Paper

Radio Channels Modeling for Adaptive Antennas Applications – Analysis of Elevation, Azimuth and Delay Spread

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Abstract—Research of modeling urban environment channel has been presented in this paper. Measurements were performed for 2.2 GHz band. Test environment was based on existing 3G sites. Elevation, delay and azimuth spreads were analyzed. Both theoretical channel modeling and similar tests campaign were subject for analysis in this paper. Based on radio channel modeling further investigations are presented and the adaptive antenna implementation was proposed.

Keywords—adaptive antenna, cellular systems, radio channel modeling.

1. Introduction

Intensive development of urban environment causes that c.a. 80% of cellular traffic is generated in cities [1]. Research on beam steering algorithms for adaptive antennas force to investigate fundamental questions related to channel modeling.

Proper channel modeling and selection of its key parameters for urban environment is fundamental for creating effective adaptive algorithms for cellular systems. Measurements dedicated to urban environment allowed validation of theoretical channel models and were accounted for the major aim of this research. This paper aggregates available measurements campaign results and contains tests outputs presentation. Analysis of statistical delay, azimuth and elevation spreads range allows recommendation preparation for adaptive antenna concept.

The research takes under account several selected propagation models for which theoretical key parameters values for adaptive algorithms have been calculated. Measurements were done for 2.2 GHz mid-frequency in urban environment and were analyzed for 1.8–5.3 GHz bands. Concept of adaptive antenna presented [2] is foreseen for LTE bands (1.8 or 2.6 GHz). To observe 3D propagation phenomena in urban environment for both bands, the 2.2 GHz central frequency was selected. Tests were conducted for both channels uplink (UL) and downlink (DL).

Measurements results and theoretical channel model parameters calculations were examined in order to estimate its impact on adaptive antenna techniques. The final analysis gives allowed range of optimal beam width selection in case of horizontal beam control and downtilt adjustment optimal range for vertical sectorization. Presented in this paper results are base for adaptive antenna project specified in [2].

2. Theoretical Results

2.1. Assumptions

The range of propagation models taken into account in this (TDL) [3] and Multiple Input Multiple Output (MIMO) covering: Spatial Channel Model (SCM), ITU, and Winner specified in [4]. Typical process of modeling channel characteristic contains: measurements, path estimation, and channel parameters.

This analysis focus on key channel parameters: Azimuth Spread (AS), Elevation Spread (ES) and Delay Spread (DS). Presented studies do not contain aspects of polarization and fading. By definition typical AS is a base for expected antenna horizontal beam width. ES is used for

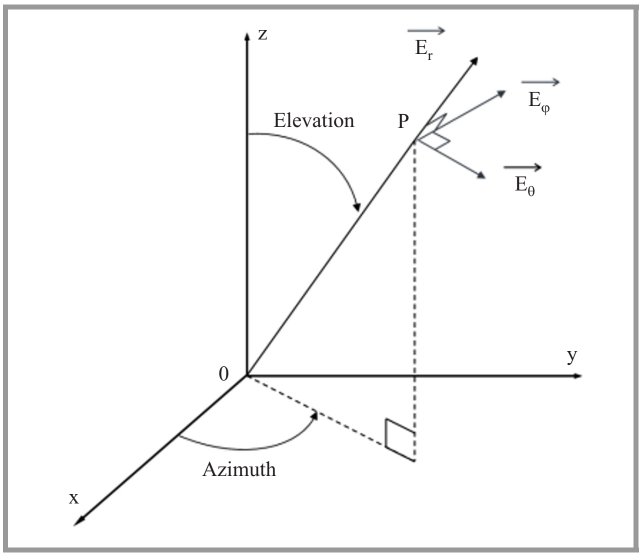

Fig. 1. Physical channel model.

the most adequate vertical beam width and range analysis of vertical beam steering. Beam switching time is compared with DS and potential loss of received signal energy. Figure 1 shows 3D channel model. The ray is azimuth and elevation angle function on both MS and BS sides, signal and delay power. The ray is described by: θ_{iMS}, φ_{iMS}, θ_{iBS}, φ_{iBS}, P_i, τ_i.

AS has been defined as follows:

$$\mathrm{AS} = \min_{\Delta=1\ldots 2\pi} \left(\mathrm{AS}(\Delta)\right), \tag{1}$$

$$\mathrm{AS}(\Delta) = \sqrt{\frac{\sum_i \left(\mathrm{mod}\left(\varphi_i + \Delta\right) - \bar{x}_{\mathrm{AS}}\right)^2 \cdot P_i}{\sum_i P_i}}, \tag{2}$$

$$\bar{x}_{\mathrm{AS}} = \frac{\sum_i \mathrm{mod}\left(\varphi_i + \Delta\right) \cdot P_i}{\sum_i P_i}, \tag{3}$$

where AS is minimal value of AS(Δ), and Δ is added to received azimuth angle φ_i. Elevation Spread based on standard deviation formula calculation:

$$\mathrm{ES} = \sqrt{\frac{\sum_i (\theta_i - \bar{x}_{\mathrm{ES}})^2 \cdot P_i}{\sum_i P_i}}, \tag{4}$$

$$\bar{x}_{\mathrm{ES}} = \frac{\sum_i \theta_i \cdot P_i}{E_i P_i}. \tag{5}$$

Theoretical value of Delay Spread is defined as:

$$\mathrm{DS} = \sqrt{\frac{\sum_i (\tau_i - \bar{x}_{\mathrm{DS}})^2 \cdot P_i}{\sum_i P_i}}, \tag{6}$$

$$\bar{x}_{\mathrm{DS}} = \frac{\sum_i \tau_i \cdot P_i}{E_i P_i}. \tag{7}$$

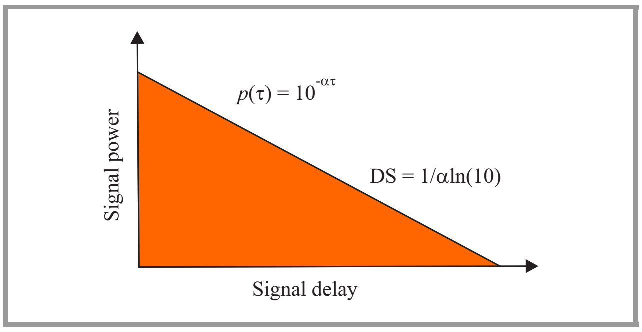

Fig. 2. DS simplified calculation model.

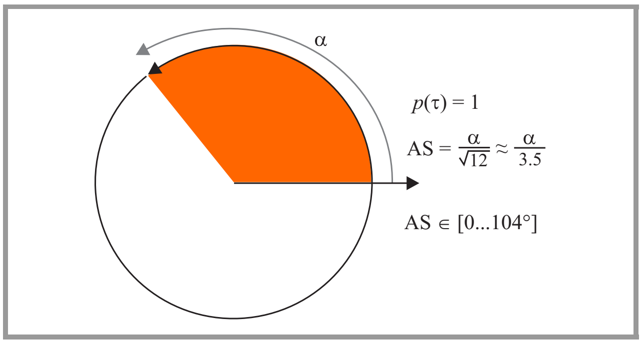

Fig. 3. Example for AS estimation range.

Equations (1)–(7) were used for calculation key channel parameters. In order to reduce time spread calculation it was assumed that signal ray received power decreases linearly. Arbitrary presumptive decrease by 20 dB was defined as a full signal package, no weaker signal was taken for consideration. Therefore, the DS parameter time period when signal get the starting point value –20 dB. The simplification is presented in Fig. 2. According to the ray definition, τ is signal delay, and $p(\tau)$ is function of the receive signal power with parameter α, where α is AS in radians.

As an example a theoretical outputs for $\tau = 1$ μs is DS = 200 ns. Next based on $p(\tau)$ AS value is calculated, and as presented in Fig. 3 case azimuth spread is $0\ldots104°$.

2.2. Results Achieved for Selected Channel Models

Table 1 shows distinguished both channels uplink and downlink parameters. AS-BS is azimuth spread observed from BS (uplink), as AS-MS from the perspective of mobile station (downlink). Presented theoretical values are based on [5], [8], [9]. Considered models are dedicated to macrocells and microcells environment (SCM and ITU models), with low and high mobility. Slow moving terminals, i.e. pedestrian type – PA, ePA, fast moving terminals, i.e., vehicle type VA, eVA as well as Winner models have been analyzed.

Table 1
DS and AS for theoretical channel models

Model	DS [μs]	AS-BS [°]	AS-MS [°]
VA	0.37		
PA	0.045		
eVA	0.357		
ePA	0.045		
Winner C2	0.23	8.5	52.5
Winner C3	0.63	17	55
Winner B1	0.076	15	35
Winner B2	0.48	33	55
SCM Micro	0.25	19	70
SCM Macro	0.65	15	70
ITU Umi	0.13	26	69
ITU Uma	0.365	26	74

The value AS-MS is much higher than AS-BS due to signal multipath propagation, scattering and reflections. Based on theoretical outputs receiving antenna, horizontal beam width at BS can be limited to 33°. This allows capturing multipath rays for all analyzed models. Theoretical DS value does not exceed 650 ns. It forces the limitation time for beam switching in implementations with adaptive antenna algorithms. Receiving time extended to maximum DS allows capturing the spread signal in time domain. Remaining time consequent to physical layer structure can be used for beam switching without received signal energy degradation.

Table 2
DS, ES and AS (UL, DL) measurements results

Location	Distance [m]	Band-width [MHz]	Carrier freq. [GHz]	DS [μs]	AS-BS [°]	ES-BS [°]	AS-MS [°]	ES-MS [°]	Year	Institution
Frankfurt	2000	6	1.8	0.5	8				1998	Deutsch Telekom
Paris Mulhouse	800	10	2.1	0.25	10				2007	Orange
Norway	400	50	2.1	0.06	10				1999	U. Trondheim/ Telenor
Sweden	500	150	1.8	0.11	8				1999	Telia
Sweden	500	150	1.8	0.08	7				1999	KTH/Telia
Aarhus Stockholm	200–1600	5	1.8	1	10				2000	U. Aalborg Nokia
Bristol	700	20	19	0.44	10				2001	U. Bristol
Bristol		20	1.9 2.1	0.13	8				2002	U. Bristol/ Telia
Bristol	1500	20	1.9 2.1	0.3			74		2003	U. Bristol
Helsinki		60	5.3		8	2	52	8	2004	U. Helsinki
Munich		120	5.3	0.5	10		60		2005	U. Ilmenau
Stockholm	150	200	5.25	0.25	20		80	20	2005	Ericsson
Helsinki	1500	100	5.3	0.13			48		2007	Nokia
Seoul	500	100	3.7	0.77			72		2007	ETRI
Beijing	1000	100	2.35	0.21			65		2008	U. Beijing/ China Mobile
Ilmenau	500	90	2.53	0.07			40	20	2010	U. Ilmenau
Paris Mulhouse	500	62.5	2.2	0.17			55	8	2011–2012	Orange
Dresden	1000	100	2.53	0.13	5		33	15	2011	U. Ilmenau/ Berlin
Karlsruhe	400	120	2	0.2	11				2006	U. Karlsruhe
Rotterdam Amsterdam	500	100	2.25	[0–0.6]$^{*)}$			[20–80]$^{*)}$		2009	U. Eindhoven/ TNO
Stockholm	1000	BE	1.8		16		72		2008	KTH

$^{*)}$ Values range for specific parameters.

Note: in cases where 2 cities are specified tests were conducted in both places to improve average values extrapolation.

It must be noticed that radio channel models studied in this paper do not include the latest results of 3GPP standardization Work Groups. It seems that general approach of taking under consideration elevation angle and terminal height are not enough for proper modeling radio channels. Modeling 3D channels need to take into account real length of signal path in three dimensional space. Flat 2×2D model with mapping real signal path on horizontal and vertical layers causes inaccuracy in signal path. Actually this conclusion is also in line with further presented field measured results. The theoretical DS maximum value presented in Table 1 is 650 ns. Due to longer path in real 3D environment the observed Delay Spread is reaching 770 ns as it presented in Section 3.

3. Measurement Results

The field trials results are shown in Table 2. All data were collected during measurements over last decade, detail references to individual tests are in [9]. The spread of achieved results are showing complexity level of analyzed phenomena. Conclusion on typical values for AS, ES, DS is not obvious, therefore any estimation contains a high level of uncertainty. While AS-BS is below 20°, at the same time for downlink parameter AS-MS is significantly higher, and reaches 80°. DS time is close to theoretical values with maximum at 770 ns and in majority cases (95%) is no higher than 450 ns.

Test series done by Orange Labs in Paris 2011/2012 is a subject for detail analysis in this paper. Detail tests conditions are described in [5]. Measurements were done for 10 MHz bandwidth with center frequency set on $f =$ 2.241 GHz. The dedicated test series was focused on selection the typical values range for key 3D channel parameters in urban environment. AS and DS values were studied for uplink based on 450 measurements. There has been also examined correlation between parameters: DS, AS, ES for downlink based on 50 acquisitions.

There were done two test series for uplink and downlink transmission:

- for UL – a 10 elements linear antenna array with on site location was used and for terminal an omnidirectional antenna mounted on test car roof top. There were done 9 measurements cycles for each BS location;
- for DL – a bipolar omnidirectional antenna was mounted and virtual planar array concept was used for receiving signal on terminal site. In this case bandwidth was extended from 10 to 62.5 MHz.

For the first part of tests - for UL, it has been specified three channels:

- typical 1 – 30% measured points AS = 4°, DS = 175 ns,
- typical 2 – 30% measured points AS = 5°, DS = 240 ns,
- typical 3 – 20% measured points AS = 16°, DS = 300 ns.

Additionally it has been defined 3 rare channel characteristics:

- high DS – 5% measured points AS = 6°, DS = 550 ns;
- high BS-AS – 5% measured points AS = 23°, DS = 110 ns;
- low BS-AS – 5% measured points AS = 0.5°, DS = 170 ns.

Figure 4 presents results achieved for UL, measured points colors are chosen based on 6 different channel models definition. However for the purpose of finding "typical" values the higher weight in analysis is given to the channels called typical 1–3.

The high AS spreads are observed for locations close BS, less than 100 m. Further from the site the AS maximum values are decreasing from 35° to 10° at the cell edge.

For ISD defined as 800 m AS is dropping below 7–10° level at the cell edge. This phenomenon can be observed in results shown in Fig. 5.

The AS high values observed close to the site are mainly caused by multipath signal propagation. The first strong buildings reflections cause azimuth wide range observed from BS perspective for measurement locations close to the site center. The AS observed from BS is decreasing as distance to the site center is increasing with constant distance between buildings conditions. There were no dominant tall objects in neighborhood and buildings were similar heights. Due to unified urban environment with regular street blocks strong reflections from far objects have been limited. This phenomenon can be used in dynamic adaptation for beam-azimuth as well as for beamwidth. Increasing distance and path loss requires budget link compensation that can be achieved by narrowing the beam width and increasing antenna gain.

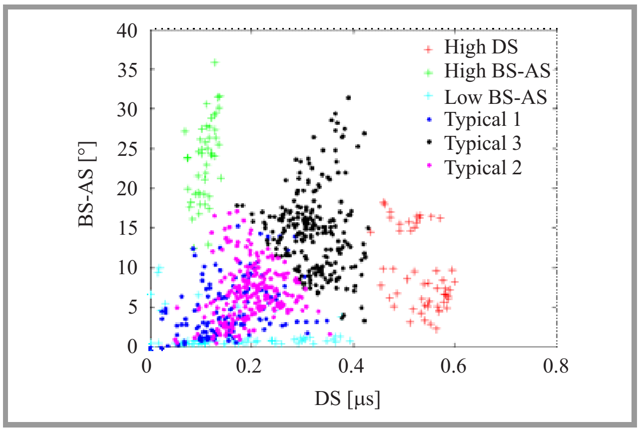

Fig. 4. Results for DS and AS (UL).

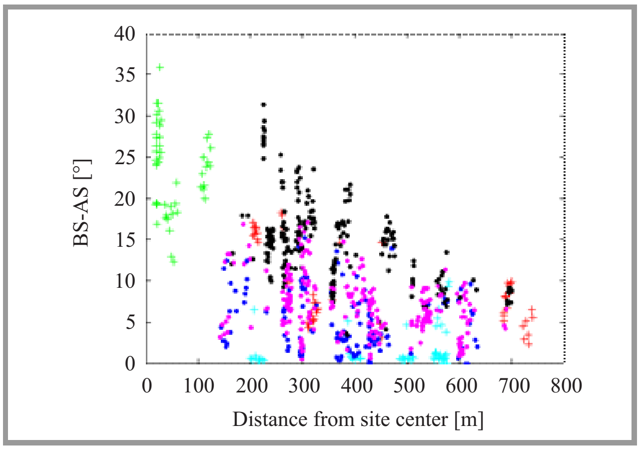

Fig. 5. Results for DS and AS (UL).

There is no correlation observed in DS distribution in relation to terminal distance from the site center. Data collected on measurements are presented in Fig. 6.

DS high values are mainly observed at the cell edge, however generally it is uniform distribution. Beam switching speed is much slower than measured level of delay spreads and at least for slow adaptive algorithm implementation should not cause issues.

In second test campaign dedicated to DL channel characteristic it has been discovered significant difference in range of key parameters comparable to UL. Measurements were done in 50 locations within selected single base station

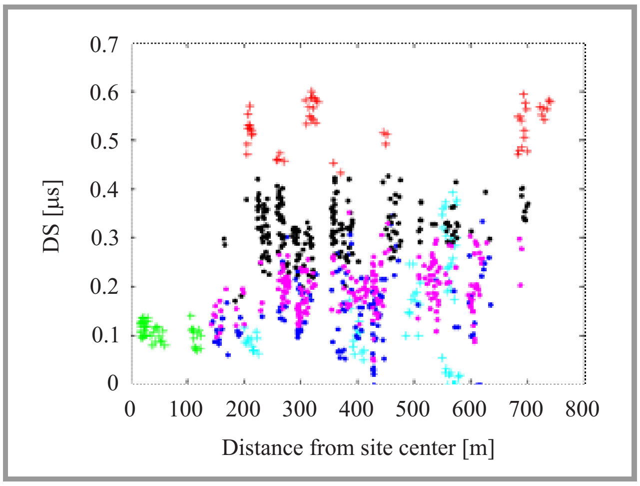

Fig. 6. DS vs distance (UL).

coverage. Photo documentation was collected to further estimate ES. Average achieved AS value is 55°. Relation between AS and ES is shown in Fig. 7.

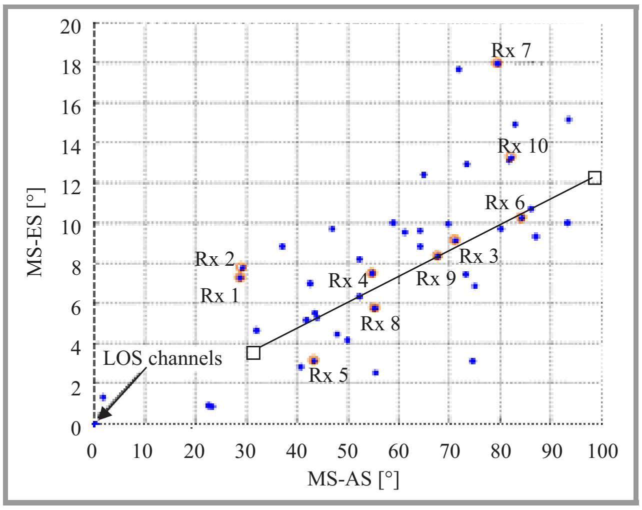

Fig. 7. ES vs. AS (DL) measuring outputs.

As depicted there is observed linear correlation between analyzed parameters usually for locations with high AS, high ES is also observed. This correlation could also be a trigger for potential implementation of adaptive algorithms. Two groups of results are taken under consideration: first one with low AS/ES: Rx1, Rx2, Rx4, Rx5, Rx8 and second one with high AS/ES: Rx3, Rx6, Rx4, Rx7, Rx9, Rx10. The corresponding values are: low (AS = 25–55°, ES = 3–8°), and high (AS = 65–85°, ES = 8–18°). Creating a common antenna patterns for those two major groups is not obvious. The results are observed for DL on terminal site and sophisticated beam creation by mobile terminal might be physical implementation issue.

Figures 8 and 9 presenting photo documentation for locations Rx8 and Rx9. Multipath propagation of received DL signal have been mapped on surroundings with color and circle size scale. The circles indicate direction of received signal. Scale is calibrated to the main path (0 dB) and ranges of studied signals were limited to –20 dB. Each location of circle on the pictures is representing estimated signal path direction and multipath channel signal strength. Both examples have been retrieved from measured documentation published in [5].

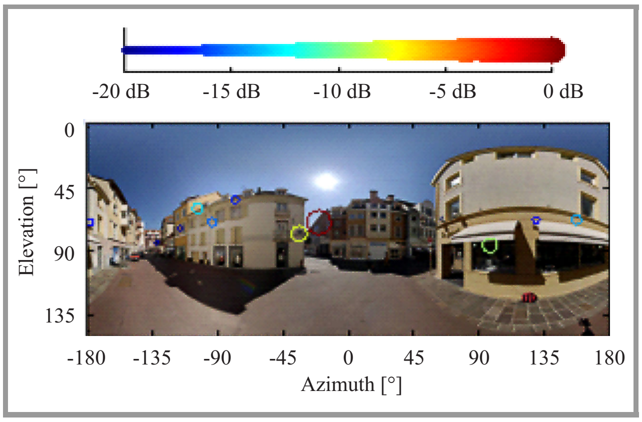

Fig. 8. Main signal directions in point Rx8.

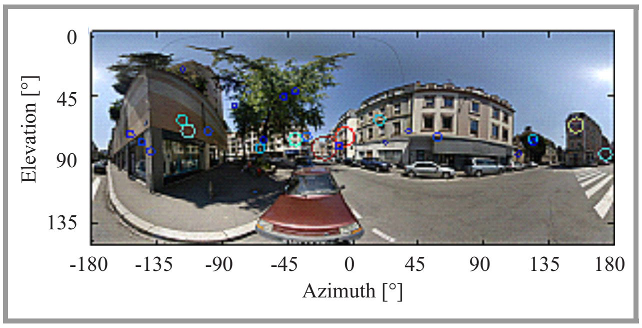

Fig. 9. Main signal directions in point Rx9.

There is limited number of available results for measured ES. An average value ES-MS presented in Fig. 7 is 9° with maximum value as high as 18°. In other tests listed in Table 2 the range of ES-MS is between 8–20°. However, data available for ES observed form base station is very limited. The only test proved in to estimate for ES-BS is based on [7] and [8] and returns the average estimated value 2°. The level of uncertainty is high and independent

Fig. 10. Selected 13 measurements points.

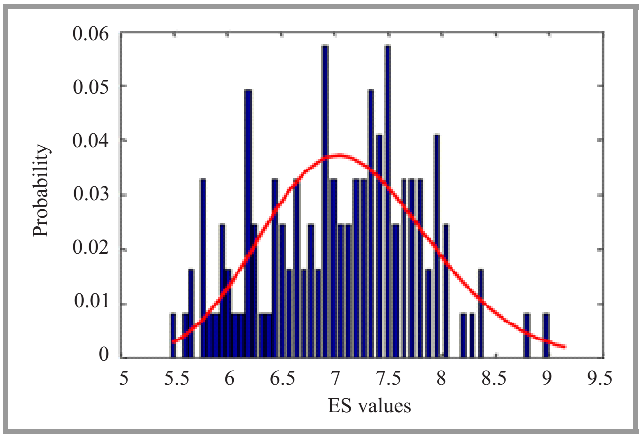

Fig. 11. ES-BS consolidated results.

field data source was required. In order to collect missing radio channel modeling key parameters dedicated tests have been done in typical street block dense urban environment as shown in Fig. 10. Dedicated tests outputs are presented in Fig. 11. ES-BS parameter is critical for adaptive antenna prerequisites and is used for an antenna model proposal presented in Section 4. The ES-BS average value is much higher than expected and equals 7°, the results range is between 5.5° and 9.5°.

4. Adaptive Antenna Implementations

Based on theoretical results and measured radio channels parameters it was concluded that examined two key parameters (AS, ES) are much higher for DL than UL signals paths. Additionally AS and ES spread for DL is uncorrelated and it required adaptation not only to azimuth direction but also for effective adaptive algorithm beamwidth. Terminal antenna pattern adaptation to DL receiving paths is difficult for implementation due to cost, construction problems and space limitation. Further base station adaptive antenna analyzes were done with simplified algorithms that might be trigger for commercialization of some presented solutions.

4.1. Horizontal Antenna Pattern

Based on analysis done in Section 3 half power beamwidth ($HPBW_{-3dB}$) for horizontal plane can be limited to 20° in most cases assuming ideal beam azimuth adaptation. The maximum values of BS-AS do not exceed horizontal spread above 33°. It seems reasonable to create adaptive algorithm that get usage of this phenomenon and build an antenna with sharp horizontal pattern that allow increase its gain. At the same time the implementation can be possible only if complete sector (typically 120°) is covered by adaptive beams set. This basic idea is well known, however collected field data analysis allow to create some fundamental conclusions. The optimum scenario for urban environment with ideal or near ideal adaptive algorithm should be based on 6 beams scenario for beam switching techniques. Eventually an advanced beam forming with individual channel analysis (main beam direction and "zeros" control to limit interference) might be implemented and take place of simple pattern switching. However, currently simulated gains of adaptive algorithms do not justify the high complexity. Significant processor load increase and finally bigger energy consumption for complex beamforming implementations are required. Following the pragmatical solutions way a concept based on limitation the portfolio of available beams to two major patterns in horizontal plane was proposed. There is an engineering approach for addressing the analysis observed in typical urban radio channels phenomena – an adaptive antenna concept is presented in Fig. 12.

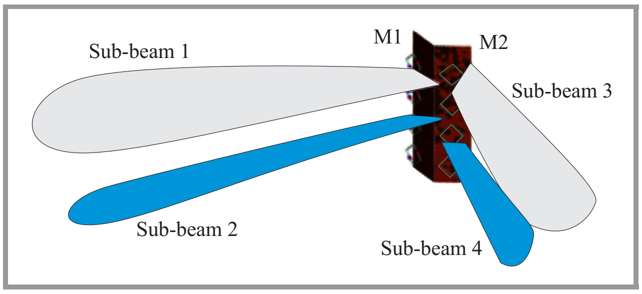

Fig. 12. Adaptive antenna model with vertical and horizontal beam steering.

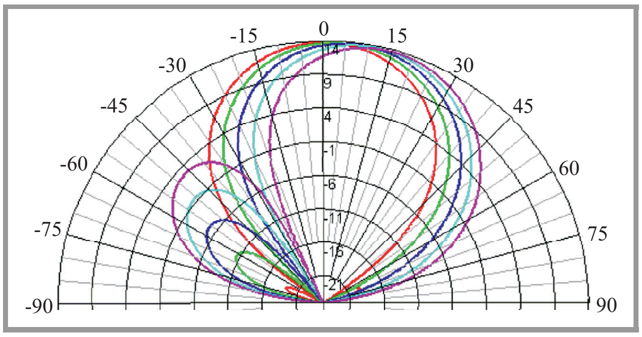

Fig. 13. Horizontal beam steering – main side lobe.

The physical separation between two M1 and M2 modules allow receiving narrow antenna radome with 320 mm wide for 1800 MHz center frequency and antenna patterns for two beams without unwanted side lobes effect. Side lobes suspension is one of the major proposed solution advantages as it is difficult to avoid in beam steering supported by antenna array case, when beams are created based on individual antenna array elements phase shifting either in baseband. Typical narrow array results for simplified antenna pattern with beam steering up to ±17° are presented in Fig. 13.

4.2. Vertical Antenna Pattern

The antenna model presented in Fig. 12 is also equipped in vertical beam forming feature that dynamically allows adapting the optimum downtilt independently for antenna module 1 and 2. Additionally $\mathrm{HPBW}_{-3\mathrm{dB}}$ in vertical plane optimization was done. Taking the same analogy to the horizontal plane the ultimate goal for vertical beam width is 7°. Creation narrower beam from hardware perspective requires vertical elements number increase, which negatively impact antenna size, complexity, weight and cost. Observed radio channels phenomena in urban environment do not justify narrowing the receiving window and signal energy losing part – maximum observed ES limits the $\mathrm{HPBW}_{-3\mathrm{dB}}$ in vertical plane. The proposed in Fig. 12 model [9] with simulated adaptive features, i.e., virtual vertical sectorization and horizontal beam switching, allows LTE-A cell throughput increase in downlink by 40–70%.

5. Summary

In this paper results of radio channel modeling analysis were presented for number of theoretical models based on literature and test campaigns results for 1.8–5.3 GHz bands. There were analyzed in details for UL and DL conducted in Paris and Mulhouse. ES measurements were done for selected UMTS site in dense urban environment. For 2.2 GHz band ES, AS, DS were analyzed as key parameters for design adaptive antenna model prerequisites. Further studies were limited to base station antenna and proposal for $\mathrm{HPBW}_{-3\mathrm{dB}}$ for horizontal and vertical plane have been presented: 20–33° and 7° accordingly.

Time required for beam switching techniques are not limited by DS values. The maximum DS is below 1 μs. This should allow slow switching adaptive algorithms implementation that based on example presented in [9] requires 40 ms for adaptation period and every 10 ms takes a switch decision.

The overall pragmatic adaptive antenna solution for low cost implementation into commercial LTE/LTE-A networks is possible and recommended. The number of tests data collected for radio channels modeling indicate typical AS, ES and DS values. The key radio parameters range spread analysis provide requirements used for design the adaptive antenna concepts based on horizontal and vertical beams selection.

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