Development of Array Antenna for LTE Small Cell Base Stations

Yoji OKADA*, Eiji MOCHIDA, Takashi YAMAMOTO, Yoshihiro HAMADA, Yoshizo TANAKA and Mitsuo SUGIMOTO

In recent years, mobile service providers are facing rapid increase in data traffic, and so they have much interest in picocells and femtocells which can significantly improve network capacity. Deploying picocells and femtocells, however, can potentially cause inter-cell interference in the case of co-channel operation. We have studied the interference suppression method using an array antenna system for 3GPP Long Term Evolution (LTE) uplinks based on minimum mean square error (MMSE) beamforming. This paper proposes a new method to calculate the MMSE weight in a resource block (RB) basis and shows some simulation results. Furthermore, we have successfully implemented the proposed method on a system-on-chip (SoC) and verified that it successfully suppresses interference in real time.

Keywords: array antenna, interference suppression, Evolved UTRA, Long Term Evolution, femtocell, picocell

1. Introduction

Mobile service providers in recent years have been facing rapid increases in data traffic, so have much interest in small cell base stations such as picocells and femtocells. However, these small cell base stations are recognized as potential causes of inter-cell interference, since it is highly probable that they will be deployed using the same radio frequency as used by macrocells, due to the scarcity of available radio frequencies. To address this problem, we have developed an interference suppression array antenna for Long Term Evolution (LTE) uplinks, to provide directivity based on a minimum mean square error (MMSE) algorithm. This paper proposes a new method for calculating MMSE weighting factors at the LTE resource block (RB) level. Furthermore, we indicate that this method is excellent in that it requires neither the resource assignment information of the adjacent cells nor the scheduling information used by higher layers. Lastly, this paper shows that the proposed method is suitable for the latest software-defined radio technology, as proven through implementation on a system-on-chip (SoC) consisting of a multicore digital signal processor and an ARM processor.

2. Long Term Evolution (LTE)

The wideband code division multiple access (W-CDMA) standard is one of the cellular phone systems currently in use. As a successor to W-CDMA, LTE was standardized by the Third-Generation Partnership Project (3GPP). For access schemes, LTE uses orthogonal frequency division multiple access (OFDMA) for downlink and single carrier frequency division multiple access (SC-FDMA) for uplink. Its maximum frequency band is 20 MHz wide for both uplink and downlink. Maximum downlink and uplink peak rates reach 300 Mbps and 75 Mbps, respectively [(1)-(4)].

Meanwhile, mobile service providers are facing rapid increases in data traffic, due to the recent widespread use of smartphones and other mobile devices. LTE is anticipated as a solution. However, according to Ministry of Internal Affairs and Communications statistics, cumulative monthly data traffic has doubled since a year ago [(5)]. If this pace of traffic growth continues, data traffic will increase approximately 1,000 times in 10 years. Standardization bodies, such as 3GPP, are therefore discussing a heterogeneous network (HetNet) [(6)] that serves areas combining cells of varying sizes, such as macrocells, picocells and femtocells.

The HetNet has attracted interest in recent years as a means of reducing loading on macrocell base stations (traffic offloading) by deploying macrocell base stations to provide coverage for wide communication areas and by installing (or overlaying) picocell and femtocell base stations locally in zones of greater data traffic needs. This arrangement enables mobile service providers to increase the communication capacity of their systems. One drawback, though, is that use of the same frequency by a macrocell and a picocell or a femtocell results in serious interference between them. **Figure 1** shows how a mobile station in a macrocell interferes with a mobile station in a femtocell.

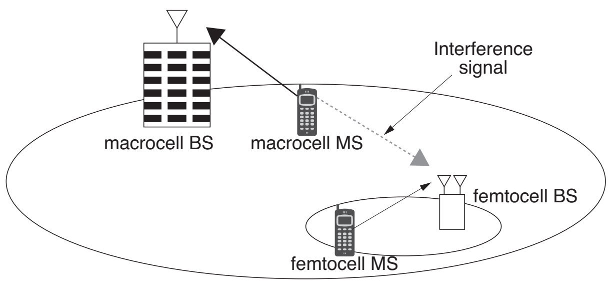


Fig. 1. Interference in HetNet

3. Interference Suppression Array Antenna for LTE Uplink Channels

Figure 2 shows the configuration of an array antenna for LTE uplink channels.

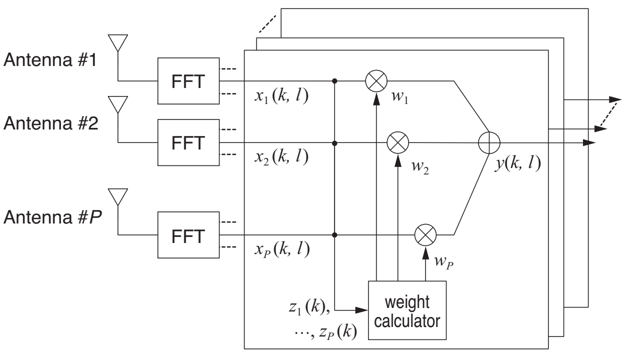


Fig. 2. Array antenna for LTE uplink channels

Each signal sent from a mobile station is received by antenna elements numbering P and is then divided into individual subcarriers $x_p(k, l)$ through a fast Fourier transform (FFT) algorithm where p is an antenna element number, k is the subcarrier (frequency) number and l is the OFDM symbol (time) number. Each subcarrier is multiplied by weighting factor w_p corresponding to each antenna and synthesized into $y(k, l)$.

A weight calculator performs weighting factor w_p calculation so as to cancel interference waves. We designed this calculation so that maximum capacity is achieved using the LTE communication protocol. The design considerations are explained below.

3-1 LTE frame structure

Figure 3 shows an LTE frequency division duplex (FDD) frame structure [1]. The length of one frame is 10 ms, which comprises 10 subframes. Each subframe consists of two slots.

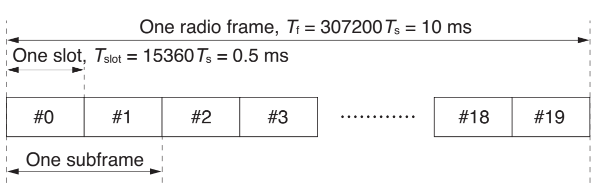


Fig. 3. LTE FDD frame structure [1]

Figure 4 shows the structure of a subframe. A resource block (RB) is an area defined by subcarriers numbering N_{sc}^{RB} (normally 12) and symbols (180 [kHz] along the frequency axis, 0.5 [ms] along the time axis) numbering N_{symb}^{UL}

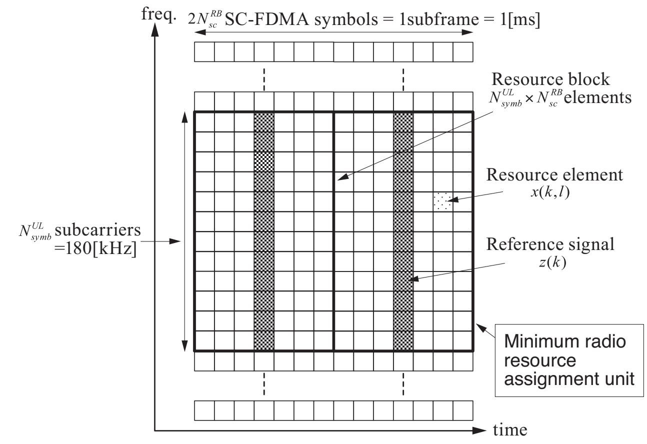


Fig. 4. Minimum radio resource assignment unit (localized type) [1]

(normally 7). Each RB has a reference signal assigned to the fourth symbol. Furthermore, the area containing two RBs aligned on the time axis is the minimum resource assignment unit in LTE radio frames, as shown in the figure. RBs are arranged on the time axis in two ways: localized and distributed. The former type places two RBs consecutively on the same subcarrier frequency, while the latter places them on different subcarrier frequencies. The better of the two types is selected according to the state of the base station radio transmission channel.

3-2 Number of antenna elements and frequency assignment

Generally, a greater number of array elements translates into more interference waves being suppressed. However, fewer antenna elements are desirable, because base stations are subject to tight location restrictions irrespective of whether they are macrocells, picocells or femtocells. A two-element antenna is expected to suppress only one interference wave; accordingly, such an antenna may not provide sufficient interference suppression if multiple interference sources are present.

Take, for example, communication sessions between a macrocell base station and four mobile stations, and a

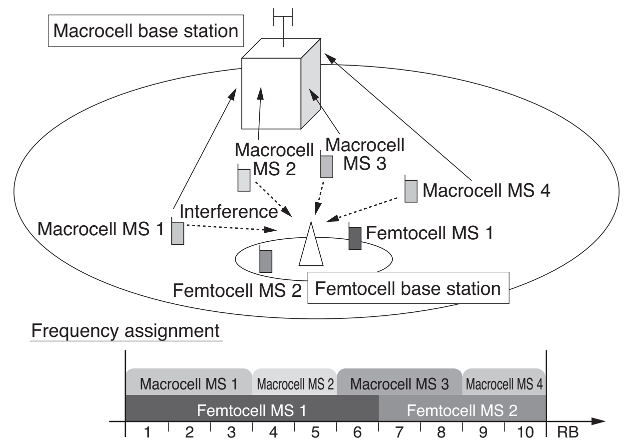


Fig. 5. Frequency assignment and interference from macrocell mobile stations (MS)

femtocell base station and two mobile stations, as shown in **Fig. 5**. To simplify the explanation, assume that 10 RBs are present along the frequency axis and that each mobile station is assigned frequencies by each base station, as shown in **Fig. 5**.

In this situation, when the femtocell base station receives signals from mobile station 1, three macrocell mobile stations cause interference from their respective different directions. Femtocell base stations generally require four or more antenna elements.

3-3 Convergence rate and time assignment

In general, compared with small cell base stations such as picocells and femtocells, macrocell base stations cover a greater number of mobile stations and are subject to rapid changes in the radio environment. Consequently, as shown in **Fig. 6**, macrocell base stations are expected to assign resources in relatively shorter cycles than femtocells. In other words, for femtocell base stations, it is highly likely that resource assignment to interference sources undergoes rapid temporal changes. Consequently, the convergence performance of array weight calculation becomes important.

Table 1 compares array antenna weighting factor calculation methods. The maximal ratio combining (MRC) method enables instant weight calculation and is easy to implement. When an interference wave is present, however, this method is subject to degraded accuracy in channel estimates and substantially decreased weighting accuracy. This drawback comes from the fact that the method determines weighting factors so as to maximize the signal-to-noise power ratio (SNR) of the desired signal; in other words, the method does not take into account the effects of interference waves.

On the other hand, the MMSE method determines weighting factors so as to minimize mean square errors between the known desired signal and the received signal; that is, it determines weighting factors while taking interference wave effects into consideration. Least mean square (LMS) and recursive least square (RLS) adaptation algorithms, which are widely known as MMSE solutions, require repeated calculations until convergence, though they involve little computational effort and are easy to implement. If a macrocell base station adopts resource assignment change in minimum assignment units of 1 ms, the MMSE method is not a suitable calculation method for the purposes of the present study.

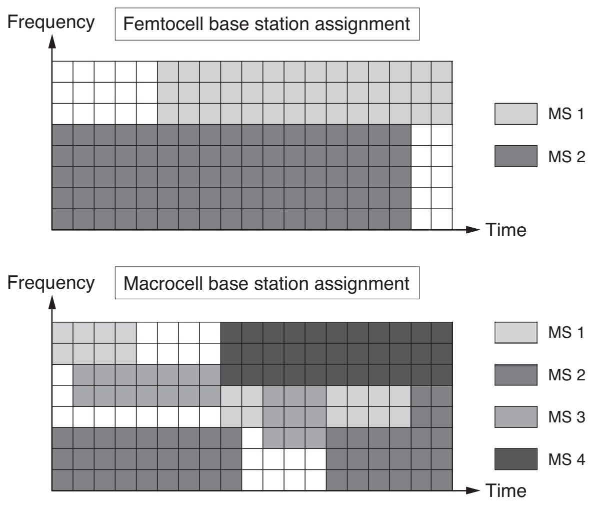


Fig. 6. Example resource assignment schedule

Table 1. Comparison of weighting factor calculation methods

	MRC	MMSE	
		LMS	RLS
Convergence rate	○	×	△
Interference suppression capacity	×	○	

○: good, ×: poor, △: uncertain, depend on situation

4. Overview of Our Proposed Method

As a solution to the problems stated in Section 3, we have developed a MMSE adaptive array antenna, which is used to calculate array weights within the smallest area possible on the two-dimensional plane of time and frequency axes conforming to the LTE standard. In short, our method performs weight calculations for each RB, as shown in **Fig. 7**.

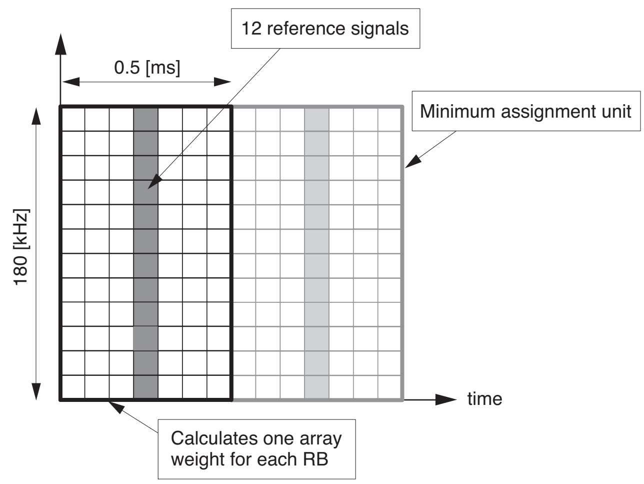


Fig. 7. RB based array weight

First, since a RB is smaller than the minimum radio assignment unit, the method calculates array weights independently of resource assignment by the macrocell base station with regard both to time and frequency axes. In general, a femtocell base station covers a smaller area with fewer mobile stations than does a macrocell base station. Consequently, the femtocell base station assigns a wide bandwidth to each mobile station. This implies a high possibility of multiple interference sources in the bandwidth assigned to a user. However, in the case shown in **Fig. 5**, putting aside user assignment, each minimum assignment unit from 1 to 10 has only one interference source. Noting this feature, we developed a design to process array antenna signals in frequency units (RB units) smaller than user frequency assignment bandwidths, so that fewer array elements can suppress a larger number of interference waves.

Second, the synthesized output signal $y(k;\, l)$ of each subcarrier of an array antenna comprising P elements is expressed as follows:

$$y\,(k;\, l) = \mathbf{w}^H \mathbf{x}\,(k,\, l) \qquad \text{(1)}$$

where k and l represent the frequency and time indices, respectively, of RB; $\mathbf{x}(k,\, l)$, $(P \times 1)$ is the vector of the received signal; $\mathbf{w}$ is the array weight vector, and $(\bullet)^H$ is the Hermitian transpose.

Here, MMSE weight $\mathbf{w}$ is determined by Equation (2).

$$\mathbf{w} = \mathbf{R}^{-1}\,\mathbf{r} \qquad \text{(2)}$$

where $\mathbf{R}$ is $(P \times P)$ correlation matrix and $\mathbf{r}$, a $(P \times 1)$ correlation vector. For RB-based weight calculation, we estimated $\mathbf{R}$ and $\mathbf{r}$ by Equations (3) and (4).

$$\tilde{\mathbf{R}} = \sum_{k=0}^{N_{sc}^{RB}-1} \mathbf{z}\,(k)\,\mathbf{z}^H\,(k) \qquad \text{(3)}$$

$$\tilde{\mathbf{r}} = \sum_{k=0}^{N_{sc}^{RB}-1} \mathbf{z}\,(k)\, s^*\,(k) \qquad \text{(4)}$$

where $\mathbf{z}(k)$ is a received vector (its size being Px 1) for the kth subcarrier in the reference symbol in RB; $s(k)$ is the transmit signal of the same subcarrier and $(\bullet)^*$ is the complex conjugate.

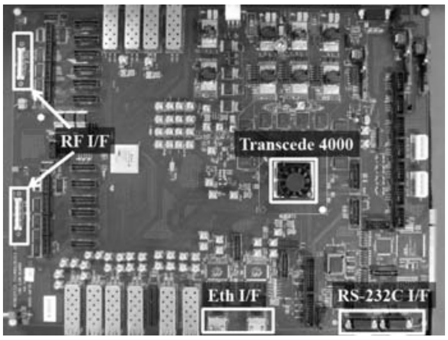
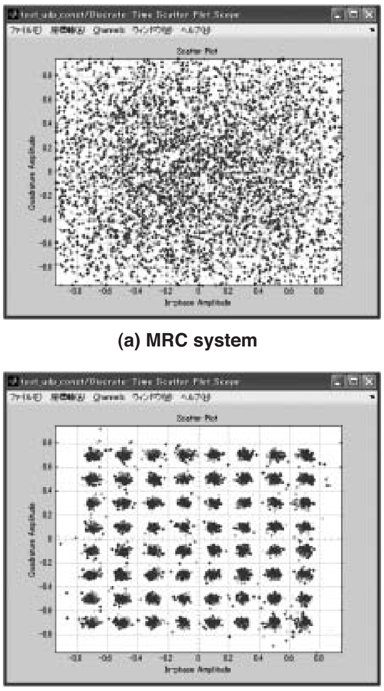


Photo 1. MindSpeed Transcede 4000 test board



(a) MRC system

(b) Our system

Fig. 9. SC-FDMA signal constellation

5. Evaluation Results

5-1 Software implementation

Our array antenna system as described in Section 4 was implemented on system-on-chip (SoC) Transcede 4000, developed by MindSpeed Technologies, Inc. of the United States. More specifically, our system was implemented additionally on LTE physical layer software implemented by MindSpeed and proved to operate in real time. **Photo 1** shows the Transcede 4000 test board. **Figure 8** shows interference resistance test setup.

Figure 9 (a) and (b) shows SC-FDMA signal 64-QAM constellations of the maximal ratio combining system and our system operating in real time on an actual board. In this test, the carrier-to-interference power ratio (CIR) was set to 3 dB. The test results show the performance improvements achieved by our system.

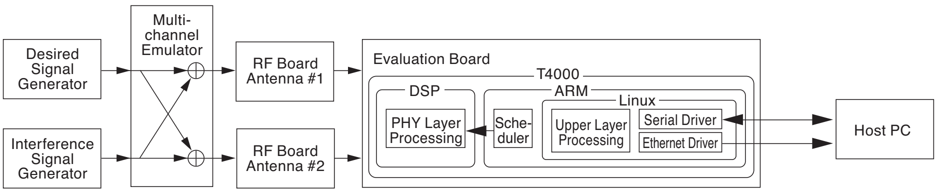


Fig. 8. Test setup

5-2 Computer simulation

To evaluate the characteristics of the proposed system, we tested it by computer simulation. **Table 2** shows the simulation conditions. The number of antenna elements was two, white Gaussian noise was used as thermal noise and the ITU-R M2135 indoor hotspot model (InH) was used as a propagation model. With this model, since multipath and other conditions vary depending on propagation distance, it was assumed that femtocell mobile stations were present within a 50 m radius area, and macrocell mobile stations within a 150 m radius area.

It was also assumed that the bandwidth was 10 MHz (with RBs numbering 50); one mobile station was connected to the femtocell base station, with all bandwidth, or 50 RBs, being assigned to it, and two mobile stations were connected to the macrocell base station, each assigned 25 RBs.

Figure 10 shows a cumulative carrier to interference and noise ratio (CINR) probability distribution of array output signals, determined by Monte Carlo simulation, at varying mobile station locations. Comparisons of bandwide array antenna processing and RB based array antenna processing, using 50% CDF as a reference, show that RB based MMSE array antenna processing improves CINR by approximately 15 dB at half of the mobile stations.

Table 2. Simulation specifications

Number of BS antennas	2
BS antenna element spacing	0.5 wavelength
Carrier frequency	2 [GHz]
System bandwidth	10 [MHz]
Sampling frequency	30.72 [MHz]
CP configuration	Normal CP
Modulation	16-QAM
Physical channel	PUSCH
Propagation model	ITU-R M.2135 (InH)
Maximum MS velocity	3 [km/h]
CNR	20 [dB]
CIR	0 [dB]

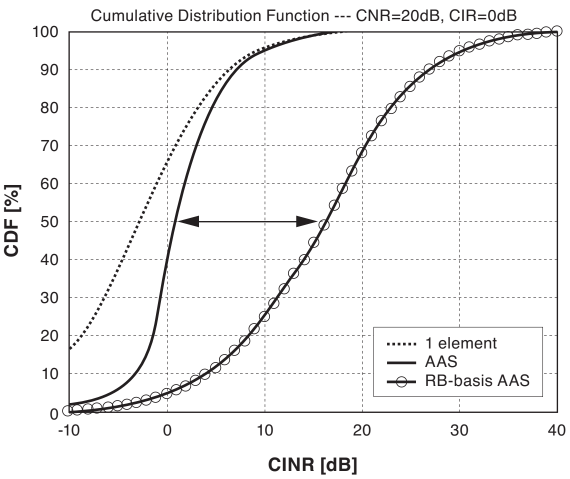


Fig. 10. Comparison of cumulative CINR probability distribution

6. Conclusion

This paper presented analysis and implementation results regarding an interference suppression array antenna suitable for LTE small cell base stations.

An array antenna designed to suppress, at a small cell base station, interference from macrocell mobile stations was developed to reduce interference with macrocell base stations from mobile stations connected to the small cell base station in LTE uplink channels. The usefulness of this array antenna was proven by real-time operation of actual equipment and by computer simulation.

References

(1) 3GPP TS36.211 V8.9.0 (2009-12), "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 8)."

(2) 3GPP TS36.212 V8.8.0 (2009-12), "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding (Release 8)."

(3) 3GPP TS36.213 V8.8.0 (2009-09), "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 8)."

(4) http://www.3gpp.com/LTE

(5) http://www.soumu.go.jp/johotsusintokei/english/

(6) Sara Landström, Anders Furuskär, Klas Johansson, Laetitia Falconetti and Frederic Kronestedt, "Heterogeneous networks – increasing cellular capacity," ERICSSON REVIEW, 1 2011, pp.4-9.

(7) Kikuma, N. Adapted Signal Processing by Array Antenna. Kagaku Gijutsu Shuppan (1999).

Contributors (The lead author is indicated by an asterisk (*).)

Y. OKADA*
• Group Manager, Information & Communications Labs.

E. MOCHIDA
• Ph.D. in engineering
Information & Communications Labs.

T. YAMAMOTO
- Information & Communications Labs.

Y. HAMADA
- Assistant Manager, Information & Communications Labs.

Y. TANAKA
- Assistant General Manager, Information & Communications Labs.

M. SUGIMOTO
- Department Manager, Information & Communications Labs.