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Title: **Smart Antenna Technology**

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Introduction

Following the harmonization of TD-SCDMA and UTRA-TDD, this document introduces the principle of smart antenna, which is one of the most important parts of the CWTS RTT proposal. The harmonization process was agreed among ARIB, CATT, DoCoMo, Ericsson, Nokia, Panasonic, RITT and Siemens (RP-99248).

A smart antenna system is composed of an array of multiple antenna elements and coherent transceivers with advanced digital signal processing algorithms. Instead of a single fixed beam pattern from a traditional antenna, the smart antenna can dynamically generate multiple beam patterns, each of them is pointed to a particular UE, and such beam patterns can adapt to follow any UE intelligently. On the Rx side of Node B, such a feature, i.e., spatially selective Rx (uplink) beamforming, can greatly minimize co-channel interference from the co-channel UEs at different locations, thus increase the Rx sensitivity and lead to higher capacity. It can also effectively coherently add multipath components to combat multipath fading. On the Tx side of Node B, intelligent spatially selective Tx (downlink) beamforming can also greatly reduce the interference to other co-channel UEs, then dramatically save the output power requirement and lead to higher capacity.

The rest of this document presents the principles and some theoretical background about the use of Smart Antenna. Its application is part of the TD-SCDMA (UTRA-TDD low chiprate mode).

1. The basic structure of smart antenna based Node B in the TD-SCDMA (UTRA-TDD low chiprate mode) system

1.1. References

1. CWTS WG1 TS C1.24, “Physical layer procedures (TDD)”

2. CWTS WG1 xxx, “Method and Principle of Uplink Synchronization”

1.2. Smart antenna structure

The proposed TD-SCDMA RTT is mainly based on the smart antenna technology as described. Generally speaking, a smart antenna based Node B should be that shown in Figure 1. The smart antenna array is composed of N antenna elements, N related feed cables and N coherent RF transceivers in RF part. By use of the A/D converters or D/A converters in analog baseband (ABB), the Rx and Tx analog signals are interfaced to the digital baseband (DBB) part over the high-speed data bus. In this model, all antenna elements, related feed cables and coherent RF transceivers will be calibrated before operating.

1.3. Basic operation principle

Reference to Figure 1, the Node B is equipped with smart antenna array and DBB DSP. When a signal comes from one UE within the coverage of the Node B, each antenna element and coherent RF receiver will get it. Because of the different location of the different antenna element, the phase of the Rx signal will be different. In case of multipath propagation, each path will come from different directions with different amplitude and delay. Then the Rx signal at each antenna element will show different phase and amplitude. After the front-end processing in RF part and A/D converters processing in ABB, digitized Rx signal with the phase and amplitude information will be sent to DSP in DBB part. In a CDMA cellular system, there are many UEs working simultaneously. The Rx signals will be the sum of the signals (including main path and multipath) coming from all the active UEs within the cell and the interference coming from nearby cells.

Let the output of the i-th receiver be $s_i(n)$ at the time n. After despreading, one may obtain the Rx data of each code channel as $x_{ji}(l)$ for the l-th symbol, where j means the j-th code channel. The purpose of smart antenna in uplink is to find the best E_b/I_0 after the combination, The signal of the l-th symbol in the j-th code channel is denoted as $X_j(l)$, then

$$X_j(l) = \sum_{i=1}^{N} x_{ji}(l) w_{ij}(l) \tag{1}$$

where W is the uplink beamforming matrix with element $w_{ij}(l)$.

Many beamforming algorithms can be found in published papers. Theoretically, the uplink beamforming can add up all useful signals while canceling all multipath interference.

Next step in smart antenna is to realize downlink beamforming. The Tx signal of the j-th code channel is denoted as $Y_j(l)$ for the l-th symbol. Let the UE obtain the best E_b/I_0, then it can be obtained that

$$y_{ij}(l) = \sum_{i=1}^{N} Y_j(l) u_{ji}(l) \tag{2}$$

where

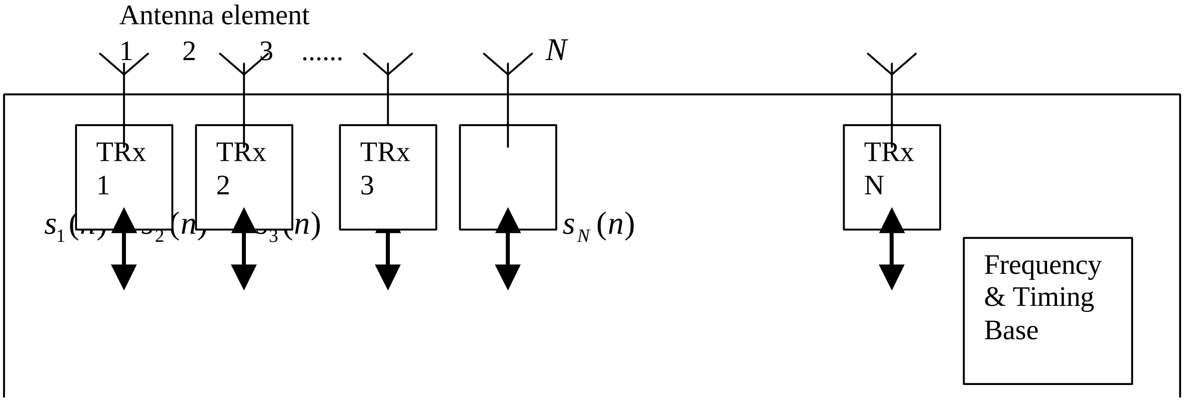
$y_{ij}(l)$ is the Tx signal on the i-th antenna for the l-th symbol in the j-th code channel;

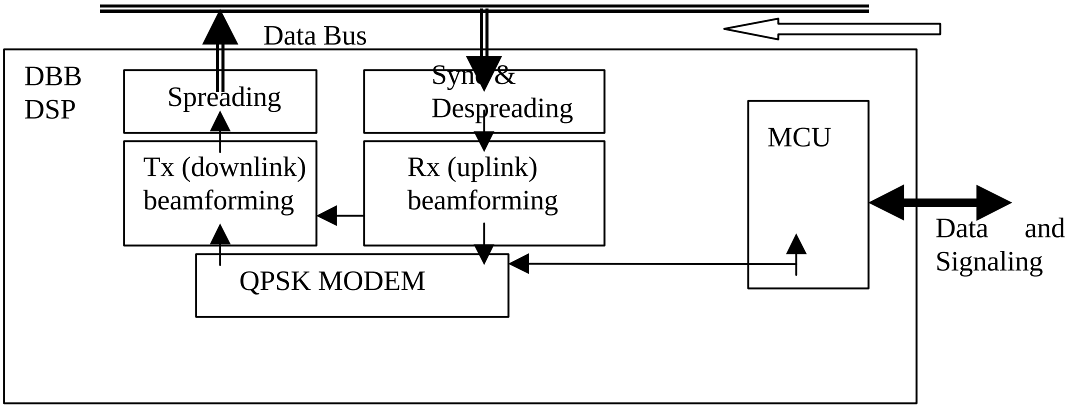
U is the downlink beamforming matrix with element $u_{ji}(l)$.

1.4. TDD and FDD

It is well known that there are two duplexing modes in IMT2000 RTTs: TDD and FDD.

The wave propagation environment is very complex, and it is closely related to working frequency and time when the UE is in moving. Reference to section 1.3, the downlink beamforming is always followed by uplink beamforming. And it is always very important to reach fast beamforming to catch the time variation in mobile network.



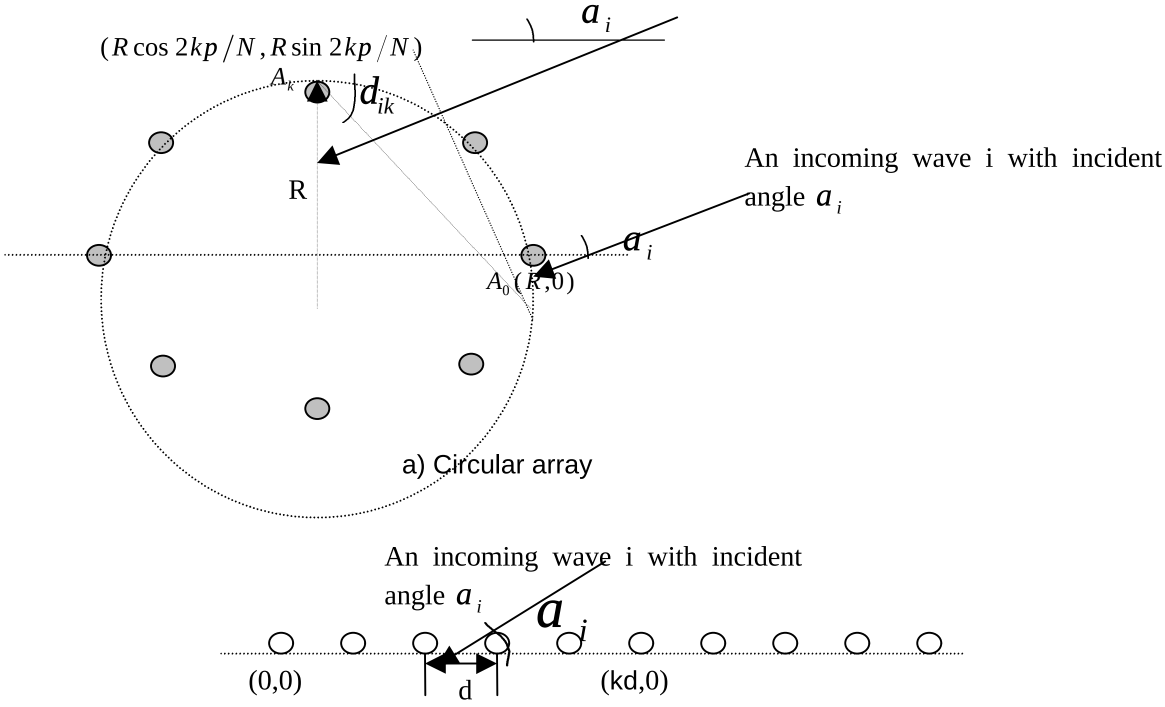


In TDD system, the uplink and downlink are operated at the same frequency but in different time slots. This make it possible to directly use the uplink beamforming results (W in equation (1)) to downlink beamforming (U in equation (2)) because of the symmetrical performance in wave propagation. The reciprocal principle in electro-magnetic theory provides the theoretical foundation.
In FDD mode, the different carrier frequencies between downlink and uplink results in different wave propagation environments. Theoretically, for FDD system, there is no practical model can be used to foresee the downlink propagation in a real environment. What one can do is only to provide a pencil beam for downlink focusing on the direction of the UE.

2. Beamforming

2.1. The maximum energy combination

As shown in Figure 2, the most practical array used in smart antenna is circular array or linear array. The circular array is suitable for omnidirectional cell design while the linear one is suitable for sectorial (180^o or 120^o) cell design. Let the array be composed of N antenna elements, where the first (reference) antenna element is located at the position of (R, 0), and the k -th element is located at the location of ($R\cos 2kp/N, R\sin 2kp/N$) in circular array. And the first (reference) antenna element is located at the position of (0, 0), and the k -th element is located at the location of (kd , 0) in linear array respectively.



a) Circular array

b) Linear array

Figure 2. The geometric illustration for antenna array

Then, when an incoming wave i from the direction of a_i, for circular array, the differential optical distance (D_{ik}) between the first and the k-th antenna element will be

$$D_{ik} = R\cos d_{ik}[2(1-\cos 2kp/N)]^{1/2} \qquad (3)$$

where R is the radius of the circular array;
$k = 1,2,\cdots,N-1$;
N is the total number of antenna element.

The incident wave comes from the direction of a_i as shown in Figure2, and

$$d_{ik} = a_i + p(1/2 - k/N)$$

For linear array, the differential optical distance will be:

$$D_{ik} = k \cdot d\cos a_i \qquad (4)$$

Where d is the distance between adjacent antenna elements.

$S_{kj}(n)$ as the Rx signal at the k-th antenna element from the i-th path of the j-th UE ,then

$$S_{kj}(n) = \sum_i a_{ji}(n)\exp[-j(wt_{ji} + j_{kji})] \quad \text{for the } n\text{-th sampling} \qquad (5)$$

where, $a_{ji}(n)$ is the amplitude of the i-th path from the j-th UE;

t_{ji} is the time delay of the i-th path from the j-th UE;

j_{kji} is the phase different between the k-th element and the reference element for the i-th path from the j-th UE:

$j_{jik} = 2p\, D_{jik}/l$

and D_{jik} is the differential optical distance between the first and the k-th antenna element for the i-th path from the j-th UE;

w is the angle frequency and l is the wavelength.

Let's denote $S_k(n)$ as the total output from the k-th receiver to DBB, then:

$$S_k(n) = \sum_j S_{kj}(n) \quad \text{for the } n\text{-th sampling} \qquad (6)$$

After despreading in the DBB processor, the data related to each code channel will be obtained as $x_{jk}(l)$ at the symbol l.

The goal of smart antenna in uplink is to find the best E_b/I_0 for Rx signal at the DBB,

Let's denote the $X_j(l)$ as the output of smart antenna for the l-th symbol from the j-th UE, then it can be obtained that

$$X_j(l) = \sum_{k=1}^{N-1} x_{jk} w_{kj} \qquad (7)$$

where W is the uplink beamforming matrix with its element w_{kj}. Considering the requirement of real time operation and the present level of microelectronics, the maximum energy combination algorithm is used in beamforming as follows:

$$w_{kj} = x_{jk}^{*} \qquad (8)$$

In TDD mode, as mentioned in section 2 of this document, we calculate the average of the uplink beamforming data in 40 symbols and use it as the downlink beamforming matrix directly.

3. Features

3.1. Capacity issue

Capacity or spectrum efficiency is one of the most important issues in requirements of IMT2000. In most traditional CDMA system, the CDMA resources can not be fully used because of the interference from the other code channels and multipath. For examples, without smart antenna, there are 64 code channels designed in IS-95 system, but approximately only 20~30 code channels can be simultaneously put into traffic service; in the UTRA-TDD with 4.096 Mcps mode, 8~10 code channels may be simultaneously used for traffic service although the spreading factor is 16.

On the basic principle in usual antenna array, the beamwidth will be y/N in the case of maximum energy combination algorithm, where y is the beamwidth of one antenna element and N is the number of antenna elements in the array. This means that the beamforming of smart antenna system will narrow the beamwidth. In other words, the energy of the received interference will be reduced by the same level as that in the uniform distribution model. Lower interference means higher capacity in CDMA system. In the TD-SCDMA RTT proposal, the spreading factor is 16 and the 16 code channels can be simultaneously put into traffic service. This is the main advantageous feature of smart antenna technology.

3.2. Coverage issue

The smart antenna system will increase both the Rx sensitivity and the Tx EIRP of Node B. When the maximum energy combination beamforming algorithm is deployed, both the Rx sensitivity and the Tx EIRP will increase $10\lg N$ dB and $20\lg N$ dB respectively. The coverage distance will increase 80% when N =10 and the 4-order propagation law is used. In other words, one can use low cost LNA with higher NF in Rx and low cost PA with lower Tx power in Tx in a smart antenna system, but the coverage is still up to or even better than that of the traditional wireless communication system.

3.3. Cost issue

It is well known that the most expensive part in Node B is the last-stage linear HPA. And the cost for linear HPA is not easy to reduce. For examples, a linear HPA with P_{out} of 30W will cost a few thousand \$US, and a linear HPA with P_{out} more than 100W will cost more than 10 thousand \$US. When the smart antenna technology is deployed, the cost for PA can be greatly reduced for the lower Tx power PA can be used in system. For example, if one use a 12-element circular antenna array with maximum power combination beamforming algorithm, and P_{out} of 1W in each PA, the Tx EIRP will be equal to $20\lg(12)+30\text{dBm}=52\text{dBm}$ or 160W. But the cost for the 12 pieces of transceivers including PAs will be less than a few thousand \$US.

In the reliability issue, the multiple transceivers and PAs in the smart antenna system will solve the redundancy problem in Node B. In other words, the reliability of the smart antenna system will be much higher than a single HPA system. Of course, one may design a Node B with more than one HPA for redundancy, but then the high cost will double. In addition, less power consumption of low output PA will reduce the cost for power supply unit.

As a conclusion, the smart antenna technology is a low cost solution to Node B in IMT2000, and it meets the main requirements of ITU.

4. Related technologies and parameters

4.1. Chiprate and software radio

Reference to Figure 3, an example of the Rx path in a smart antenna based Node B. One may calculate the bitrate on the high-speed bus under the following basic conditions:

- Number of antenna elements: N ;
- QPSK modulation;
- 16-bit parallel input and output bus;
- Chiprate: R;
- 8-time oversampling in both I and Q branches;

then the bitrate will be:

$$bitrate = 2\times N\times 8\times R = 260Mbps\ (R = 1.3542Mcps) \text{ Or } 786.4Mbps\ (R = 4.096Mcps)$$

where $N = 12$ as an example. Obviously, so high rate bitstream can not be processed in DSP in real time. One way is to separate the high-rate part (over sampling, for example) in each TRx by DSP or ASIC, then the bitrate on the bus will be reduced by a factor of 8 that:

$$bitrate = 32.5Mbps\ \ (R = 1.3542Mcps) \text{ Or } 98.3Mbps\ \ (R = 4.096Mcps)$$

Obviously, lower chiprate is easier to process on the bus.

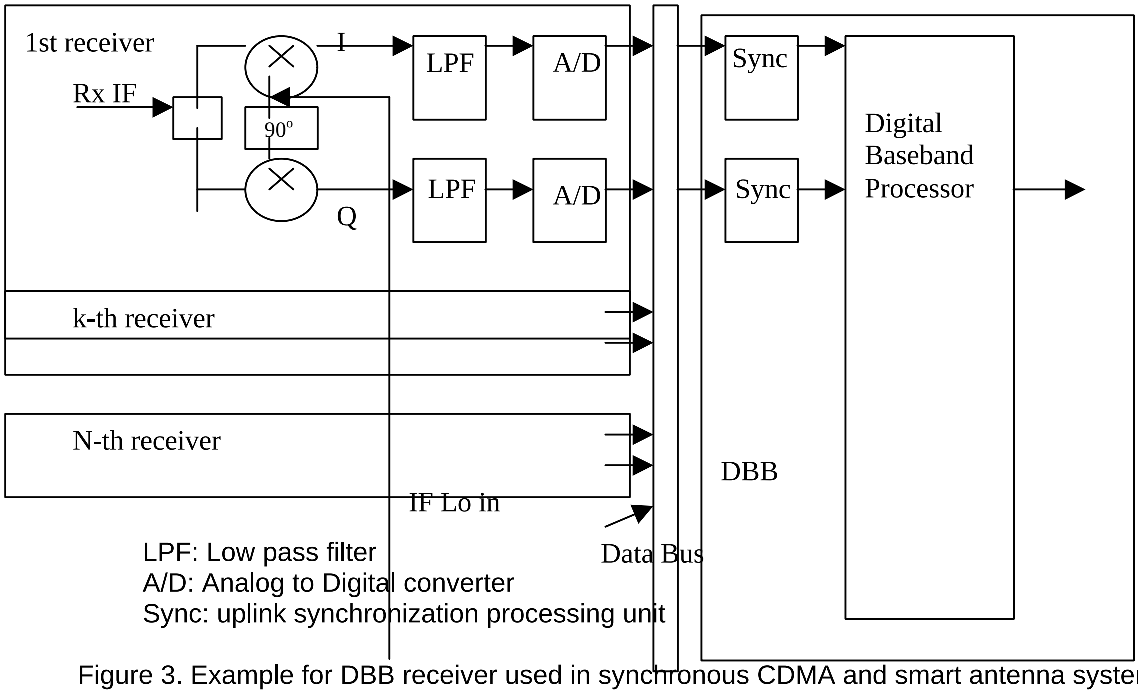


Figure 3. Example for DBB receiver used in synchronous CDMA and smart antenna system

As mentioned above, the beamforming will be processed in DSP by software. The processing capacity of the available commercial DSP at present is about 1GIPS, and may be up to 2 to 3 GIPS by end of 2001. If the DSP is interfaced to bus with a rate of a few hundreds Mbps, it will have no time for data processing! Parallel processing may be a solution, but it will bring complexity.

As a conclusion, lower chiprate will be easy to adopt smart antenna technology based on the present and the short future level in software radio technology.

4.2. Uplink synchronization

As mentioned before, the DOA estimation and beamforming of smart antenna is performed in DBB DSP. It is requested that the DBB receivers in each Rx path in Node B should bring the phase and amplitude information of the Rx signal to DBB processor for smart antenna processing. The simplest way to design the DBB receiver is that illustrated in Figure 3. It is obvious that the receiver can only be used in a CDMA system with uplink synchronization. In other words, synchronous CDMA will lead to a simplified solution to smart antenna system.

4.3. Multipath

It is well known that multipath propagation is the major interference source in CDMA system. In smart antenna system, formed beam will be pointed to the target UE, and the interference with DOA out of the main lob of the formed beam will be pressed down approximately 10dB. This will greatly enhance the capacity of the system. However, the multipath may arrive in the nearby incident angle as main lob, then the interference can not be canceled by space filter. This worst situation may appear in the vehicle environment.

Simulation result shows that, when transmitting 2Mbps high-speed data service, smart antenna can make great benefit because there is only one user in the system in indoor environment. But the capacity will be limited to 8 users in one time slot when the number of the antenna elements in the array is 8 and without additional data processing solutions in outdoor to indoor environment. To get the maximum capacity, one may use an array with 16 antenna elements or deploy additional solutions to combating multipath such as channel equalization after space filtering.

5. Conclusion

In this working document, a basic description for the structure of smart antenna system in Node B is provided, as well as the beamforming principle and features in TD-SCDMA system. It is shown that the advantageous features such as high spectrum efficiency, low cost, etc., are mainly contributed by the smart antenna technology. Smart antenna is one of the most important parts in TD-SCDMA (UTRA-TDD low chiprate mode) Node B.