4.7dB to -3.8dB (Gotsis et al., 2009). This means that anywhere in the  $120^\circ$  sector a MS can be served by nearly the maximum of one of the main lobes, which has the narrowest possible HPBW. For example the 1:0 beam with maximum at  $\theta_0 = 61^\circ$  has  $HPBW = 14.2^\circ$ , while the 1:1 beam with maximum at  $\theta_0 = 62^\circ$  has  $HPBW = 18.5^\circ$ . The 1:0 excitations give narrower beamwidths than all the possible corresponding combined excitations  $1 : x$ , where  $0 < x < 1$ . On the other hand, the 1:0 beams have the highest SLL.

Besides producing the desired radiation patterns, the SLPS addition is practical and easy to implement. Their integration in a single layer microstrip structure is simple and the SPDT

<sup>2</sup> It should be noted that for the 1<sup>st</sup> element there is no phase shifter, since its phase is taken as a reference.

Beam	$\beta(^{\circ})$	HPBW( $^{\circ}$ )	SLL (dB)	$\theta_0 (^{\circ})$	CL (dB)
7L	-157.5	19.2	-7.6	35	6L-7L: -2.6
6L	-135.0	17.2	-9.3	44.5	5L-6L: -1.9
5L	-112.5	15.5	-10.4	53	4L-5L: -1.6
4L	-90.0	14.2	-11.2	61	3L-4L: -1.3
3L	-67.5	13.4	-11.9	68.5	2L-3L: -1.1
2L	-45.0	13.0	-12.5	76	1L-2L: -1.0
1L	-22.5	12.8	-13.1	83	1L-0: -0.9
0	0	12.6	-13.7	90	1R-0: -0.9
1R	22.5	12.8	-13.1	97	1R-2R: -1.0
2R	45.0	13.0	-12.5	104	2R-3R: -1.1
3R	67.5	13.4	-11.9	111.5	3R-4R: -1.3
4R	90.0	14.2	-11.2	119	4R-5R: -1.6
5R	112.5	15.5	-10.4	127	5R-6R: -1.9
6R	135.0	17.2	-9.3	135.5	6R-7R: -2.6
7R	157.5	19.2	-7.6	145	

Table 1. Radiation pattern characteristics of the enhanced grid of 15 beams resulting from the addition of the SLPS.

switches offer very fast (nanosecond) switching between their two states. An important feature of the SLPS is their equivalent operation for both transmission and reception. The proposed way of their integration reserves the typical BM functionality and does not modify the SN, which has been designed for simplicity and minimization of losses.

## 2.2 The neural network direction of arrival estimation method

Several algorithms have been proposed concerning DoA estimation (Godara, 2004). In principle, most of these have been designed for adaptive systems. Very popular are the super resolution algorithms, MUSIC (Schmidt, 1986), ESPRIT (Ray & Kailath, 1989), and their variants (e.g. ROOT MUSIC). Over two decades later, many research proposals are still based on the concept of these classic methods, e.g. (Ying & Boon, 2010). However, the drawback of these approaches is the need for intensive signal processing, like eigenvalue decomposition and signal autocorrelation matrix calculations. In order to avoid eigenvalue decomposition, NN-DoA finding procedures have been developed, which basically apply the mapping of the signal autocorrelation matrix with the signals' angles of arrival (AoA) (Christodoulou & Georgiopoulos, 2001; El Zooghby et al., 2000). A DoA estimation methodology has been firstly presented in (Gotsis et al., 2007), based on the mapping between the signals' AoA and the power measured at the input/output of the BFN. The mapping is exploited through the supervised learning of NNs. The main novelty of this approach has been the special design for SBS in conjunction with NNs, without any other complex signal processing techniques. The advantage of NNs is that although their training may be time consuming, the response of their application is instant. This makes them appropriate for real time applications like DoA estimation and beamforming.

In (Gotsis et al., 2008) the signal model has been given and the generic concept of the method has been extended to a DS-CDMA mobile communications scheme, focusing on the DoA estimation of the desired mobile user at the presence of many other interfering signals that constitute the Multiple Access Interference (MAI). In (Gotsis et al., 2009) the method has been described in detail and studied in depth through extensive simulations. It has been shown

that the desired signal's DoA can be extracted with a less than one degree Root Mean Square Error (RMSE), even if its power level is 6dB less than each one of 39 interfering signals. A basic conclusion was that the 1:1 excitation of the BM should be used for the uplink communication between the MS and the base station. Due to the non-orthogonality and the high CL of the seven beams pattern, the 1:1 mode gives much better DoA estimation results than the typical 1:0. The orthogonality and higher directivity of the eight beams pattern are better for the downlink transmission towards the desired MS. That is why the SN of the SBS has been designed to support both excitation modes.

In the next section various beamforming possibilities involving the proposed SBS and the NN-DoA estimation method are presented and evaluated in terms of their performance in the framework of UMTS.

### 3. Smart switched beamforming in UMTS

UMTS has been standardized by the 3rd Generation Partnership Project (3GPP), which has been a collaboration of various telecommunications associations from Europe, Japan, Korea, USA and China. The original scope of 3GPP was to produce technical specifications and technical reports for a 3G and beyond mobile system. Release 99 was the first release of 3G specifications and it was essentially a consolidation of the underlying Global System for Mobile Communications (GSM) and the development of the new Universal Terrestrial Radio Access Network (UTRAN). There have been many steps till 3GPP reached the Long Term Evolution (LTE), which is a pre-4G standard, one step behind the LTE Advanced that fully complies with the IMT-Advanced (International Mobile Telecommunications Advanced) requirements for 4G standards ([www.3gpp.org](http://www.3gpp.org)).

#### 3.1 Beam switching modes

Base station beamforming for UMTS has followed the general classification described in the introduction. Particularly, UMTS Release 6 (3GPP, 2004) specified three possible modes: "none", "flexible beamforming", and "grid of fixed beams". The "none" mode signifies that beamforming is optional. "Flexible beamforming" corresponds to the adaptive beamforming used by an AAS, whereas the "grid of fixed beams" corresponds to a set of predefined beams used by a SBS. As it was mentioned in the introduction, the SBS may operate either in the TS or the DoAS mode.

##### 3.1.1 Typical Switching (TS)

In (3GPP, 2004) it has been specified that the operation of a SBS depends on the so called 'best cell portion measurement', which corresponds to the TS operation mode. A cell portion has been "the part of a cell that is covered by a specific beam antenna radiation pattern, which can be created using a grid of fixed beam directions". In this context a cell is a "logical cell", which is the area covered by the Primary Common Pilot Channel (P-CPICH) (Pedersen et al., 2003). When a call is initiated, the User Equipment (UE)<sup>3</sup> is being accepted by the beam that measures the highest SINR for the Physical Random Access Channel (PRACH). During the communication the switching is activated depending on the SINR measurement for the Dedicated Physical Control Channel (DPCCH) and it is reported to the Radio Network Controller (RNC). The difference between common and dedicated channels is that in the first case the channels' resources are shared to all or a group of cell users, whereas in the second

<sup>3</sup> In UMTS terminology the mobile station is called User Equipment and the base station Node-B.



realized. However, the "best cell portion measurement" is not determined by the highest SINR, but by the estimated actual DoA of the signal. The choice of the downlink beam is based on the uplink DoA estimation, which is a realistic approach that is used in wireless communications. This has been shown experimentally for the communication between a BS with an eight element linear antenna array and a single element MS (Pedersen et al., 1999).

### 3.2 Performance of TS and DoAS

Depending on the switches' state, the proposed SBS (Fig. 2b) supports various switched-beam configurations. The simplest one is the typical use of the eight orthogonal beams (1:0) for both the Up and Down (UD) link. This configuration should work in the TS mode and is called '8UD'. An advanced choice for the TS mode, which is a proposition of this work, is the use of fifteen beams (1:0) for both the uplink and downlink (i.e. '15UD' configuration). Finally, a novel structure called '7U15D', works in the DoAS mode using the seven beams (1:1) for the uplink and the fifteen beams (1:0) for the downlink. A simulation model has been developed in order to perform a comparison between 15UD and 7U15D with the conventional 8UD. The model makes use of the Monte Carlo approach.  $N$  mobile stations are randomly located in an angular sector of  $120^\circ$  with radius  $R_0$  (the logical cell of the communication scenario) (Fig. 5). The stations are served by a single SBS that covers the sector and it is assumed that there is no interference from other adjacent cells. In the case of DoAS mode the downlink beam is chosen from a predefined lookup table, depending on the estimated DoA of the desired signal on the uplink. In the TS mode the NN-DoA algorithm is not involved and the downlink beam is the one that has measured the highest uplink received power.

Since the downlink beam has been chosen, power control is assumed and a particular  $SINR_t$  target is set, in order to calculate the transmit power required for the desired mobile user. The SINR for the  $n^{th}$  UE is calculated by

$$\lambda_n = \frac{\frac{P_{n,b}}{L_{n,b}} Q}{N_0 + (1 - \alpha) I_{n,b}} = \frac{\frac{P_{n,b}}{L_{n,b}} Q}{I_n^{tot}} \quad (1)$$

where  $P_{n,b}$  is the transmit power of the beam  $b$  that serves the mobile  $n$ ,  $Q$  is the processing gain,  $L_{n,b}$  is the path loss between the  $n^{th}$  station and beam  $b$ ,  $I_{n,b}$  is the received power at the  $n^{th}$  station due to all other stations served by the same beam,  $N_0$  is the thermal noise, and  $I_n^{tot}$  is the total interference at station  $n$ . The non-orthogonality factor  $0 \leq \alpha \leq 1$  takes into

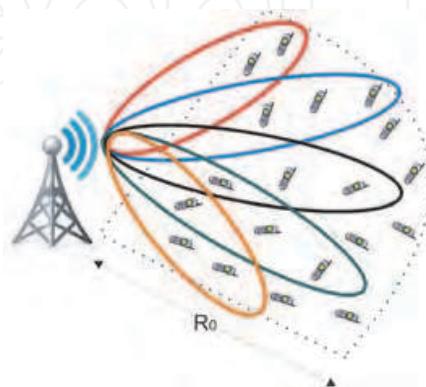


Fig. 5. The SBS covers an angular sector of  $120^\circ$  and serves  $N$  randomly located mobile stations.

account that signals spread with different code-words are not fully orthogonal after travelling through a radio channel with more than one delay tap (Baumgartner, 2003). The path loss in dB is calculated using the COST Walfisch-Ikegami-Model (COST-WI), for the line-of-sight (LOS) case between the base station and the mobile antennas

$$L_{n,b}[\text{dB}] = 42.6 + 26 \log(R_n/\text{km}) + 20 \log(f/\text{MHz}) - D_b(\theta_n), R_n \geq 20\text{m} \quad (2)$$

where  $R_n$  is the distance between the  $n^{\text{th}}$  UE and the base station,  $f$  is the downlink operation frequency and  $D_b(\theta_n)$  is the directivity pattern of beam  $b$  towards the angle  $\theta_n$  of the station. The directivity patterns come from the radiation patterns, taking also into account the directivity of each beam calculated by the ORAMA computer tool (Sahalos, 2006). Given that moving towards the edges of the sector the beams have wider HPBW, the directivity patterns give even weaker coverage at these angular regions, compared to the corresponding radiation patterns. The received interference at the  $n^{\text{th}}$  UE, served by beam  $b$ , due to the  $M$  stations served by the same beam is

$$I_{n,b} = \sum_{m=1 \neq n,b}^M \frac{P_{m,b}}{L_{n,b}} = \sum_{m=1 \neq n,b}^M 10^{0.1(P_{m,b}[\text{dBm}] - L_{n,b}[\text{dB}])} [\text{mW}] \quad (3)$$

where  $P_{m,b}$  is the transmit power of the beam  $b$  that serves the mobile  $m$ .  $P_{m,b}$  is calculated so as to achieve at the corresponding UE a particular  $SNR_t$ . Therefore

$$P_{m,b}[\text{dBm}] = N_0[\text{dBm}] + L_{m,b}[\text{dB}] + SNR_t[\text{dB}] \quad (4)$$

The required transmit power  $P_{n,b}^r$  is given by

$$P_{n,b}^r[\text{dBm}] = I_n^{\text{tot}}[\text{dBm}] + L_{m(n),b}[\text{dB}] + SINR_t[\text{dB}] - 10 \log Q \quad (5)$$

where

$$I_n^{\text{tot}}[\text{dBm}] = 10 \log \{ 10^{0.1 N_0[\text{dBm}]} [\text{mW}] + (1 - \alpha) I_{n,b} [\text{mW}] \} \quad (6)$$

The simulation equations are followed by a specific numerical application in order to quantify the performance of each beam configuration. Thermal noise is calculated for  $N_0 = -99\text{dBm}$  (3GPP, 2007). The non-orthogonality factor is taken for  $\alpha = 0.5$ , the cell radius  $R_0 = 1\text{km}$ , the processing gain for both uplink and downlink  $Q = 128$ , the downlink operation frequency  $f = 2000\text{MHz}$ , the SINR target  $SINR_t = 20\text{dB}$ , the SNR target  $SNR_t = 10\text{dB}$  and the total number of simultaneous users ranges from 10 to 80.

Depending on the type of switching the downlink beam is chosen for each one of the three beam configurations and a mean  $P_{n,b}^r$  is calculated for the desired user, for each beamforming case and number of users. The simulation results (after 10000 independent runs) show that when 15 downlink beams are used (either TS or DoAS), the performance is almost identical and there is a power gain of about 5 dB per user compared to the 8 beams case. This is depicted in Fig. 6a, where the mean required transmit power towards the desired user, is plotted for each switched-beam structure. The improvement comes from a) the fact of fewer interfering signals per beam and b) the more directive transmission due to the bigger number of available beams. The coincidence between 15UD and 7U15D happens since normally the DoAS mode activates the same downlink beam as the typical one. This stands even when the number of

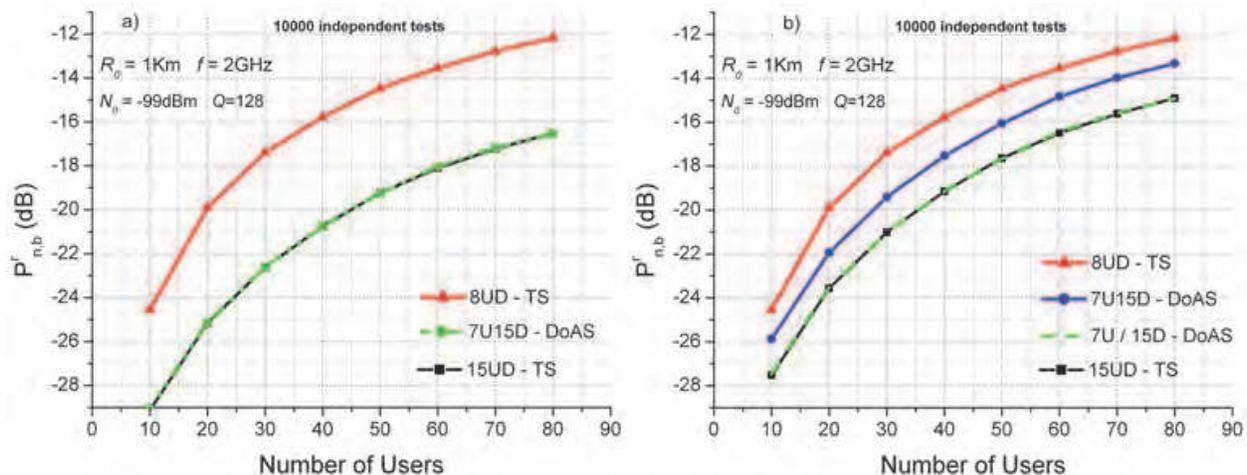


Fig. 6. a) Mean transmit power required for each switched-beam configuration in order to achieve at the desired user an  $SINR_t = 20\text{dB}$ . In b) the results take also into account the BFN power losses due to the SPDT switches.

simultaneous users increases and the DoA estimation performance deteriorates, mostly at the edges of the sector where the coverage is weaker.

The 5 dB power gain does not take into account the BFN losses due to the SPDT switches. In order to have a more 'complete' evaluation of the three switched-beam configurations, the performance study considers three separate SBS, one for each configuration. Figure 2b shows the 7U15D SBS, whose SN has both the 1:0 and 1:1 excitation possibility and at the output of the BM there is a group of SLPS for the extra seven 1:0 orthogonal beams. In Fig. 2a, it is shown that a typical 8UD SBS needs only a simple SN (without a 3 dB divider) for the eight 1:0 orthogonal beams. Finally, a 15UD SBS needs the same SN as the 8UD SBS, plus the group of SLPS. It is obvious that the 8UD system uses the fewer SPDT switches, whereas the 7U15D the more. Figure 6b gives the mean required transmit power taking also into account that each switch has an insertion loss of about 0.8 dB. The power level reference for the curves of Fig. 6 is the required transmit power of a sector beam that comes from one microstrip patch (at the presence of 40 users).

Both modes that use fifteen downlink beams perform better than the typical eight beams case. The 7U15D (DoAS) has less gain than the 15UD (TS), due to the extra switches of the SN. However, DoAS uses only seven instead of fifteen uplink beams, and thus there is less administrative cost. The above lead us to another possible configuration that consists of two separate SBS, one for the uplink and one for the downlink. The uplink SBS works with an SN that supports only the 1:1 mode and it is responsible for the DoA estimation using the grid of 7 beams. The downlink SBS works only in the 1:0 mode and uses the enhanced grid of 15 beams to transmit towards the mobile users. This structure, symbolised as 7U / 15D, uses less uplink beams, having the same downlink performance with the 15UD case (dashed line in Fig. 6).

#### 4. Beamforming in beyond 3G and 4G mobile communications

An extension of the DoAS concept towards next generation beamforming, would require the application of the proposed DoA estimation method to an Orthogonal Frequency-Division Multiple Access (OFDMA) scheme (instead of DS-CDMA), since OFDMA is the dominant

multiple access technique for 4G mobile communications systems. However, according to the latest 3GPP releases, base station multi-antenna configurations should be able to choose the appropriate smart antenna technique, depending on the radiocommunications requirements and the channel characteristics. Thus, it is important to consider beamforming in an overall smart antenna context, together with spatial multiplexing and diversity. Following this context, a practical example of combining SM and beamforming will be described in this section.

#### 4.1 Transmission rank

Spatial multiplexing is a MIMO scheme that employs multiple antennas at both sides of the radio link, in order to create multiple parallel channels that share the overall SINR and increase the data transmission rate. The number of simultaneously transmitted parallel streams is termed as 'transmission rank'. Generally speaking, the transmission rank can be defined as the number of independent symbols transmitted per time-frequency resource (3G-Americas, 2009). Although the need for this definition comes from spatial multiplexing (transmission ranks higher than one), it can be also used for beamforming and transmit diversity, which obviously are considered as single rank schemes. As it has been mentioned in the introductory section, beamforming and diversity aim at improving SINR, whereas SM aims at sharing SINR. Thus, generally speaking, rank-one transmissions increase coverage and keep a steady quality, whereas higher ranks improve data rates.

#### 4.2 Codebook & non-codebook based spatial precoding

##### 4.2.1 Spatial multiplexing

The various ways an antenna array transmits the modulated symbols with spatial multiplexing precoding, can be given by a general expression for the transmit vector  $\mathbf{T}$

$$\mathbf{T} = \begin{bmatrix} w_{11} & \cdots & w_{1K} \\ \vdots & \cdots & \vdots \\ w_{N1} & \cdots & w_{NK} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_K \end{bmatrix} = [\mathbf{w}_1 \ \mathbf{w}_2 \ \dots \ \mathbf{w}_K] \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_K \end{bmatrix} = \mathbf{W}\mathbf{s} \quad (7)$$

where  $w_{nk}$  is the  $n^{\text{th}}$  element of the  $k^{\text{th}}$  weight vector  $\mathbf{w}_k$ ;  $\mathbf{w}_k$  weights the symbol  $s_k$ , which corresponds to the  $k^{\text{th}}$  symbol stream. The weight vectors may be dependent or independent of the channel, depending on the availability of channel information on the transmit side. Moreover, when the weight matrix  $\mathbf{W}$  is chosen from a pre-fixed set of matrices we have the so-called 'codebook-based precoding', whereas when the weight choice is free we have the 'non-codebook-based precoding'.

Spatial multiplexing needs low spatial correlation on both the transmitter and receiver side. This can be accomplished by either co-polarized antenna elements with large distance between them, or cross-polarized elements with small inter-element distance. The definitions of 'large' and 'small' depend on the angular spread and the wavelength, however for a base station a typical small inter-antenna distance may be taken as half a wavelength, whereas a large as four to ten wavelengths.

##### 4.2.2 Beamforming

Unlike SM, beamforming needs strong spatial correlation, which typically means a half-wavelength spaced antenna array of co-polarized antenna elements. Beamforming can

be expressed by a vector  $\mathbf{T}_{bf}$ , which comes from a reduced form of (7)

$$\mathbf{T}_{bf} = \mathbf{w}_1 s_1 = \begin{bmatrix} w_1 s_1 \\ w_2 s_1 \\ \vdots \\ w_N s_1 \end{bmatrix} \tag{8}$$

where only a single symbol  $s_1$  is multiplied by a weight vector  $\mathbf{w}_1$ . The  $n^{th}$  element of the weight vector ( $w_n$ ) controls the phase and the amplitude of the  $n^{th}$  antenna element. If the weight vector is chosen from a set of predefined vectors we have 'codebook-based beamforming', whereas when the weight choice is not restricted and dynamically adapts to channel's variations we refer to 'non-codebook-based beamforming'. Beam switching using a set of fixed beams may be considered as a simple form of codebook-based beamforming, since each beam corresponds to a predefined weight vector.

**4.3 Beam switching combined with spatial multiplexing**

Consider two antenna arrays separated by a distance of several wavelengths (e.g. four). Each array consists of two half-wavelength spaced elements. The small distance between the antenna elements favors the use of beamforming, whereas the large inter-array distance is useful for spatial multiplexing. Therefore, such a structure may be used for the parallel transmission of two symbol streams  $s_1$  &  $s_2$ , one from each beamforming antenna array. Thus, besides the increase in data transmission rate, there may be also SINR improvement due to the directive transmission of the symbols.

Figure 7 depicts a simple implementation that combines beam switching with SM. Two BM  $2 \times 2$  provide the antenna arrays with the pre-defined necessary phase adjustments, in order to cover the desired sector with two beams instead of a typical sector beam from a single element. A BM  $2 \times 2$  is practically an  $90^\circ$  hybrid coupler. An SPDT switch is used to select between the two ports of the coupler, which give a phase difference between the elements of either  $90^\circ$  or  $-90^\circ$ . Figure 8 shows the resulting beams 1L and 1R. Depending on the channel condition and the DoA information the best beam should be chosen for transmission.

The beamforming concept described above can be extended to antenna configurations with more elements and Butler matrices with bigger dimensions. For example, a structure with a

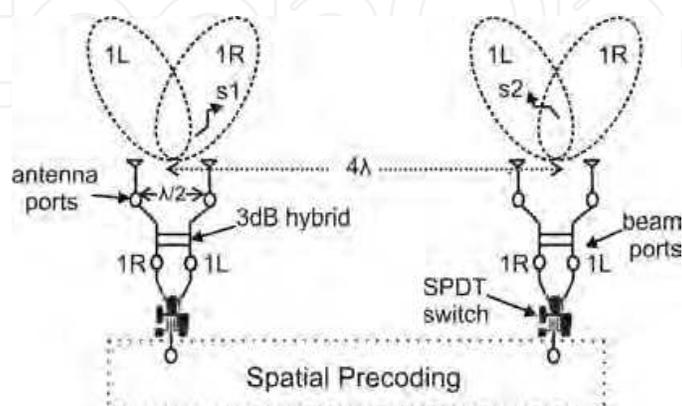


Fig. 7. Schematic of a transmitter combining spatial multiplexing and beam switching for a  $2 \times 2$  MIMO scheme.

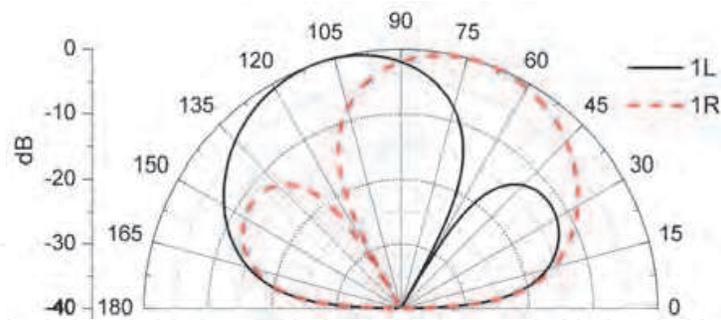


Fig. 8. Beams produced by an antenna array of two orthogonal microstrip patches fed by a BM  $2 \times 2$ .

BM  $4 \times 4$  may be also used for a  $2 \times 2$  transmission scheme. However, in this case there are more beam choices regarding the symbol transmission.

## 5. Conclusions

The research on smart beamforming systems has been started several decades before, when the first radars were developed for military purposes. The term beamforming refers to the function done by a group of co-operating antenna elements (called an antenna array), in order to form the desired radiation pattern and direct the radiated energy towards a specific target. Adaptive beamforming, namely the formation of a dynamically changing beam pattern that continuously directs a maximum towards the desired user and nulls towards the interfering signals, is theoretically an ideal operation. However, despite the great research done on this field, adaptive array systems have not been adopted by the wireless communications market, mainly due to their cost and complexity. Contrary to them, switched-beam systems (SBS) constitute probably the most easily implemented choice. Instead of adaptive array processors, a SBS uses a simple switching network (SN) to select the most appropriate beam from a set of predefined beams produced by a fixed beamforming network (BFN). The main scope of this chapter has been the investigation of the potential of the switched-beam approach in modern mobile communications.

The most popular fixed BFN for applications in mobile communications is the Butler Matrix (BM). The various beamforming possibilities of an improved BM based SBS have been discussed and extensive simulations took place, in order to compare their performance in terms of the required base station transmit power towards the desired mobile user. Besides the Typical Switching (TS) determined by the highest received power or SINR, a novel beamforming proposal has been also examined, which is the operation of a SBS that uses the DoA information of the desired user. The proposal is called DoA-based Switching (DoAS) and uses the neural network (NN) DoA estimation methodology developed by the authors in a previous work (Gotsis et al., 2009). The NN has low processing time compared to an adaptive array processor that runs a typical adaptive beamforming algorithm. This, together with the rapid response of the SN's switches provides fast decision and operation.

The simulation results lead to general conclusions concerning the operation of a SBS in a UMTS base station and also evaluate DoAS. The improved SBS besides supporting DoAS, it also provides a set of extra directive beams for more accurate transmission towards a target. The use of these fixed beams either in a typical way or in conjunction with DoAS gives improved performance results and shows very good potentiality. However, in order to

further increase the overall power gain, the losses of the described BFN should be reduced. The design of a more power-effective BFN could be a next step of our work.

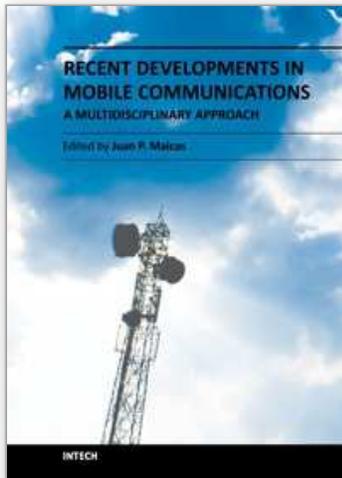
The chapter ends with a brief discussion regarding the evolution of beamforming, and especially the role of switched-beam techniques, from 3G towards 4G mobile communications systems. Modern implementations require that smart antenna configurations adapt to the varying conditions of a radiocommunications link and choose accordingly the most suitable smart antenna technique or even a combination of them. Within this context, a simple antenna structure has been described that applies beam switching (using a BM) in conjunction with spatial multiplexing (SM). Such a structure combines the increase in coverage and capacity due to beamforming, with the increase in the data transmission rate due to SM. SM is a Multiple Input-Multiple Output (MIMO) scheme that involves the parallel transmission of multiple data streams, using two or more antenna elements at both sides of the link. Contrary to that, beamforming is a Multiple Input-Single Output (MISO) technique, since it uses an array of antenna elements only at one side of the link (typically the base station).

As a future work in this field we intend to investigate the possibility of the simultaneous transmission of orthogonal beams from a single BM, in order to combine beam switching with SM into a single antenna array. The BM beam orthogonality may be useful in the context of MIMO processing, where low correlation between signals is needed.

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Recent Developments in Mobile Communications - A Multidisciplinary Approach offers a multidisciplinary perspective on the mobile telecommunications industry. The aim of the chapters is to offer both comprehensive and up-to-date surveys of recent developments and the state-of-the-art of various economical and technical aspects of mobile telecommunications markets. The economy-oriented section offers a variety of chapters dealing with different topics within the field. An overview is given on the effects of privatization on mobile service providers' performance; application of the LAM model to market segmentation; the details of WAC; the current state of the telecommunication market; a potential framework for the analysis of the composition of both ecosystems and value networks using tussles and control points; the return of quality investments applied to the mobile telecommunications industry; the current state in the networks effects literature. The other section of the book approaches the field from the technical side. Some of the topics dealt with are antenna parameters for mobile communication systems; emerging wireless technologies that can be employed in RVC communication; ad hoc networks in mobile communications; DoA-based Switching (DoAS); Coordinated MultiPoint transmission and reception (CoMP); conventional and unconventional CACs; and water quality dynamic monitoring systems based on web-server-embedded technology.

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