

A BEAMFORMER FOR 120-DEGREE SECTORIZATION IN LTE SYSTEMS

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Abstract

Long term evolution (LTE) technology is the most likely candidate for the next generation of mobile wireless communications. One drawback of LTE is interference from neighboring cells, so called inter-cell interference. Fractional frequency reuse (FFR) has been proposed to handle the problem. Also lately, a soft FFR technique has been introduced for better utilization of the frequency spectrum. In addition, the beamforming technique is considered to be the solution to improve the performance of wireless communication systems. Therefore, this paper proposes a new beamforming matrix suitable for LTE systems in which the coverage area is divided into 3 120°-sectors. The appropriate number of antenna elements and beam patterns is discussed. The computer simulation in terms of beam patterns confirms the proposed concept. Also, a prototype of the new beamformer is fabricated and tested to reveal the real performance in terms of the signal-to-interference ratio and channel capacity. The obtained results show that the soft FFR technique including beamforming is the best choice for LTE systems.

Keywords: Beamforming network, inter-cell interference, LTE, mobile networks, switched-beam antennas, sectorization

Introduction

Recently, mobile wireless communication users have been demanding the use of multimedia services with the requirement of higher data access capability for subscribers together with guaranteed quality of services. In addition, the number of users has grown at an unprecedented speed. A long term evolution (LTE) system is the most likely candidate for the next generation of mobile wireless communications. From the first to the third generation of mobile wireless

communications, attention was paid to support a fast data transfer-rate devoted to the transmission of voice, image, and video. However, some drawbacks have been left from previous generations and it is envisaged that the next generation of mobile wireless communications will tackle the problems, e.g. a higher speed data transfer-rate, a global standard to support usage in different areas, and a stable connection for multi-media and video or wireless teleconference.

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The LTE systems are a preliminary mobile wireless communication standard, formally submitted to the International Telecommunications Union's (ITU) Telecommunication Standardization Sector in late 2009 as a candidate for the fourth generation of mobile wireless communications. LTE is standardized by the 3rd Generation Partnership Project (3GPP) as a major enhancement of the 4G 3GPP LTE standard. The goal of LTE is to provide a high data-rate transmission, low-latency, packet-optimized radio-access technology supporting flexible bandwidth deployments, and an improved quality of service to reduce delay (The 3rd Generation Partnership Project, 2006). However, the LTE technology cannot provide full benefits for mobile communications due to the problem of interference signals from neighboring cells, which is called inter-cell interference (ICI).

The ICI problem is more pronounced when users are moving away from the cell center towards the cell edge. As a result of this, the signal-to-interference ratio (SIR) at the user or mobile terminal is reduced due to 2 major reasons, as follows: first, the signal transmitted from the base station to mobile terminals is dropped because of an increase in path loss; secondly, the ICI from neighboring cells becomes more pronounced when users are moving to the cell edge. The techniques proposed to mitigate the ICI can be classified into several types and can be surveyed in Khan, 2009. So far, the fractional frequency reuse (FFR) technique divides a whole frequency band into several sub-bands wisely allocated to some specific areas in order to improve signal quality at the cell edge. Recently, a soft FFR technique has been proposed by managing the different levels of transmitted power respective to the distance between the users and the cell center. However, the mentioned technique cannot completely mitigate the ICI.

Therefore, a smart antenna technology cooperating with the soft FFR technique is envisaged as the best solution to enhance the system quality. The smart antennas are termed technology which constitutes an antenna array and signal processing unit (Alexiou and Haardt, 2004). The key to the success of smart antennas

is to form the main beam to a desired direction while the nulls or side lobes can be pointed to the directions of the interference signals, so called beamforming. The smart antennas can be generally classified into 2 types: adaptive and switched beam antennas. Comparing between these types, the switched beam antennas have more advantages in terms of low complexity and implementation cost. The switched beam systems require only a beamforming network, a radio frequency switch, and a logic controller to select a suitable beam (Liberti and Rappaport, 1999). With its many advantages, the adoption of smart antenna technology in future wireless systems will have a significant impact on the efficient use of the spectrum, the minimization of the establishment cost, the optimization of service quality, and the realization of a transparent operation across multi-technology wireless networks. The work presented in Liu *et al.* (2009) 2009 has revealed that beamforming is 1 technique to improve the cell edge performance. Also, an advantage of beamforming in 4G mobile networks, in terms of avoiding collided mobile terminals in 1 beam, has been shown in Lott (2006).

From the above motivation, this paper investigates the LTE system's performance when employing FFR schemes, including conventional FFR and soft FFR. Also, several scenarios are assumed, including 120° sectorization and beamforming. In this paper, 2 parameters indicating the systems performance and signal quality are the signal-to-interference ratio (SIR) and the channel capacity. This paper begins with a brief concept of mobile communication evolution in Section 2 followed by some background of LTE in Section 3. Some introductions to the frequency reuse technique and smart antennas are discussed in Sections 4 and 5, respectively. Then, performance of the frequency reuse technique, including beamforming for LTE systems, is revealed in Sections 6 and 7. In addition, an appropriate number of antenna elements and beam patterns for LTE systems is also discussed in this section. Section 8 shows a design for a beamforming matrix suitable for LTE systems. Moreover, Section 9 demonstrates a beamformer prototype

proposed in this paper. Also, a result comparison in terms of beam patterns, SIR, and the capacity between the ones obtained from the simulation and experiment is shown in Section 9. Finally, Section 10 concludes the paper.

Evolution of Mobile Wireless Communications Systems

Mobile cellular systems are 1 of the most popular wireless communication systems nowadays as they have a profound impact on people's daily lives. As mobile wireless communications are a factor of five for human life, so they have grown with unprecedented speed. In 1979, the first cellular system was introduced by Nippon Telephone and Telegraph in Tokyo, Japan. So far, the evolution of mobile cellular systems has been categorized into generations, as shown in Figure 1.

- The first generation of mobile wireless communications (1G) transmits an analog signal for speech services. The 1G systems offer handover and roaming capabilities but the 1G cellular networks are unable to interoperate between countries. This restraint is 1 of the inevitable disadvantages of 1G mobile networks.

- The second generation of mobile wireless communications (2G) was introduced at the end of the 1980s. Compared with 1G systems, 2G systems use digital multiple access technologies, such as time division multiple access (TDMA) and code division multiple access (CDMA). These 2G systems provide circuit switched data communication services at a low speed transmission (Ibrahim, 2002). Compared with 1G systems, higher spectrum efficiency, better data services, and more advanced roaming

can be offered by 2G systems. In Europe, the Global System for Mobile Communications (GSM) was deployed to provide a single unified standard. This has enabled seamless services throughout Europe by means of international roaming. The GSM has used TDMA technology to support multiple users during development over more than 20 years. The GSM technology has been continuously improved to offer better services in the market. New technologies have been developed based on the original GSM system, leading to some more advanced systems known as 2.5 generation (2.5G) systems. Third generation (3G) systems have been introduced in the market, but their penetration is quite limited because of several techno-economic reasons.

- Third generation (3G) systems have been introduced in the market, but their penetration is quite limited because of several techno-economic reasons. For 3G mobile wireless communications, the ITU defined the demands for 3G mobile networks with the IMT-2000 standard. The 3GPP organization has continued that work by defining mobile systems which fulfill the International Mobile Technology (IMT-2000) standard. The 3G networks enable network operators to offer a wider range of more advanced services while achieving greater network capacity through improved spectral efficiency. Services include wide area wireless voice telephony, video calls, and broadband wireless data, all in a mobile environment. Additional features also include high speed packet access (HSPA) data transmission capabilities which allow delivery of transmission speeds up to 14.4 Mbps on downlink and 5.8 Mbps on uplink

- New technologies in mobile commu-

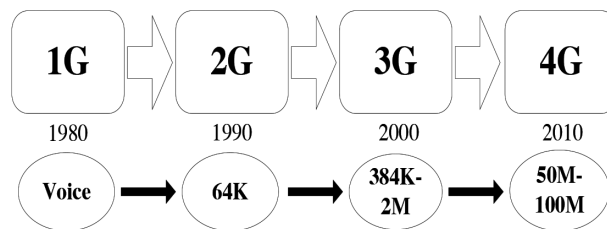


Figure 1. Evolution of mobile wireless communications

nication systems and also the ever increasing growth of user demand have triggered researchers and industries to come up with a comprehensive manifestation of the upcoming fourth generation (4G) mobile communication systems. In contrast to 3G, the new 4G framework tries to accomplish new levels of user experience and multi-service capacity by also integrating all the mobile technologies that exist (e.g. GSM, General Packet Radio Service (GPRS), IMT-2000, Wireless Fidelity (Wi-Fi), and Bluetooth). Industry experts say that users will not be able to take advantages of multimedia content across wireless networks with 3G. In contrast, the 4G systems will feature extremely high quality video of a quality comparable to high definition television. The wireless download speed reaches to 100 Mbps, i.e. 50 times that of 3G (Santhi *et al.*, 2003).

Long Term Evolution

The LTE technology is a standard for wireless data communication technology and an evolution of the GSM/UMTS standards. The goal of LTE is to increase the capacity and speed of wireless data networks using new digital signal processing techniques and modulations which were developed around the turn of the millennium. A further goal is the redesign and simplification of the network architecture to an IP-based system with

significantly reduced transfer latency compared with the 3G architecture. The LTE wireless interface is incompatible with 2G and 3G networks, so that it must be operated on a separate wireless spectrum. However, LTE technology cannot provide full benefits due to the problem of signal interference coming from neighboring cells, the ICI. Figure 2 shows a scenario of the ICI. The ICI occurs when users are moving away from the cell center towards the cell edge. As a result of this, the SIR at a mobile terminal is reduced due to 2 reasons, as follows: first, the signal transmitted from the base station to mobile terminals is dropped because of an increase in path loss; secondly, the ICI from neighboring cells becomes more pronounced when users are close to their cell edge. The SIR of the mentioned system can be expressed as follows:

$$SIR = \frac{P_c r_c^{-\alpha}}{\sum_{i=1}^n P_{Ei} r_{Ei}^{-\alpha}} \quad (1)$$

where α is the path-loss exponent, is the transmitted power from the base station to the cell center area of interest, P_{Ei} is the transmitted power in the region of the cell edge belonging to the i^{th} base station (neighboring cell), r_c is the distance from a user to the own base station at the cell center, and r_{Ei} is the distance from a user staying in the cell edge region of a neighboring cell to the base station of interest. Please note that all base stations in the system transmit the same level of power.

Furthermore, the channel capacity is 1 factor which can describe the performance of wireless communication systems. The channel capacity used in this paper can be expressed by

$$\frac{C}{B} = \log_2(1 + SIR) \quad (2)$$

where B is the channel bandwidth.

Fractional Frequency Reuse Techniques

So far, the LTE technology has employed several techniques to mitigate the ICI. FFR is a technique to relieve the ICI problem mentioned in Section 3. This technique offers the separation of the frequency spectrum resource into sectors. The

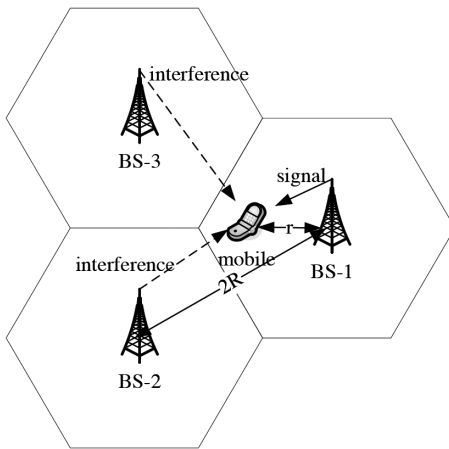


Figure 2. Inter-cell interference scenario

reused frequency spectrum resource is shown in Figure 3. This method also provides maximum utilization of the frequency spectrum. Lately, a soft FFR technique has been proposed for better utilization of the frequency spectrum, as shown in Figure 4. For this technique, the transmitted power at some sub-frequencies is higher in order to cover the area of the cell edge. This technique provides a power allocation arrangement to improve the cell-edge SIR while degrading the SIR for users towards the other cells.

Smart Antenna Technology

Smart antennas are an antenna technology with the capacity for beamforming to a specific direction while pointing the nulls or side lobes to the directions of the interference signal, resulting in an increase in the transmission rate and quality. The smart antennas are composed of an antenna array cooperating with a signal processing unit. For some beamforming schemes, the direction of interest is calculated so that the beam can be adjusted to the desired target destination. In this way, the smart antennas can improve the link quality by combating the effect of multipath propagation or by constructively exploiting the different paths, and also increasing the system capacity by mitigating interference and allowing transmission of different data streams from different antennas. Moreover, the delay in the arrival of a signal caused by the environment can be decreased. In general, there are 2 typical configurations of smart antennas (Balanis and Ioannides, 2007).

A. Switched Beam Antennas

Switched-beam antennas are the simplest

type of a smart antenna technique (Ho *et al.*, 1998; Balanis and Ioannides, 2007). The switched beam antennas are formed by an antenna array working with a signal beamforming network, called the beamformer. The inter-element spacing in the array is generally at a definite distance. The antennas provide multiple-fixed beams with high sensitivity in particular directions. The beam formation scenario of switched beam antennas is illustrated in Figure 5(a). Generally, the switched-beam procedures are based on a basic switching function. First, the system searches for the signal strengths from all the formed beams. When the beam with the highest signal strength has been identified, the system switches beams to such a direction. These procedures are repeated when the user starts moving from 1 place to another. These systems are not complicated, so that they have gained a lot of attention from researchers and also communications companies lately. However, the speed of tracking users totally depends on the beam-switching rate. In addition, the SIR is relatively low when interference sources are in the region of the main beam.

B. Adaptive Antennas

Adaptive antennas are formed from components similar to switched beam antennas with an antenna array and beamforming networks. However, the signal processing scheme utilized on adaptive antennas is totally different. There is some comparison between the system output and the desired signal (or reference signal) after performing the beam-formation process. The error from this comparison is fed back to adjust the weighting coefficients repeatedly. This procedure is called an adaptive process and will be stopped when there is no error in the

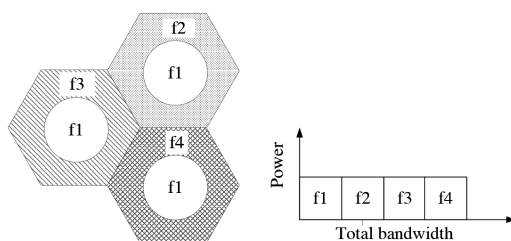


Figure 3. Fractional frequency reuse

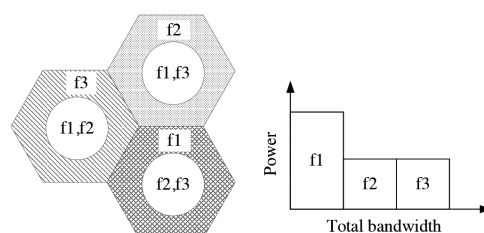


Figure 4. Soft fractional frequency reuse

comparison. This adaptive process helps the beamformer to point its main beam to a desired direction while pointing the nulls to undesired directions, as shown in Figure 5(b). Because of this, the system is able to provide a higher SIR compared with switched beam antennas. In addition, there is no need for antenna calibration and also the system works well even when the number of signals is greater than that of the antenna elements. However, these systems require a hi-speed processing unit to calculate the weighting coefficients utilized for an independent-beam adjustment. Moreover, they need a good reference signal for maximum performance.

From the above brief discussion, switched beam antennas excluding adaptive processing are suitable for implementation at a base station as they are low in cost and complexity. Therefore, this paper investigates into the performance of switched beam antennas on cellular networks. Also, several types of frequency reuse techniques are included in the investigation which will be revealed in the next section.

Simulation

The performance of the LTE systems in this paper is evaluated by the authors' own developed Matlab programming. The total number of adjacent base stations is assumed to be 19 cells. Every base station is assumed to transmit an equal power to the same number of mobile users. The scenarios of the simulations are based on several schemes of FFR, shown in Figure 6, which are (a) sector, (b) FFR, (c) sector with FFR, (d) soft FFR, and (e) sector with soft FFR. Both the FFR and soft FFR have been introduced in order to relieve the effect of the ICI, especially at the region of the cell edge. Also, as the beamforming technique is expected to be another solution to boost up the systems' performance, this paper takes into account the use of beamforming. The simulation parameters are shown in Tables 1 and 2 for the cases of excluding and including beamforming, respectively. The systems' performance in this paper is reflected through 2 indicators: the SIR and the capacity. The SIR for the case when

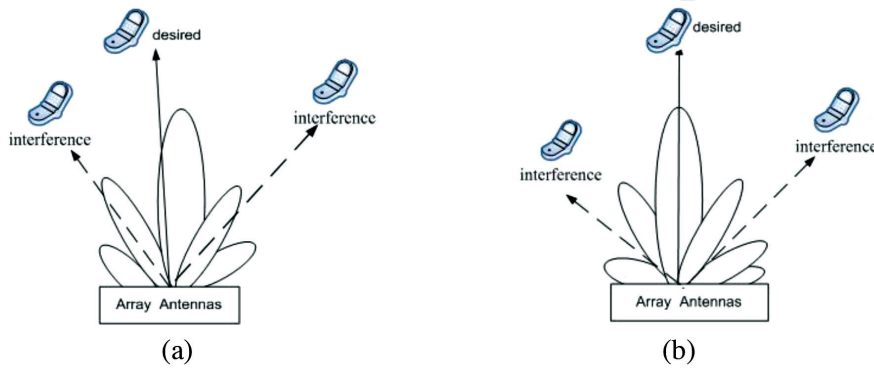


Figure 5. Beam formation for (a) switched beam antennas and (b) adaptive antennas

Table 1. Simulation parameters for case of FFR without beamforming schemes

Number of base station	19
Inter-base station distance	1000 m
Path loss model	3GPP Macro cell [4]
Number of antenna elements	5
Inter-element spacing	$d = \lambda/2$
Number of users random	100
Degree of sector	120°

beamforming is excluded can be calculated using (1), but the expression shown in (3) is used to calculate the SIR in the case of including beamforming:

$$SIR = \frac{G(\theta)_c P_c r_c^{-\alpha}}{\sum_{i=1}^n G(\theta)_{Ei} P_{Ei} r_{Ei}^{-\alpha}} \quad (3)$$

where $G(\theta)_c$ is the gain of the antenna at the base station transmitting to the region of the cell center and $G(\theta)_{Ei}$ is the gain of the antenna at the base station transmitting to the region of the cell edge.

Figure 7 shows the probability density function (PDF) of the SIR for the systems with various scenarios. There is a comparison of the cases: sector no FFR, only FFR, soft FFR, this simulation yet. As we can see, cellular systems with the use of FFR and sectorization statistically provide a higher SIR compared with the ones without FFR and sector. Similarly, for the ones including the beamforming technique, soft FFR with sectorization statistically gives the highest SIR, as seen in Figure 8. This is because of the benefits from allocating a different transmitted power between the cell center and the cell edge

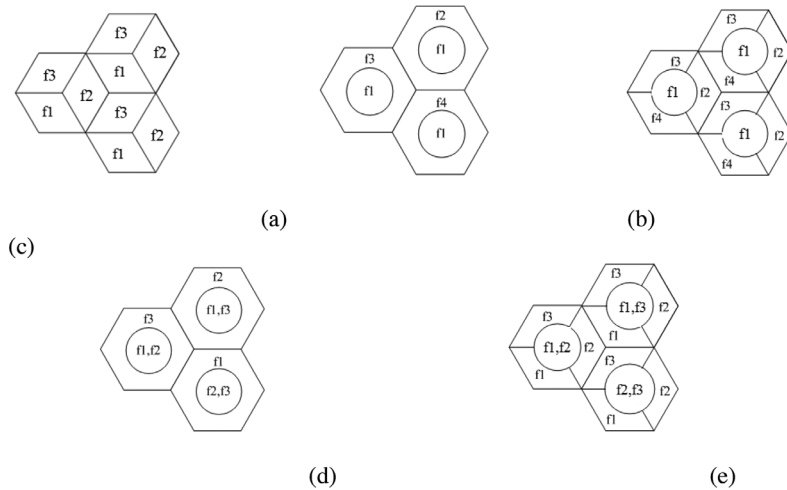


Figure 6. Configuration of FFR schemes: (a) Sector (b) FFR (c) FFR sector (d) Soft FFR (e) Soft FFR sector

Table 2. Simulation parameters for case of FFR with beamforming schemes

Number of base station	19
Inter-base station distance	1000 m
Path loss model	3GPP Macro cell [4]
Number of antenna elements	5
Inter-element spacing	$d = \lambda/2$
Number of users random	100
Degree of sector	120°
Antenna array	Linear array antenna
Element of antenna	5 element
frequency	2.595 GHz

(soft FFR). This brings about the reduction of the ICI. Also, allocating different frequencies to sectors can reduce the effect of the ICI. For a clearer understanding, these 2 cases (with and without beamforming) are also combined, as shown in Figure 9. As we can see, the group of SIR employing the beamforming technique statistically provides a higher SIR, even in the case of without FFR. This is because the beamforming technique helps to provide an

increase in antenna gain at the desired direction, while providing a low gain in the directions of the interference signal, thus resulting in the ICI reduction.

For the evaluation of the channel capacity for the LTE systems, the formulas of channel capacity according to Shannon's channel capacity theorem are introduced in (4) to (8). Please note that the beamforming technique was not taken into account for:

$$\frac{C}{B} = \log_2(1 + SIR) \quad (4)$$

$$\frac{C}{B} = \frac{1}{4} \log_2(1 + SIR_{center}) + \frac{1}{4} \log_2(1 + SIR_{edge}) \quad (5)$$

$$\frac{C}{B} = \frac{1}{4} \log_2(1 + SIR_{center}) + \frac{3}{4} \log_2(1 + SIR_{edge}) \quad (6)$$

$$\frac{C}{B} = \frac{2}{3} \log_2(1 + SIR_{center}) + \frac{1}{3} \log_2(1 + SIR_{edge}) \quad (7)$$

$$\frac{C}{B} = \frac{2}{3} \log_2(1 + SIR_{center}) + \log_2(1 + SIR_{edge}) \quad (8)$$

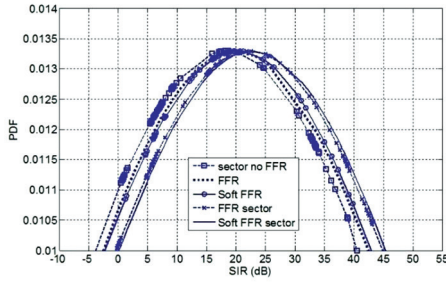


Figure 7. PDF versus SIR of the systems without beamforming

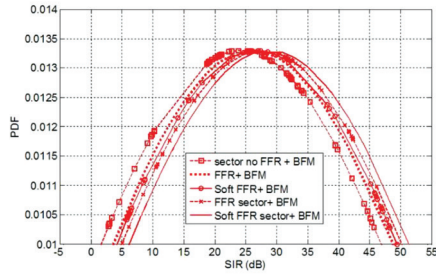


Figure 8. PDF versus SIR of the systems with beamforming

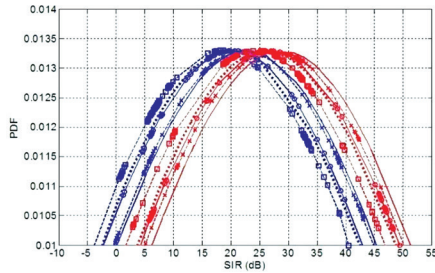


Figure 9. Comparison of SIR for cellular systems: with (red line) and without (blue line) beamforming techniques

where B is a channel bandwidth, SIR_{center} is the SIR in the region of the cell center, and SIR_{edge} is the SIR in the region of the cell edge. These equations are in order with respect to the configuration illustrated in Figure 6(a) to (e). Please note that the capacity in this paper is calculated per cell. Table 3 shows the calculated channel capacity for those 5 cases. It reveals that utilizing the soft FFR technique including beamforming provides the highest channel capacity for both cases: with and without beamforming. This is because the soft FFR provides the best SIR from the previous results presented in Figures 7 and 8.

From the above simulation results, it can be said that the soft FFR including beamforming technique is 1 of the best choices to improve the performance of LTE systems. The next section presents a discussion of the beamforming concept suitable for LTE systems.

Beam-Formation Concept for LTE

As mentioned in Section 5, switched beam antennas are the most suitable choice for implementation at the base station. The basic configuration of these systems is presented in Figure 10 and consists of antenna array, beamforming networks, and beam selector.

The beam selection can be simply performed using basic switching networks which do not require a fast or high computational function, which are out of the scope of this paper. Also, the well-known Butler matrix beamformer is the most popular technique for a beamforming network at the present time (Moody, 1964; Bona *et al.*, 2002; Chu *et al.*, 2005). According to the original concept, a Butler matrix requires 4 inputs received from a 4×1 antenna array, and then provides 4 outputs for 4 different beam patterns. However, this kind of beamformer has been introduced for general purposes in which the maximum performance of cellular systems has not been addressed. Therefore, this paper investigates the optimum number of antenna elements which has an effect on the optimum number of beam patterns and the beam width for LTE cellular

systems.

In this investigation, the coverage area is assumed to be equally divided into 3 sectors (120° /sector). From running a number of simulations, we have found that using 3 beams gives the maximum SIR covering a 120° sector, as depicted in Figure 11. According to this, the beam width of each beam is 40° . Next, the appropriate number of antenna elements giving the beam width of 40° is discussed. Some computer simulations have been developed to validate the concept, as follows. Figure 12 shows the beam pattern of a linear array employing 4, 5, and 6 antenna elements. The obtained results show that we can have a beam width of 63.41° , 41° , and 29.4° , respectively. According to this, 5 antenna elements providing a 41° beam width is the most suitable choice when a 120° sector

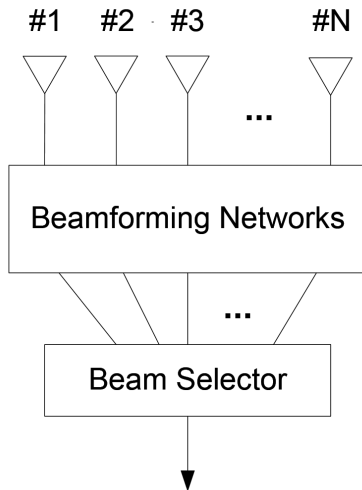


Figure 10. Configuration of switched beam antennas

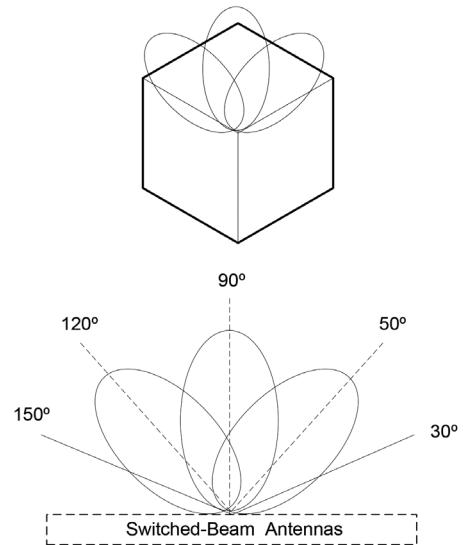


Figure 11. Beam formation in 120° section

Table 3. Simulated channel capacity

Type	Without beamforming	With
beamforming		
Sector no FFR	1.4655	2.0127
FFR	2.4513	2.9962
FFR sector	2.9987	3.3491
Soft FFR	2.8769	3.2697
Soft FFR sector	3.0176	3.5531

having a 40° beam width is required. Also, Figure 13 shows a simulation investigating the optimum number of beams per sector. For this simulation, the number of antenna elements at 4, 5, and 6 are assumed. As we can see, utilizing 3 beams provides the maximum SIR for all 3 cases.

From the above simulation results, a Butler matrix is not the best choice for LTE cellular systems anymore. This means that we need a modification of the beamformer to form 3 beams with their beam width of 41°. Also, this beamformer has to employ 5×1 antenna elements to give the maximum SIR. The beamformer is designed and discussed in the next section.

5 × 3 Beamforming Matrix

As revealed in the previous section, the optimum number of antenna elements is 5 and also the number of beams should be 3 to obtain the maximum SIR. This means that we have to design a new 5×3 beamformer. The design starts with the calculation of the inter-element phasing relative to the desired direction of arrival (θ) in azimuth, as shown in (9):

$$\text{Inter-element phasing} = kd \cos \theta \quad (9)$$

where k stands for the wave number ($2\pi/\lambda$) and d is the inter-element spacing of the array. Figure 14 shows the beamforming matrix for the proposed 5×3 beamformer. This beamformer consists of basic elements, e.g. hybrid couplers, crossovers, phase shifters, combiners, and a splitter. The inter-element phasing and directions of the output beams are given in Table 4. As we can see, the beamformer can form its main beam to 27.26°, 61.82°, and 96.37°. This results in an average beam width of 34° (15% error from 40°). A Matlab code has been developed to test the beamforming performance of the proposed 5×3 beamformer. The obtained beam patterns are shown in Figure 15. As we can see, the proposed beamformer provides 3 different beams having the main beam at 27.26°, 61.82°, and 96.37°, resulting in a beam width of 34°. Although there is an error in the beam width from the expected value of 40°, as seen in Figure 15, the patterns cover all the 120° sector, especially when considering a half-power beam width. After having a design for the beamformer, a hardware realization is discussed in the next section.

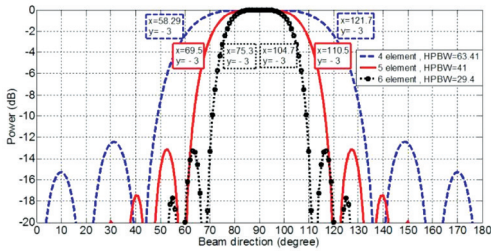


Figure 12. Simulated beam patterns employing linear array antennas having 4, 5, and 6 antenna elements

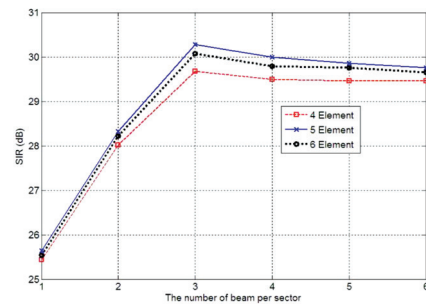


Figure 13. SIR vs. number of beams per sector

Table 4. Beam direction and inter-element phasing for 5×3 beamforming network

Output	Antenna					Beamforming direction
	1	2	3	4	5	
1	0°	-20°	-40°	-60°	-80°	96.37°
2	90°	-110°	50°	-150°	10°	27.26°
3	0°	85°	170°	-105°	-20°	61.82°

Prototype Realization

After having a design for a 5×3 beamformer compatible with the LTE systems presented in the previous section, a prototype of the proposed beamformer was constructed and tested, as described in this section. The prototype was designed for operating at 2.5-2.69 GHz. Our own-developed programming using CST Microwave Studio (Computer Simulation Technology AG, Darmstadt, Germany) was created to design the prototype. This prototype is composed of an antenna array, hybrid coupler, crossover, combiner/splitter, and phase shifter. Those components are detailed as follows.

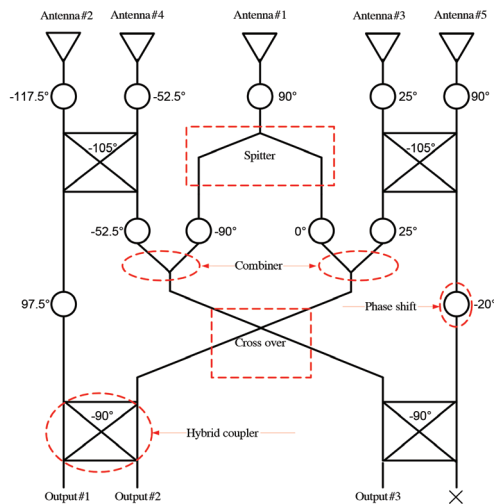


Figure 14. Configuration of proposed 5×3 beamformer for 120° -sector

A. Antenna Array

Linear array antennas are chosen for their simplicity. Also, the number of antenna elements is 5 to have maximum performance, as pointed out in Section 7. The antenna elements are equally spaced by the half-wavelength at the center frequency, 2.595 GHz. In this paper, a printed monopole antenna is chosen and its configuration is shown in Figure 16. The reason for this is that it is simple and also its width is shorter than the half-wavelength at 2.595 GHz. The antenna is designed based on the FR4 substrate having a dielectric constant of 4.5 and thickness of 1.66 mm. The feed line of the

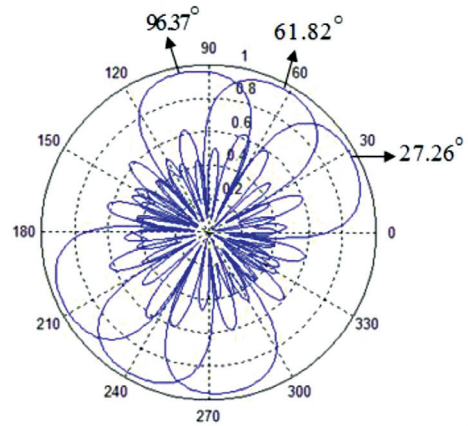


Figure 15. Simulated beam pattern in azimuth of proposed 5×3 beamformer

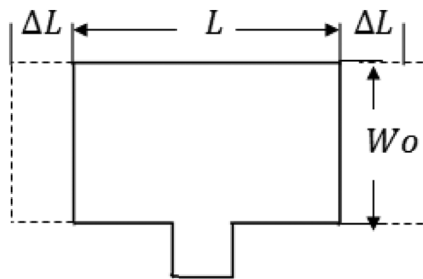


Figure 16. Printed monopole antenna configuration

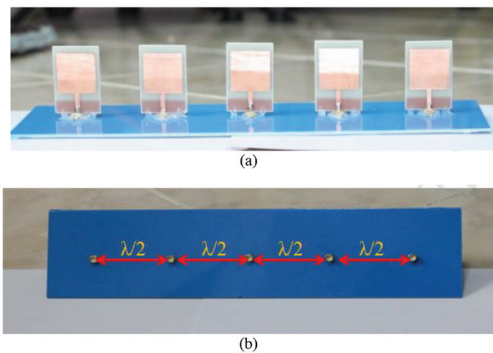


Figure 17. Photograph of fabricated 5×1 antenna array

antenna can be calculated using the following expressions:

$$\frac{w}{h} = \begin{cases} \frac{8e^A}{e^{2A}-2} & \text{for } W/d < 2 \\ \frac{2}{\pi} \left[B - 1 - \ln(2B-1) + \frac{\epsilon_r-1}{2\epsilon_r} \left\{ \ln(B-1) + 0.39 - \frac{0.61}{\epsilon_r} \right\} \right] & \text{for } W/d > 2 \end{cases} \quad (10)$$

$$A = \frac{Z_o}{60} \sqrt{\frac{\epsilon_r+1}{2}} + \frac{\epsilon_r-1}{\epsilon_r+1} \left(0.23 + \frac{0.11}{\epsilon_r} \right), \quad B = \frac{377\pi}{2Z_o\sqrt{\epsilon_r}} \quad (11)$$

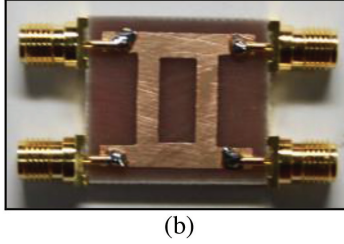
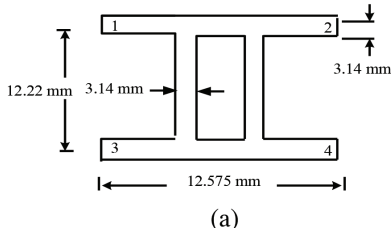


Figure 18. Hybrid coupler -90°

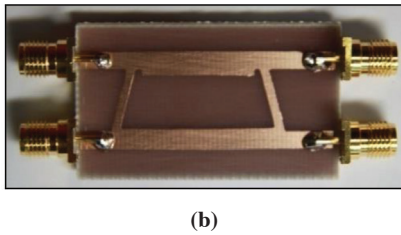
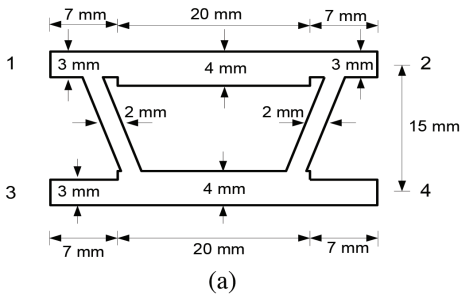


Figure 19. Hybrid coupler -105°

where w and h are the width and height of the strip line, respectively. Also, ϵ_r is the relative permittivity of the substrate and Z_o is the line characteristic impedance. The parameters A and B are connecting parameters to combine (11) into (10). Then, we can calculate the width and length of the antenna respectively to the configuration shown in Figure 16, as follows:

Width:

$$W_o = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r+1}} \quad (12)$$

$$f_r = f \sqrt{\epsilon_{eff}} \quad (13)$$

Length:

$$L = \frac{c}{2f\sqrt{\epsilon_{eff}}} - 2\Delta L \quad (14)$$

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{eff} + 0.3) \left(\frac{W_o}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W_o}{h} + 0.8 \right)} \quad (15)$$

where ϵ_{eff} is the effective permittivity, L is the strip length, and f_r is the resonant frequency. Following the above calculation, we obtain the antenna width of $W_o = 20.19$ mm, the length of $L = 31.18$ mm, and also the width of the feed line of 3.14 mm. The 5 designed antennas are arranged in a linear manner. The inter-element spacing can be calculated as follows:

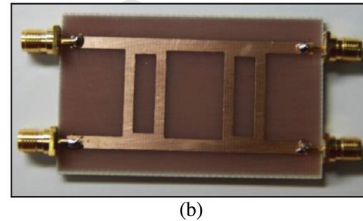
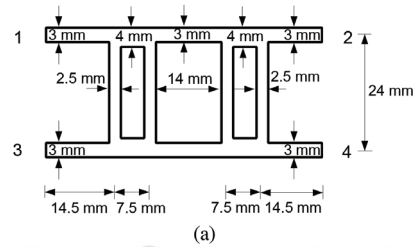


Figure 20. Crossover

$$\lambda = \frac{c}{f} \quad (16)$$

when $\lambda = 10.17$ cm, then we can have the inter-element spacing of $d = 5.085$ cm. Figure 17 shows a photograph of the fabricated antenna according to the above design. Next, the construction of the 5×3 beamformer is discussed.

B. Beamforming Networks

As pointed out from Section 7, we need to design a beamformer for 5 inputs and 3 outputs, called a 5×3 beamformer. The design has been discussed in Section 8. This section provides the detail of the beamforming network fabrication, as follows:

- Hybrid Coupler

From the design which is shown in Figure 14, 2 hybrid couplers having different phase-shifting values (-90° and -105°) are required. These phase

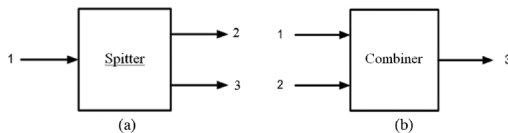


Figure 21. Block diagram of splitter and combiner

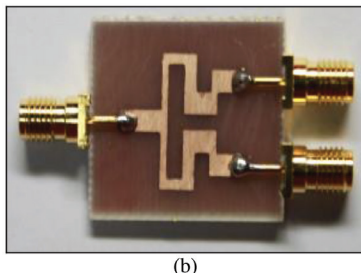
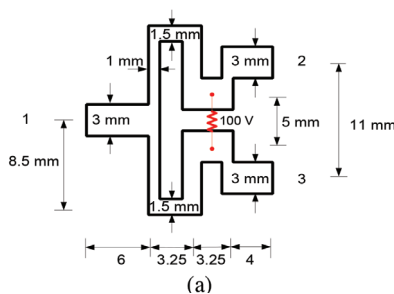


Figure 22. Splitter and combiner

values are the phase difference between the through and coupled ports. As can be seen in Figure 18(a), it is the difference between ports 2 and 4. Note that the signal is not supposed to go to port 3 (the isolated port). The design can be found in several microwave engineering books (Pozar, 1998; Das and Das, 2000; Collin, 2001). Finally, we can have the size and dimension of the 90° hybrid coupler, as shown in Figure 18(a). A photograph of the fabricated one is shown in Figure 18(b). Then, some adjustment is performed using CST Microwave Studio to change the phase difference between the through and coupled ports from -90° to -105° . The final size and dimension of the -105° hybrid coupler is shown in Figure 19(a) and also a photograph of the fabricated one is presented in Figure 19(b).

- Crossover

As can be seen in Figure 14, we need to switch or change the path of the signal. Therefore, a component named a crossover is required. The design method of the crossover can be found in some of the literature (Bona *et al.*, 2002; Moody, 1964). Some adjustment was performed using CST Microwave Studio. Then, the final size and dimension of the crossover designed at 2.595 GHz is shown in Figure 20(a). Also, a photograph of the fabricated crossover is presented in Figure 20(b).

- Combiner/Splitter

The basic concept of the splitter and combiner is presented in Figure 21. The famous Wilkinson design (Pozar, 1998; Collin, 2001) is chosen for the design of the splitter and combiner. The performance of the designed combiner and splitter was tested using CST Microwave Studio. The final design is shown in Figure 22(a) and also its photograph is presented in Figure 22(b).

- Phase Shifter

As seen in Figure 14, we need several phase shift values i.e., 0° , 25° , 90° , -20° , -90° , -117.5° , and 92.5° . These shiftings can be performed using a microstrip line. They were designed using CST Microwave Studio. Then, the final design and also the photographs of the fabricated ones are presented in Figures 23–29.

After confirming the performance of all

the components, the prototype assembly was carried out and its photograph is shown in Figure 30. Figure 31 shows a photograph after it has been connected to the fabricated antenna array using SMA connectors.

The assembled prototype shown in Figure 31 was tested in an anechoic chamber using a network analyzer. Table 5 shows the measured return loss, isolation loss, and coupling loss for

the 5×3 beamforming network. As can be seen, the 5×3 beamforming network provides a return loss lower than -10 dB, lower than -15 dB for the isolation loss, and higher than -5 dB for the coupling loss within the designated band. Next, the measurement of the beamforming performance for the proposed prototype is shown. The experimental results in terms of phase shifting and also beam directions are shown in

Table 5. Return loss, isolation loss, and coupling loss for 5×3 beamforming network

Return Loss			
S-Parameter	Amplitude (dB)	S-Parameter	Amplitude (dB)
S11	-18.73	S55	-16.67
S22	-17.54	S66	-19.01
S33	-17.12	S77	-18.47
S44	-16.96	S88	-17.78
Isolation loss			
S-Parameter	Amplitude (dB)	S-Parameter	Amplitude (dB)
S21	-22.14	S51	-24.56
S31	-23.53	S76	-23.59
S41	-25.22	S86	-22.61
S51	-23.86		
Coupling loss			
S-Parameter	Amplitude (dB)	S-Parameter	Amplitude (dB)
S61	-3.56	S83	-3.67
S71	-3.82	S64	-3.77
S81	-3.66	S74	-3.85
S62	-3.68	S84	-3.92
S72	-3.71	S65	-3.83
S82	-3.77	S75	-3.86
S63	-3.59	S85	-3.96
S73	-3.84		

Table 6. Measured beam direction, and inter-element phasing for 5×3 beamforming network

Output	Antenna					Beamforming Direction
	1	2	3	4	5	
1	2.54°	-18.64°	-41.63°	-59.84°	-76.49°	94.58°
2	87.83°	-106.88°	53.42°	-146.57°	13.62°	24.82°
3	2.38°	83.91°	164.61°	-108.39°	-25.69°	58.73°

Table 6. As we can see, we obtained the beam directions are 24.82° , 58.73° , and 94.58° . Compared with the ones expected from the simulation (27.26° , 61.82° , and 96.37°), the small deviation from the expected values is within 10%. This is because some errors occurred during the fabrication process. In addition, the beam formation comparison between the ones obtained from the simulation and the experiment is shown in Figure 32. This shows that the prototype performs a beam formation similar to the simulation. In addition, these measured results are taken into account to see the real performance when operating with LTE systems working with FFR techniques. The obtained results which are shown in Figure 33, are the PDF of the SIR for 5 cases: sector no FFR, only FFR, soft FFR, FFR sector, and soft FFR sector. As expected, utilizing the soft FFR plus sectorization and beamforming provides the best chance of getting a higher SIR than the other cases. This outcome is similar to the one obtained via computer simulation, as pointed out earlier. The reason for this outcome is that the soft FFR allocates a different transmitted power between the cell edge and cell center. As a result, the ICI can be decreased. In addition, the beamforming technique helps to increase the antenna gain in the direction of the desired user while reducing the gain in the direction of the ICI. Moreover, Table 7 shows the channel capacity calculated using information from the simulation and measurement. As we can see, the results are in good agreement. It reveals that the FFR technique is able to boost the performance of LTE systems. The best choice must be the soft FFR. However, the highest performance can be obtained when including the beamforming technique.

Conclusions

This paper has investigated the benefit of several types of frequency reuse techniques for LTE systems. The computer results have indicated that soft FFR is the best choice providing maximum performance in terms of SIR and channel capacity. Moreover, the investigation has included the beam formation in the systems. Then, from running a number of simulations, the

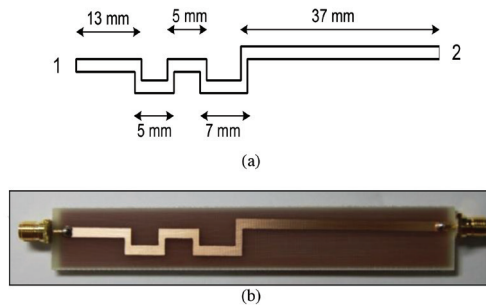


Figure 26. Phase shift -20°

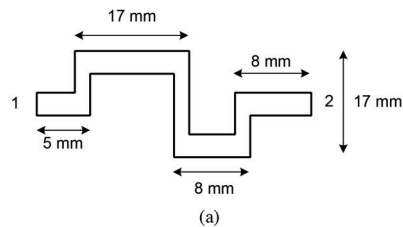


Figure 27. Phase shift -90°

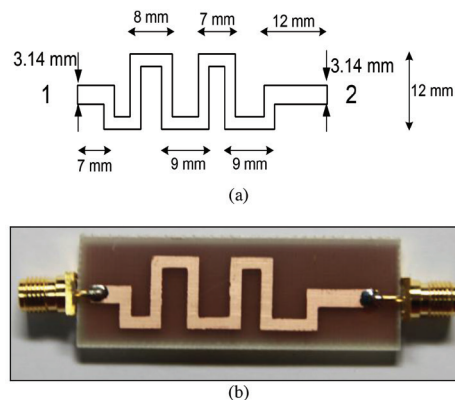


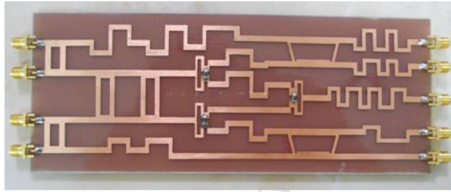
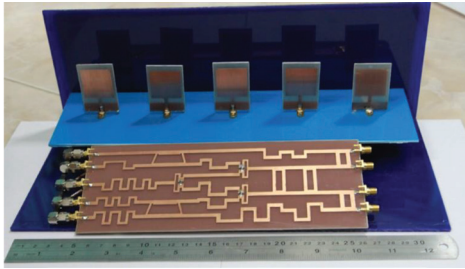
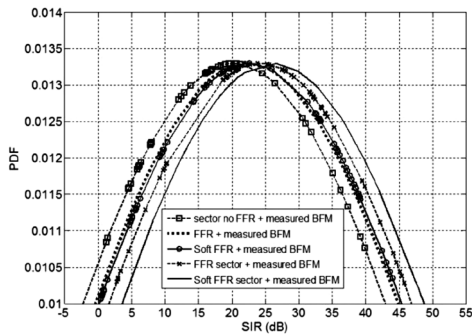
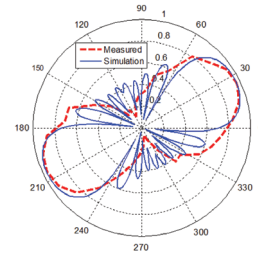
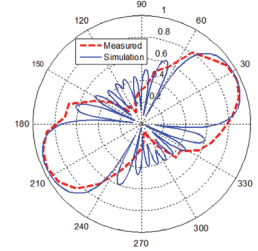
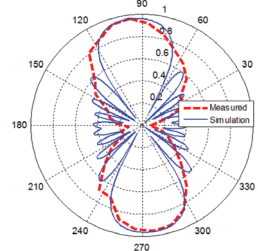
Figure 28. Phase shift -117.5°



Figure 29. Phase shift 92.5°

Table 7. Channel capacity

Type	Without beamforming	With beamforming (simulation)	With beamforming (measurement)
Sector no FFR	1.4655	2.0127	1.9878
FFR	2.4513	2.9962	2.8539
FFR sector	2.9987	3.3491	3.2989
Soft FFR	2.8769	3.2697	3.1445
Soft FFR sector	3.0176	3.5531	3.4543

**Figure 30. Photograph of 5x3 beamformer****Figure 31. Photograph of assembled prototype****Figure 33. PDF versus SIR of the systems including beamforming capability from experiment****(a)****(a)****(c)****Figure 32. Beamforming performance of proposed prototype from simulation (solid line) and experiment (dash line)**

optimum number of array antenna elements and beam patterns to cover all over the 120° sector is 5 and 3, respectively. Therefore, a prototype of the 5×3 beamformer has been originally designed and tested in an anechoic chamber. The obtained results have indicated that the proposed prototype works well, as expected. Also, the soft FFR plus sectorization and beamforming provides the maximum SIR and channel capacity.

Acknowledgment

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