Distributed Wireless Communication System: A New Architecture for Future Public Wireless Access

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ABSTRACT

Distributed wireless communication system (DWCS) is a new architecture for a wireless access system with distributed antennas, distributed processors, and distributed controlling. With distributed antennas, system capacity can be expanded through dense frequency reuse, and transmission power can be greatly decreased. With distributed processors controlling, the system works like a software or network radio, so different standards can coexist, and the system capacity can be increased by coprocessing of signals to and from multiple antennas.

INTRODUCTION

WIRED VS. WIRELESS

With the rapid progress in telecommunications, more and more services are provided on the basis of broadband communications, such as video services and high-speed Internet. With worldwide fundamental construction of a backbone network based on optical fiber providing almost unlimited communications capability, the limited throughput of the subscriber loop becomes one of the most stringent bottlenecks. Compared to the capacity of the backbone network, which is measured by tens of gigabits per second, the throughput of the subscriber loop is much lower, only up to hundreds of megabits per second for wired systems (including fixed wireless access). However, for mobile access the throughput is even lower, and depends on the mobility of the terminal. For example, the peak data rate is only 2 Mb/s for 3G systems.

Since there will be more and more need for mobile services, the poor throughput of mobile access not only limits user applications based on interconnection, but also wastes the capability of the backbone network. This case is quite similar to the traffic conditions shown in Fig. 1a, which is an image of an ultra-wide expressway with a few narrow entrances. Since the little paths are rough, narrow, and crowded, the problems in Fig. 1a are:

- Terminals are far away from the expressway, which will consume much power.
- Too many cars converge into the same narrow paths.
- Little paths converge several times before going into the expressway.
- The expressway is used insufficiently, since few cars are running on it.

In telecommunications, the optical fiber network (expressway) is relatively much cheaper than the wireless spectrum (little paths), while the capability of the former is much greater than that of the later. As shown in Fig. 1b, besides the backbone expressway, there are some dedicated subexpressways used to provide direct entrance for distributed subscribers.

The above example implies that the high-capacity wired network, being so cheap, can help us solve the problem of wireless access(too many users crowded in a very narrow bandwidth). The key issue is to provide each mobile user a direct or one-hop connection to an optical network. This structure also follows the trend in network evolution: the hierarchical or tree-like structure of traditional networks will be gradually flattened to simple single-layer ones.

PRIMARY PROBLEMS

The basic problem of wireless access is that the available spectrum is too limited compared to the almost unlimited service requirement, just like cars jammed in crowded narrow paths. Another basic problem is that there is great attenuation of energy. For example, the transmitter power may be 300 mW in order to transmit 2 Mb/s in a 2 GHz frequency band. Correspondingly, for a future system working on a 5 GHz band at a data rate of 100 Mb/s, we may need 30 W transmission with the same technique. This is impossible for a handset, considering the battery life and the radiation effect on the human body.

CLUES FOR SOLUTION

It seems that the only solution for the first problem is to explore the space resource. The cellular system is a successful example. With a cellular structure, the frequency can be reused as many times as needed. Also, the cellular structure reduces the maximum distance from the terminal to the nearest base station, which is also a clue to solve the second problem.

This work is co-sponsored by the National Natural Science Foundation of China, No. 90204001, and China FuTURE Project.

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However, in a traditional cellular system, when the cell size gets smaller, capacity can be increased linearly with cell density. But this is based on the assumption of a large path loss exponent. When the cell size is small enough, the exponent gets small, which may be approximately 2; thus, the interference may be so large that the system may not work, as seen in Fig. 2.

The above phenomenon indicates that the system capacity cannot be increased anymore when the density of cells reaches a certain level. Fortunately, the information theory of minimum input minimum output (MIMO) indicates that for a system with M fixed antennas and N mobile antennas (the mobile antennas belong to one or more mobile terminals), the total capacity can be expressed as

$$C = \log_2 (\det(\mathbf{I} + \mathbf{H}^H\mathbf{H}/\sigma^2)), \tag{1}$$

where σ^2 denotes the receiver noise power, and $\mathbf{H}$ denotes the matrix of channel attenuation factor, which can be expressed as

$$\mathbf{H} = \begin{pmatrix} \mathbf{H}_{11} & \mathbf{H}_{12} & \mathbf{H}_{13} & \cdots \\ \mathbf{H}_{21} & \mathbf{H}_{22} & \mathbf{H}_{23} & \cdots \\ \mathbf{H}_{31} & \mathbf{H}_{32} & \mathbf{H}_{33} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}, \tag{2}$$

where $\mathbf{H}_{ij}$ denotes the channel attenuation factor submatrix from users in the jth cell to the ith base station. For a cellular system with large path loss exponent, interference from other cells is very small, so elements in $\mathbf{H}_{ii}$ are much greater than those in $\mathbf{H}_{ij}$ $(i \neq j)$, and $\mathbf{H}$ can be approximately expressed as

$$\mathbf{H} = \begin{pmatrix} \mathbf{H}_{11} & 0 & 0 & \cdots \\ 0 & \mathbf{H}_{22} & 0 & \cdots \\ 0 & 0 & \mathbf{H}_{33} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}, \tag{3}$$

where $\mathbf{H}_{ii}$ denotes the channel attenuation factor in each cell. Thus, the signal design and processing can be dealt with by each cell independently, which is the reason for the success of the cellular system.

However, when the path loss exponent is relatively small, the interference from other cells will be intolerable if the signals in each cell are processed independently. Fortunately, in this case, since $\mathbf{H}_{ij}$s are independent, the rank of $\mathbf{H}$ is still very high, which is approximately the number of fixed antennas. Thus, the system capacity can still be proportional to the number of fixed antennas. Note that here we do not use the word *cell*, since the traditional concept of cell no longer exists. The signals to and from antennas located at different places must be designed and processed jointly. This is one of the motivations for our new architecture of distributed wireless communication system (DWCS).

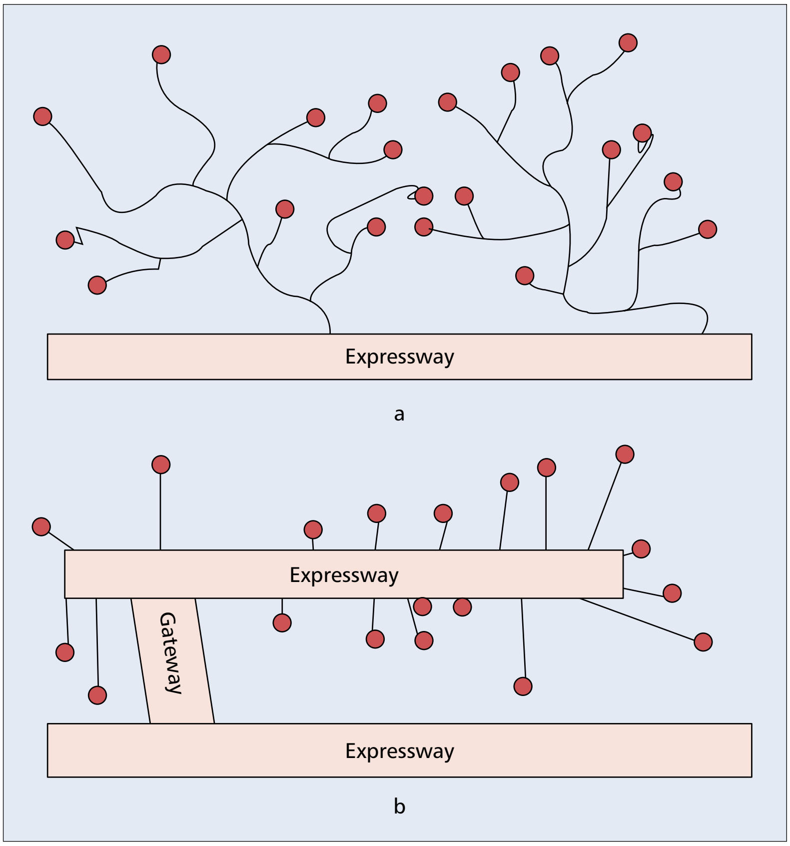

Figure 1. *The similar scenario in public traffic: a) a tree-like structure; b) direct entrance to a subexpressway.*

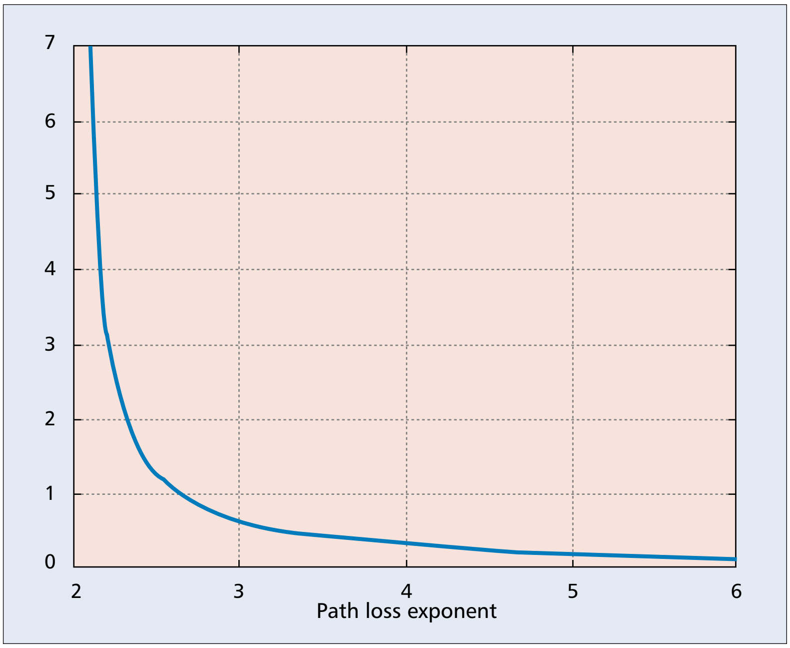

Figure 2. *Normalized interference vs. path loss exponent.*

A Description of DWCS

Logic Structure

For comparison, Fig. 3a shows the traditional tree structure of a cellular system, where each base transceiver station (BTS) processes the signals to and from mobile terminals within its coverage, and considers the signals of other cells as interference. Terminals at the boundary of cells may hand off between adjacent BTSs, and the handoff is controlled by the radio network controller (RNC). When cell size is reduced, handoff frequency increases, and system overhead will be too heavy. Meanwhile, interference from

The new structure has a very high density of distributed antennas, so that almost anywhere in the area may have line-of-sight (LOS) to at least one fixed antenna.

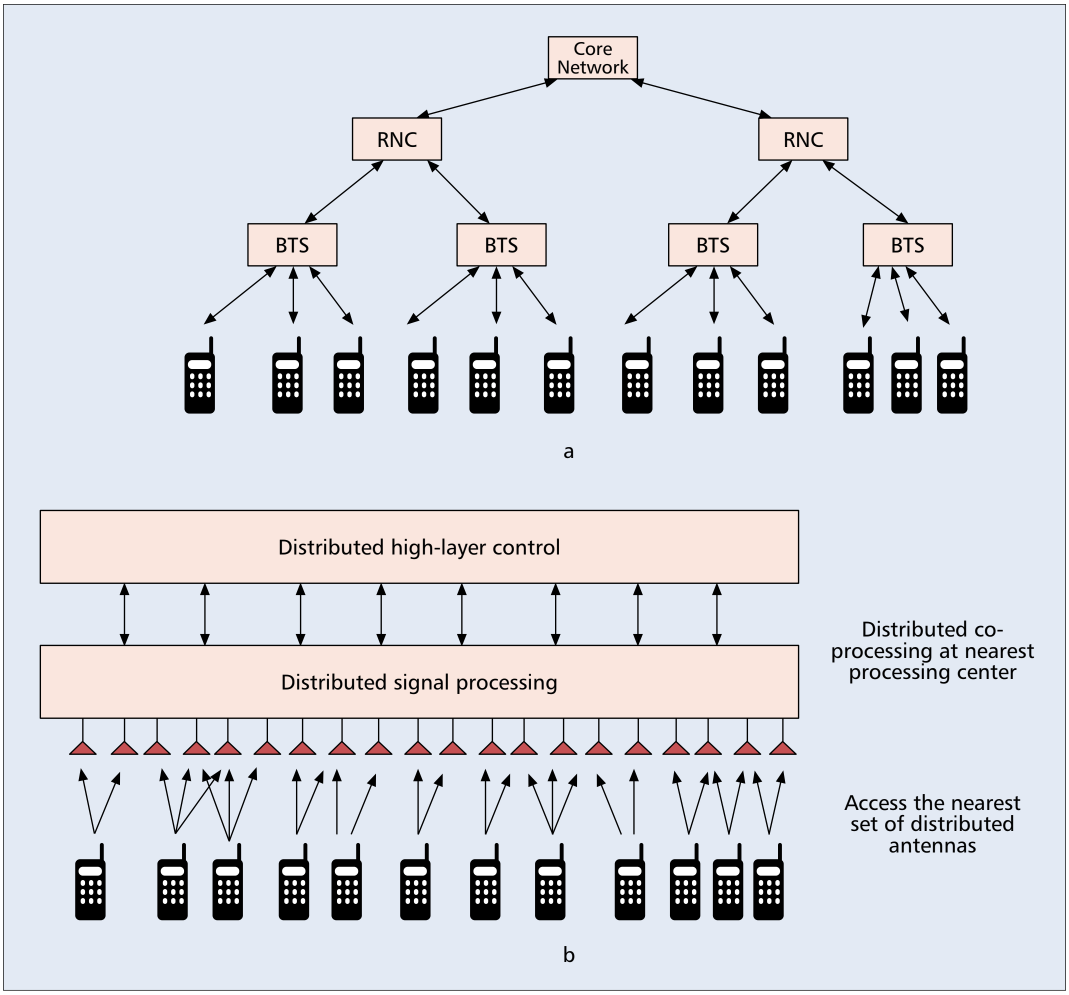

Figure 3. *Comparison of two different access architecturse: a) the traditional tree structure of acellular system; b) the DWCS architecture.*

other cells may become so strong that the capacity of each cell is very small.

The basic idea of the distributed wireless communication system is to flatten such an architecture, as indicated in Fig. 3b. The structure consists of three layers: distributed antennas, distributed signal processing, and distributed high-layer control.

Distributed Antennas — The new structure has a very high density of distributed antennas, so almost anywhere in the area may have a line of sight (LOS) to at least one fixed antenna. Each antenna is equipped with a transceiving device, which converts radio frequency (RF) to and from digital intermediate frequency (IF) signals. The received IF signal is transmitted to the processing center through optical fiber. The IF signals for transmission and system timing are also provided by the processing center through optical fiber. Thus, we may have a large number of very low-cost transceivers with no information loss introduced, since no baseband signal processing is performed here.

Distributed Signal Processing — This is the essential part of the architecture. All signal processing concerning wireless access is involved in this layer, including modulation/demodulation, channel coding/decoding, joint detection, channel measurements, medium access control (MAC), link layer control (LLC), radio link control (RLC), radio network control (RNC), and so on.

Physically, this layer consists of two sublayers, *distributed processing centers* (DPCs) and the *dedicated optical network*. The optical network has two main tasks: to collect and deliver digital IF signals to and from distributed antennas, and to connect the processing centers so that co-processing among different DPCs can be performed based on high-speed real-time data exchange. The optical network may have any kind of topology — star, bus, ring, or any other.

Logically, this layer can be regarded as an extremely powerful processor (EPP), which connects all the RF modules of distributed antennas. This EPP is actually software radio equipment, and is realized by many workstations in parallel while exchanging data through a high-speed network, as shown in Fig. 4.

With such a structure, the EPP knows all signals received from all antennas, and can control the transmission of all the antennas. Thus, the whole system works like a point-to-multipoint system with a large number of distributed antennas, which is actually a rather large-scale MIMO system.

Practically, the coverage of signals from each terminal or distributed antenna is relatively small compared to the whole area, so each processing center is responsible for the distributed antennas located nearby. The regions for different processing centers may overlap each other; thus, co-processing must be involved.

With a distributed processor, the system becomes scalable and software configurable. Thus, coexistence of difference systems, and system update and expansion may be quite easy.

Distributed High-Layer Control — This is also a logic layer, which may be performed on the same platform as signal processing. This layer performs all high-layer protocol control, including all signaling, switching, and mobility management (gateway to core network).

New Concepts

Distributed Processing of Wireless Signals — In a distributed wireless communication system, each layer is distributed, and the most important concept is the distributed processing of wireless signals. Unlike a traditional cellular system, whose signal processing is performed in the BTS for each cell, the processors in DWCS are separated from the antennas, each processor performs the signals to and from many antennas distributed in the area, and there is tight co-processing among different processors.

Although the processing layer can be logically considered as a central processing unit, signal processing is performed in parallel by many processors distributed in the area. In such a structure, signals to and from multiple antennas can be processed jointly at the nearest processor so that the capability of the channel can be fully utilized by a mechanism similar to MIMO.

Meanwhile, high-speed connectivity between processors enables interworking among them, and processing tasks can be dynamically arranged and delivered among the processors, which can make full use of the processing power. Distributed processors also help to increase the reliability of the system, since in the failure of one processor, its processing tasks can be moved to another processor.

This processing structure is also a kind of software radio, or network radio, which is based on configurable processors connected by a high-speed network. With its configurability, the system can easily support multiple standards and be updated and expanded freely.

The Virtual Cell — The traditional concept of cells no longer exists in DWCS; instead, we propose a new concept, the *virtual cell*. Unlikea traditional cell that is base-station-centered, a virtual cell is MT-centered. In other words, the virtual cell is a set of distributed antennas that are within reach of a certain mobile terminal (MT). Each MT has its own virtual cell, and it changes as the MT moves or the environment changes (e.g., change of system load).

A virtual cell is not exactly a real cell; it is only useful in signal processing. The processing layer selects a virtual cell for each MT dynamically, and detects and optimizes for transmission jointly with the virtual cell. Some MIMO techniques will be involved in virtual cells, so interference from other users can be canceled or suppressed.

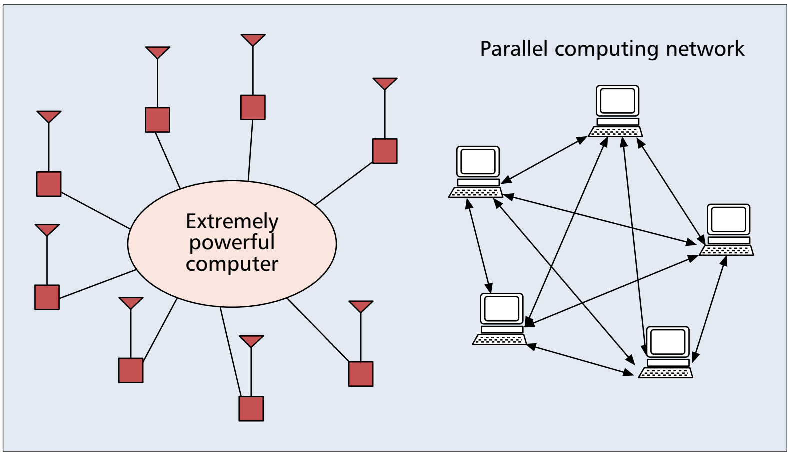

Figure 4. *Software radio/network radio.*

The Virtual Base Station — In a traditional cellular system, the base station performs the signal processing for its own antenna and users. However, in DWCS, the function of signal processing is put into a distributed processing network. Thus, the processing function for the user of a certain region no longer belongs to a certain processor, and thus becomes a *virtual base station* (VBS). A VBS provides signal processing service for users within reach of the set of antennas. The function of a VBS can be performed among several processors. In order to process the signals for the overlapping area, data communication between VBSs is necessary.

System Capacity View

In order to evaluate the system capacity, we constructed a simple system. Here, we consider a system with CDMA signals. Although in considering the high throughput requirements for future mobile communications, a multiple carrier technique such asa orthogonal frequency-division multiplex (OFDM), may be preferred, in DWCS, interference from other users is very strong, so some code-division multiple access (CDMA) mechanism must be involved to distinguish users. In our system assumption, direct sequence CDMA (DS-CDMA) is used , but the result is similar when CDMA is applied in the frequency domain.

The parameters are described as follows:
- Service activity factor: 0.375
- Spreading factor: 127
- Log-normal shadow fading parameter: 8 dB
- Required signal-to-interference ratio (SIR): 7 dB
- Number of antennas in a virtual cell: m

Uplink Capacity

Here, we will provide some of the analytical results with the assumption of perfect power control on shadowing effect. Figure 5 shows the average outage probability of uplink vs. user number per antenna, with virtual cell size as a parameter.

From the analytical results, we find an interesting phenomenon: the outage probability of users may differ from different locations. The maximum outage probability occurs at the site of

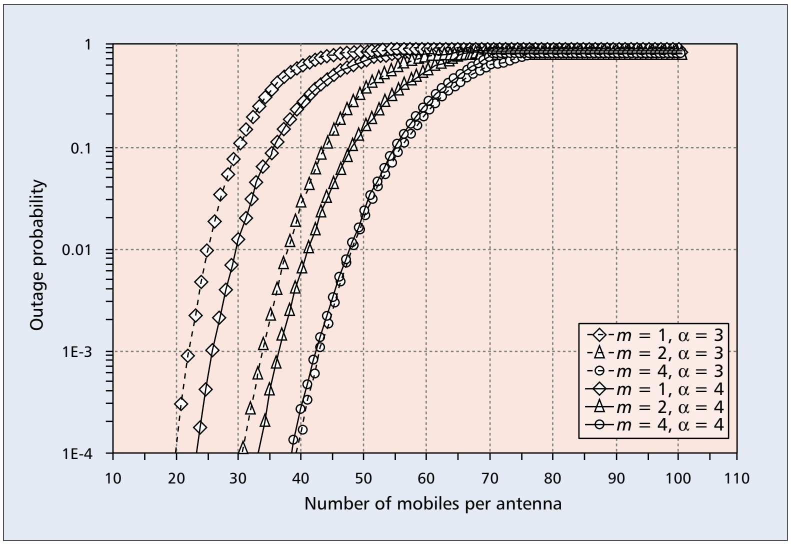

Figure 5. *Effect of path loss exponent* α *on capacity.*

the antenna. The reason may be that the effective diversity order is only 1 at this point, while at other places the diversity gain is much better.

Figure 5 also shows the effect of path loss exponent α on capacity. We can see clearly that when the virtual cell size is small, the decrease of α introduces significant capacity loss. However, this loss becomes negligibly small when *m* gets larger. Especially when user density is very small, the decrease of α may have a positive effect, since we may get more diversity gain than the loss in interference. This result indicates that system capacity can be increased almost infinitely with increased antenna density, whether or not the path loss factor changes. This is one of the most significant differences from a traditional cellular system.

Downlink Capacity

Downlink capacity depends on the assumption of the transmission scheme. The following results are based on the assumption that an MT has only one antenna. The red lines in Fig. 6 show the results for equal power allocation on *m* antennas (*m* is the virtual cell size), which means that the *m* antennas for a certain user transmit same information with different spreading codes and the same power. We can see from the figure that the capacity decreases when *m* increases. The reason is that with larger *m*, there will be more transmitted power wasted on poor antennas, which introduces more interference. Thus, it seems that selective transmission among antennas may be the best choice.

Fortunately, with another assumption we may get much better results. Here we assume that *m* best antennas for a certain user transmit the same waveform to it, and the timing and phase of transmission is adjusted so that the signals from *m* antennas arrive at the user at the same time with the same phase. The power allocation among antennas is proportional to the channel gain of the antennas. We call this scheme *maximum ratio transmission* (MRT). With MRT, the receiving SIR can be increased with *m*; thus, more capacity can be achieved (Fig. 6).

Feasibility of MRT

Of course, the success of MRT needs very strict conditions, including timing and phase adjustment. Besides, the result is only for a flat fading channel. For a frequency selective channel, the channels from different antennas may be of different delay spreads, and fading is independent.

To solve this problem, multicarrier technique may be used. For example, with OFDM, each subcarrier can be regarded as flat. Thus, we can adjust the phase of each transmitted subcarrier so that the received SIR is maximized.

Obviously, such a scheme needs knowledge of the channel at the transmitter. This can be achieved by either time-division duplex (TDD) or feedback from users. Either of these may restrict the mobility of users. Thus, one feasible solution is to involve the two transmission schemes simultaneously, MRT for low mobility and selective transmission for high mobility.

Accessing Power

Besides the benefit of capacity increase, another significant advantage of DWCS is that the accessing power of an MT may be decreased greatly. The relationship between the required transmission power is proportional to (antenna density)$^{-\alpha/2}$, where α is the path loss exponent.

Moreover, with a decrease in access distance, the path loss exponent also decreases, so the required transmission power may be even lower. Consider again the example discussed previously in this article: we may need 30 W to achieve 100 Mb/s transmission at 5 GHz in the current cellular system. However, with distributed antennas of 10 times the density, the required power can be 20 dB lower, which is less than 300 mW, and is actually quite practical.

Network Radio

The concept of software radio has progressed for about 10 years. In different environments and different systems, different kinds of software radio architecture are proposed. Software radio based on a PC network [1] is one of them, which is suitable for applications in base stations. Its basic idea is to perform the baseband signal processing in parallel among many PCs, which are connected by a network.

This idea is now extended in DWCS; here, the PCs are replaced by much more powerful processors, and the interconnection among these processors is evolved from an ether network to an optical network, to ensure high-speed data exchange and accurate timing. Another extension is that the processors are no longer located at the same place, but are distributed in a large area.

This architecture is also a kind of realization of radio functions, and thus can be called network radio. Besides all the benefits inherited from software radio (flexibility, scalability, easy update, supporting multiple standards, etc.), it is much more suitable for large area radio network processing, and enhances system reliability.

APPLICATIONS

DWCS, proposed here, is a new architecture for a future wireless access system. Although it has many advantages, discussed here, it is still immature at this time. In order to make it a reasonable structure for the future, some of its ideas must be applied in existing systems.

As the first stage, the existing distributed repeater connected by optical fibers can be regarded as a special but simple case of DWCS.

CONCLUSIONS

While the industrialization of 3G mobile communications is ongoing, studies have been started for techniques and architecture for future mobile or wireless access, namely 4G or beyond 3G. Since beyond 3G is aimed at the system for at least 10 years from now, much larger capacity and coverage requirements are put forward. DWCS is one of the candidate architectures to fulfill these requirements.

As described above, here we conclude by listing the main features and advantages of DWCS:

- ***Three distributed layers*** — Distributed antennas, distributed signal processing, and distributed high-layer control.
- ***No fast handoff problem*** — The virtual cell changes dynamically with the movement of the user, so no handoff is needed.
- ***Large capacity*** — With distributed antennas and distributed processing, the problem of increased interference in traditional cellular systems is overcome.
- ***Much lower power consumption*** — The transmission power can be greatly reduced.
- ***Seamless coverage*** — The antenna terminal is so cheap that the density of antennas can be very high.
- ***Suitable for nonuniformly distributed traffic*** — Simply by adjusting the density of antennas.
- ***Opened structure*** — Existing and future standards and techniques can be realized on the platform of DWCS, and the resources of the wired system can be utilized sufficiently.
- ***Flexible*** — The concept of software radio enables DWCS to accommodate different standards without hardware modification.
- ***Extendibility*** — The opened structure ensures that redeveloping and extension can easily be achieved on the same platform.
- ***Scalability*** — The scale of DWCS (including the number of antennas and processors) can be configured freely so that the cost of system devices can be minimized.
- ***Easy to update***
- ***Less harmful to human health*** — A result of much lower electromagnetic radiation.

ACKNOWLEDGMENT

The authors would like to thank Prof. Dr. Willie W. Lu for his invaluable supervision and advice on this topic. Without his leadership, this article can never be possible.

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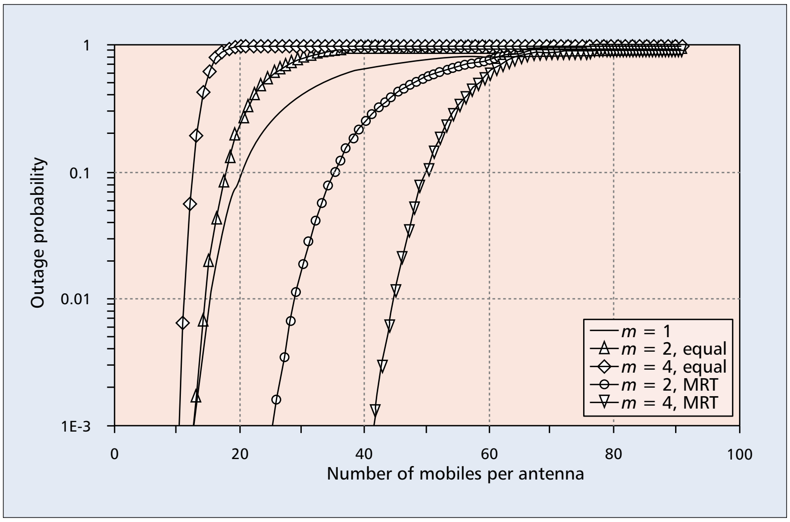

Figure 6. *Forward capacity of equal gain transmission and MRT.*

BIOGRAPHIES

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