Toward Frequency- and Energy-efficient High Mobility Wireless

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Introduction

The 1st generation (1G) public mobile wireless networks using analog technology appeared in 1990's. Since then, we have seen new wireless technology every decade, from 1G to 3.9G, called LTE. In a few years, we will see the 4th generation (4G) called LTE-advanced. In the 1G and 2G networks, voice conversation was the dominant communication service. High speed data services including video are popular in 3G and will become more and more popular in 3.9G. The wireless traffic volume has been increasing rapidly by about 2 times per year. However, the available wireless bandwidth is limited. How to cope with such a rapid increase of wireless traffic while the available frequency bandwidth is limited?

In this paper, we see how wireless technology has advanced in the last three decades and then, discuss where to go. We show the spectrum-energy efficiency tradeoff and the need of spectrum- and energy-efficient high mobility wireless. Promising solution is a heterogeneous network consisting of small-cells and macro-cells: small-cell structured network for high rate data services and macro-cell structured network for high mobility users. Various frequency- and energy-efficient high mobility wireless techniques for heterogeneous network are identified and discussed.

Spectrum- and Energy-efficiency Tradeoff

In wireless networks, the same frequency must be reused in different places in order to efficiently utilize the limited available bandwidth. However, the use of the same frequency produces a serious co-channel interference problem. Thus, the spectrum efficiency has been the most important concern during the last few decades. Recently, people strongly desire broadband wireless data services even while moving in a very fast train. Higher rate data transmission requires higher transmit power. This is a burden to battery operated mobile terminals. Therefore, more attention has been paid to the energy efficiency in addition to the spectrum efficiency. However, a tradeoff relationship exists between the spectrum efficiency and energy efficiency. The current cellular network architecture cannot achieve simultaneously both spectrum efficiency and energy efficiency. It requires us the significant restructure of the wireless networks.

Distributed Antenna Network

The time to learn from human being has come. We, human being, share the same bandwidth of about 4kHz on the globe of 7 billion people to communicate each other. This is the ultimate single frequency reuse. For the single frequency reuse, suppression of the co-channel interference (CCI) is an important problem. The key is very short range communications with

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very low energy to minimize the CCI to other users. This clearly shows that short range communication is the key to achieve simultaneously spectrum efficiency and energy efficiency. An important technical issue is how to integrate very short range communication links into a network. One promising solution is a small-cell structured network. A typical example is the distributed antenna network (DAN), where antennas are distributed over an entire service area. Each user chooses nearby antennas to form a very small wireless cell centering each user, i.e., personal wireless cell is formulated. Only a vicinity of a user is illuminated by a very narrow beam or is covered with very weak transmit signal so that the CCI to other users is minimized. Another advantage of small-cell structured network is that it can utilize the millimeter wave or wireless optical communications, where broad bandwidth is available.

Heterogeneous Network

An inherent nature of wide range of the user mobility is problematic. For high mobility users, frequent handoffs between small cells may happen. Increasing the control traffic significantly reduces the data traffic to accommodate. Therefore, traditional macro-cell structured network may be suitable for high mobility users. Furthermore, the traffic distribution is not uniform and there may be only a few scattered hotspot areas of heavy traffic in a macro-cell area. The heterogeneous network consisting of macro-cell and small-cell structures may be a practical solution. To alleviate the problem of increasing traffic in small-cell structured network, the separation of control and data paths is a good idea. The control data traffic is carried by a traditional macro-cell structured network and broadband data traffic is carried by a small-cell structured network

Waveform Design and Data Modulation

There are many important technical issues for heterogeneous network. The broadband wireless channel in a high mobility environment becomes severely doubly-selective. Cyclic prefix (CP)-inserted OFDM and single-carrier (SC) transmissions with simple one-tap frequency-domain equalization (FDE) can be used to overcome the frequency-selectivity. CP-SC has an advantage of lower peak-to-average power ratio (PAPR) than CP-OFDM and therefore, is attractive for its application to the transmit power limited wireless networks (in particular, uplink application). Instead of CP, a known training sequence (TS) can be used. The use of TS allows the robust channel estimation in a high mobility environment. Furthermore, the broadband channel of a short range data communication is a line-of-sight link and relatively stable and quite high level modulation, e.g., 256QAM, can be used to improve the spectrum efficiency.

Channel Allocation and Multi-access

Another important issue is the channel allocation. Heterogeneous network consists of small-cells with low transmit powers and macro-cells with high transmit powers. Interference between two small- and macro-cells is problematic. To avoid the co-channel interference (CCI) problem, the available channels may be divided into two orthogonal channel groups: one for small-cell network and the other for macro-cell network. However, this may degrade the spectrum utilization efficiency of limited frequency bandwidth. Higher spectrum efficiency can be achieved if both networks can share the same group of channels while avoiding the CCI between two different networks? This may be possible by using autonomous dynamic channel allocation. In a small-cell network, there are so many nearby cells. As more small-cells are deployed, the same channels tend to be reused by nearby cells, thereby producing severe CCI. Since small cells are non-uniformly deployed and the traffic changes significantly in time, the channel reusing while minimizing the CCI is a very difficult task. A promising channel reusing is possible with the dynamic channel segregation. Each transceiver in a cell measures the CCIs on all available channels periodically, updates the priority table, and selects the best channel (with minimum average CCI) to use. In this way, the channel reusing pattern with minimum average CCI according to the changes in the average traffic pattern (over tens of minutes to several hours) is formed in a distributed manner without exchanging any CCI information among cells. The dynamic channel segregation can be applied to a heterogeneous network with shared group of channels.

As for multi-access technique, either OFDMA or SC-FDMA using orthogonal channels may be used in a macro-cell network, similar to LTE and LTE-A. However, in a small-cell network, since only a few users exist in each cell, very simple multi-access technique (e.g., CSMA/CA, SDMA, etc.) may be applied.

Another interesting solution to avoid sophisticated multi-access is to revisiting to non-orthogonal code division multi-access (CDMA). However, since CDMA is very sensitive to the interference, we need to divide the available bandwidth into two: one for small-cell network and the other for macro-cell network. CDMA may be applied to small-cell network.

Conclusion

Various problems toward spectrum- and energy-efficient high mobility wireless were identified in this paper. A practical solution is an introduction of heterogeneous network consisting of two different types of cellular networks. We discussed important wireless techniques to realize heterogeneous network, i.e., control and data paths separation, waveform design, data modulation, channel segregation based autonomous channel allocation, and possible revisiting to CDMA.

Biography: Fumiyuki Adachi received the B.S. and Dr. Eng. degrees in electrical engineering from Tohoku University, Sendai, Japan, in 1973 and 1984, respectively. In April 1973, he joined the Electrical Communications Laboratories of Nippon Telegraph & Telephone Corporation (now NTT) and conducted various researches on digital cellular mobile communications. From July 1992 to December 1999, he was with NTT Mobile Communications Network, Inc. (now NTT DoCoMo, Inc.), where he led a research group on Wideband CDMA for 3G systems. Since January 2000, he has been with Tohoku University, Sendai, Japan, where he is a Distinguished Professor at the Dept. of Communications Engineering, Graduate School of Engineering. His research interest includes wireless signal processing including wireless access, equalization, transmit/receive antenna diversity, adaptive transmission, and channel coding. He is an IEEE Fellow and an IEICE Fellow. He was a recipient of the IEEE Vehicular Technology Society Avant Garde Award 2000, IEICE Achievement Award 2002, Thomson Scientific Research Front Award 2004, Ericsson Telecommunications Award 2008, Telecom System Technology Award 2010, Prime Minister Invention Award 2010, and KDDI Foundation Excellent Research Award 2012.