Architecture of Wireless Communications System with Multi-Domain Collaboration

Xiaoming TAO, Hui DENG, Tengfei XING, Jing WU, Jianhua LU
Dept. of Electronic Engineering
Tsinghua University, Beijing, P. R. China
Email: taoxm@wmc.ee.tsinghua.edu.cn

Abstract—**Multi-domain collaboration may yield quite improved capacity, which is supposed to be a potential future framework of wireless communication under study supported by the National Basic Research Program in China (973). Exploring of the architecture of wireless communications system is of primary importance to research on multi-domain collaboration. This paper provides the architecture and research framework of wireless communications system to accomplish multi-domain collaboration. In particular, key technologies to improve the transmission capacity by means of multi-domain collaboration are also addressed and evaluated.**

Keywords-Multi-Domain Collaboration; 973; Architecture; Research Framework; Transmission Capacity

I. INTRODUCTION

Wireless communication has been considered as one of the high-tech industries in the world [1]. The common objective of wireless communication system is to provide higher transmission capacity with better flexibility and lower cost. On the other hand, it is also gradually realized that the limitations of existing and upcoming systems in integrated optimization of radio resource utilization, and still, cannot be a good solution to resolve the conflict between the limited radio resources and the rapidly growing service needs. Moreover, their bottleneck problems increase prominently caused by these limitations [2].

The root of the problem is that the framework of traditional wireless communication systems is primarily based on the independent optimization of radio resource and has gradually been limited by the law of “diminishing returns” [3]. Multi-domain collaboration can be regarded as a systematic approach to solve this issue, which is under study supported by the National Basic Research Program in China (973) started in 2007 [4]. This project focuses on the development need of the National Major project ‘New Generation Broadband Wireless Communication Network’ and the key application of broadband wireless communication, studying the integrated approach collaboratively using multi-domain of space, frequency, time, power and terminals, and thus exploring fundamental theory to enhance the efficiency of spectrum resource while realizing the innovations on broadband wireless communication system and key techniques.

From a broader and higher perspective, multi-domain is utilized to create the Degrees of Freedom (DoF), and collaboration is adopted to exploit the benefit of new DoF [5]. In order to achieve this goal, exploring of the new architecture and research framework of wireless communications system is of primary importance. In this paper, we provide the architecture of wireless communications system with multi-domain collaboration. The rest of this paper is organized as follows. Section II shows the essential idea of multi-domain collaboration. Section III provides a general architecture and research framework of wireless communications system with multi-domain collaboration. Key technologies to improve the transmission capacity of wireless communications system under the general research framework are addressed in Section IV. Finally, we conclude the paper in Section V.

II. MUTI-DOMAIN COLLABORATION

A. Multi-Domain

First, let us look at the major four domains in multi-domain collaboration, that is, the service domain, the entity domain, the resource domain and the user domain (Figure 2). The service domain refers to data, images, video, voice and web, etc. The entity domain refers to the network and communication terminals of our everyday use. The resource domain constitutes space, time, frequency and power, etc. And user domain mainly indicates the user's behavior. Each domain has its own literature to discuss its characteristics and applications. Multi-domain collaboration is dedicated at exploiting the relationship among the domains to improve the transmission capacity while achieving innovations in wireless communication.

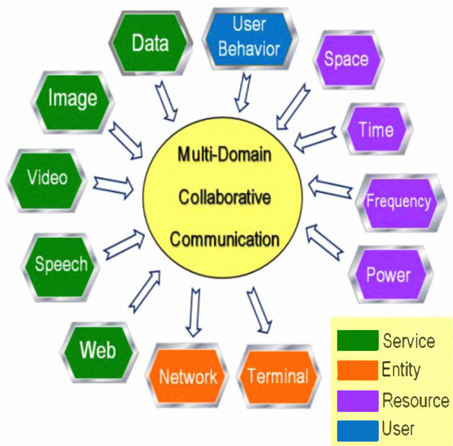

Figure 1. Multi-Domains in Collaborative Communication.

B. Essential of Multi-Domain Collaboration

The proposition of multi-domain collaboration is initially inspired by MIMO transmission scheme. Under suitable channel fading conditions, having both multiple transmit and multiple receive antennas provides an additional spatial dimension for communication and yields a Degrees of Freedom (DoF) gain [6]. These additional DoF can be exploited by spatially multiplexing several data streams onto the MIMO channel. For a MIMO system with N antennas, the additional DoF lead to an N-fold increase in the transmission capacity shown in Eq. (1), which is an enormous development to the concept of traditional Shannon capacity.

$$C = N \log_2 (1 + SNR) \tag{1}$$

C can be defined as the system capacity. The evolution of MIMO transmission scheme reveals that through increasing the DoF available for communication can open a door for substantial improvement of system performance.

Furthermore, on the basis of antenna coordination in MIMO system, we introduce multi-domain collaboration, which is the integrated approach collaboratively using multi-domain of space, frequency, time, power and terminals as shown in the above subsection, and thus increase the capacity gain dramatically. We can reformulate the equation as

$$N = \frac{C}{\log_2 (1 + SNR)} \tag{2}$$

where N is the capacity gain, and we define it as the DoF achieved by multi-domain collaboration. The essential idea of multi-domain collaboration can be characterized, where multi-domain is utilized to create the DoF from various domains and collaboration is adopted to exploit the benefit of new DoF.

III. Architecture of Wireless Communication System with Multi-Domain Collaboration

The system architecture, which relates to the network structure, the transmission schemes and the communication protocols, is accountable for the system usage of power, frequency, space, time and other resources distribution. Thus it is critical for multi-domain collaboration study.

A. System Architecture with Moti-Domain Collaboration

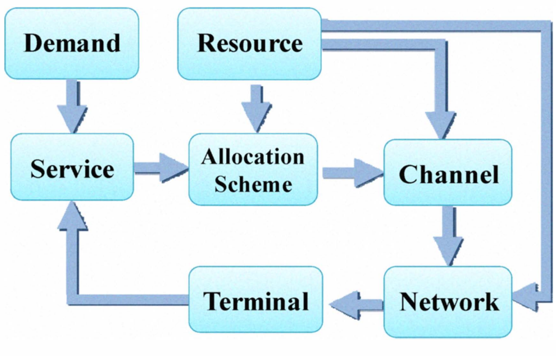

Figure 2. System Architecture with Multi-Domain Collaboration

Figure 2 gives a general architecture of wireless communications system with multi-domain collaboration. Our pushed services are decided on the demand of users. The services and resources are allocated by means of reasonable allocation schemes. Subsequently, they are sent through channel and network to reach the terminal. The transmission performance has a direct impact to the service that can be pushed. Overall, the above process forms a closed loop of the proposed architecture. The service domains, entity domain, resource domain, user domain, mentioned above, are all included in the loop.

Specifically, this architecture consists of the corresponding physical and logical frameworks. Physical framework concentrates on describing system hardware, network structure and transmission mechanism, while logical framework focuses on communication protocols and software of wireless systems. In particular, physical framework implements topology designing and network planning according to different networks. It also does the functional design of network and user's hardware, including base stations, switching units, wireless access points, relays, core network, user terminals, etc. By carrying out the operations above, the practical system topology and connections are composed. Also, the logical framework designs network and user's protocols of the system and defines functions of software according to different networks. Firstly, the corresponding protocol stack is defined, based on which analysis and design of the protocols are done. Especially, among those protocols, control and management planes are responsible for keeping wireless networks controllable at all times. Then, the focus is on designing the corresponding implementation models of signaling in wireless communications system with multi-domain collaboration. Finally, the definition and description of network and user's software functions are done according to the protocols.

B. Research Framework

Applying architecture of wireless communications system with multi-domain collaboration has a main goal: to boost the spectral efficiency and meet the system user capacity requirements effectively. The research framework is shown in Figure 3. Firstly, DoF is created from both the physical and logical frameworks. Secondly, these DoF are utilized in various levels by means of network reconfiguration. Then the searching for one or more optimal or sub-optimal structure is done to realize collaboration between different DoF in order to increase capacity greatly. After realizing the collaboration under the new system structure, we can further discover other new DoF, thus the above steps will recycle.

Figure 3. Research Framework

1) DoF in the system architecture

The nodes and their connection relationship shown in Figure 2 are the key factors that influence the DoF in the architecture of wireless communications system with multi-domain collaboration. We will illustrate the idea of the DoF from the following three perspectives.

a) Link: At link level, the ultimate goal of transmission design is to fully utilize the DoF of the channel, which can be defined as the dimension of the received signal [7]. Take modulation technology as an example. BPSK modulation utilizes only the real dimension (the I channel), while in QPSK (quadrature phase-shift-keying) modulation, an extra bit can be transmitted and both the I and Q channels are used simultaneously, increasing spectral efficiency.

b) Multiuser: Take interference channel as an example. For the fully connected K user wireless interference channel, recent results based on the idea of interference alignment [8] have shown the sum capacity is characterized as $C(SNR)=\frac{K}{2}\log(SNR)+o(\log(SNR))$. Thus, the K user time-varying interference channel almost surely has $K/2$ DoF which means even with K users competing to access the same wireless medium, it is possible for each user to communicate, free from interference, for a fraction $1/2$ of the resource. Interference alignment is in effect a method to exploit the DoF already exist in the system.

c) Network: From frequency reuse to cellular design, from TDMA, FDMA, to CDMA, OFDM, what we do is actually discover or create new network DoF and then find a way to fully exploit the freedom in the context of proper interference management and multiple accesses.

There are still many other DoF can be discovered in the system architecture shown in Figure 2 and further research is shown in Section IV.

2) Reconfiguration Technology

Reconfiguration technology refers to the process of adjustment and reconstruction of the system organization in different granularity. Altering the physical structure involves a high price, so the focus is mainly on logical reconfiguration. While, the logical reconfiguration technology is the re-adjustment and reconfiguration of the resource allocation scheme of time, frequency, space, power, entities and their connection relationship based on a certain physical structure. The ultimate goal of reconfiguration is to make full use of all kinds of DoF to improve the transmission capacity. Detailed illustration will be shown in Section IV.

3) Collaboration

Collaboration can be realized among different entities. For instance, the manager of a department has arranged employee A to complete three tasks, i.e. typing, drawing and composing the music, with reward bonus 1,000 RMB for each task carried out. Similarly, employee B and C also have been arranged to accomplish the three same kinds of tasks with the same reward bonus standard. However, employee A is good at typing, but know nothing about drawing or music composition; graduated from school of fine arts, employee B is excellent in drawing and painting, but not in typing and music composition; employee C has been learning music since childhood, and music composing is one of his specialties, but not drawing and typing. If these three employees complete their own tasks by oneself, the result is, each employee is only able to complete just one of their tasks which they are good at, thus obtain only 1,000 RMB respectively. In contrast, if these three employees can collaborate with each other, i.e. employee A completes the typing task and assists employee B and C to carry out their task simultaneously. After completing his drawing task, employee B also helps the two accomplish drawing task. Likewise, composing tasks of employee A and B are completed by the support of employee C. As the result of this collaboration, everyone is awarded up to 3,000 RMB.

In Figure 2, there exist many kinds of DoF that must be collaborated with each others. Collaboration technology is adopted to exploit the benefit of such DoF.

IV. Key Technologies and Performance Evaluation

In this section, key technologies of Cellular Controlled Short Range Communications and Delay Tolerant Networking Combining Node Mobility are addressed to introduce our current research on logic reconfiguration.

A. Cellular Controlled Short Distance Communications

The core idea of traditional cellular mobile communications is to divide the covered region into several small cells, and set up a Base Station (BS) in each cell, in which Mobile Stations (MSs) and BS establish full-duplex wireless communication to complete the wireless access. Communications between the MSs are achieved only through and by the control of BS, while, the Quality of Service (QoS) can be guaranteed, but its deployment is not flexible enough [9]. In contrast, short distance communications is a direct communication method between MSs, which do not need to get through central node [10]. It can be realized by existing cellular communication links or the communication links of UWB, blue tooth, etc. Its main features are the high data rate transmission and flexible realization. Our research goal is to make full use of DoF by combining the advantages of above two technologies.

Cellular Controlled Short Distance Communications (CCSDC) is of hybrid network topology by the control of BS. This architecture contains the communication links between BS and MSs, as well as the communication links between the MSs with short distance. CCSDC is proposed to make full use of DoF in the traditional cellular mobile communications system. Next we will describe how to utilize the DoF in spatial and service domains to accomplish multi-domain collaboration and improve the transmission capacity.

Firstly, we introduce new DoF in spatial domain. Then, the traditional star topology is reconfigured to short distance point to point direct communication topology. As shown in Figure 4, based on the physical structure of traditional cellular communication systems, we provide an overlapped logical structure with conventional communication and point to point direct communication according to the position of MSs. Meanwhile, the whole reconfiguration process is under the control of BS by signaling links.

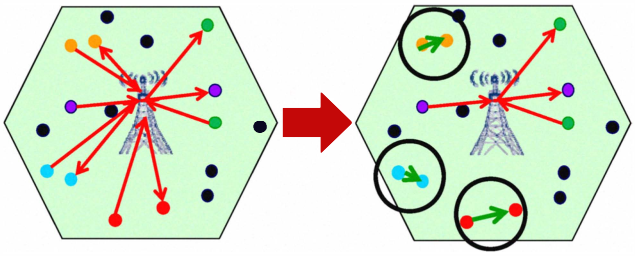

Figure 4. Logical Reconfiguration by Introducing DoF in Spatial Domain.

A single cell case with 100 MSs is considered. The distance between MSs and BS is 100m. A COST-WI propagation model is adopted with path loss indicated as $L(d) = 7.17 + 38.0\log_{10} d$, where d is distance in meters [11]. The power spectral density of AWGN noise is $-135\text{dB}\cdot\text{mW/Hz}$. Assume the transmit power from MS to BS, BS to MS (being averaged to per user), and MS to MS is 200mW. As shown in Figure 5, compared with the traditional cellular mobile communications, the bandwidth consumption can be decreased by 90% in case of the distance between MSs is 50% of that between MS and BS by introducing DoF in spatial domain.

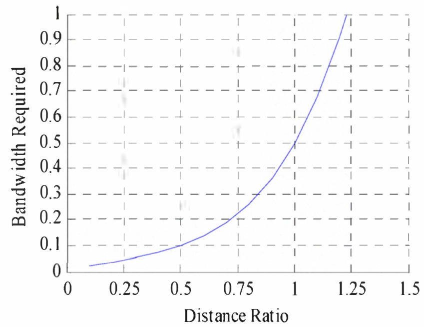

Figure 5. Performance Gain by introducing DoF in Spatial Domain.

Then, we introduce another new DoF in service domain. Then, the traditional star topology is reconfigured to short distance unicast plus multicast topology. As shown in Figure 6, we provide an overlapped logical structure with conventional communication, point to point direct communication and point to multi-point direct communication according to the position of MSs and the type of services. In Figure 6, MSs with the same color have the same service demand.

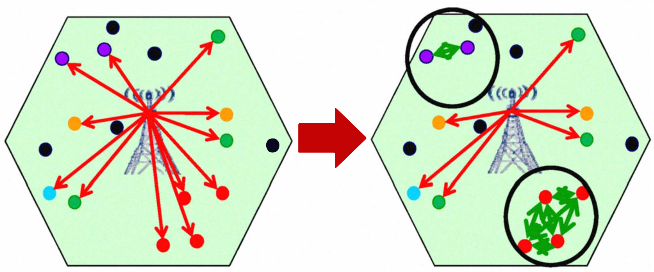

Figure 6. Logical Reconfiguration by Introducing DoF in Spatial and Service Domains.

Then we assume that there are N items needed by MSs in the cell and each item is already in one of the MSs. The N items have the same length. The achieved data rate between any two MSs is the same. The access frequency for each item is P_i and $[P_1, P_2, ..., P_N]$ is sorted descending. When the first n items are multicast by one of the MSs, the required bandwidth ratio is $\left(n+\sum_{n+1}^{N}P_n\right)/\left(\sum_{1}^{N}P_n\right)$. For example, if 5 items are accessed by MSs, and the access number for each item is set to 64, 16, 8, 4 and 2. Figure 7 shows that, when 20% of the hot items are multicast by one of the MSs, the bandwidth consumption by introducing DoF in spatial and service domains will further decrease to about 30% of that by introducing DoF in spatial domain.

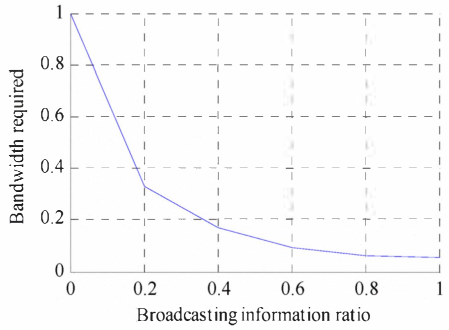

Figure 7. Performance Gain by introducing DoF in Spatial and Service Domains.

B. Delay Tolerant Networking Combining Node Mobility

Delay Tolerant Networking (DTN) is a new type of network infrastructure [12]. It deals with data transmission situations with large and indefinite end-to-end delays. Furthermore, the end-to-end connections from may be intermittent, and the link statuses often do not have guarantees. These delay and disruptions can lead to system performance degradation, and conventional chatty networking protocols do not work well under these intermittent link environments. Notice that one cause of delay in DTN is node mobility, which makes the network architecture time-variant. This includes the mobility of source, relay and destination nodes. Nevertheless, node mobility can bring advantage to system performance if used properly. For example, it can extend communication range by letting nodes carry the message. Also by opportunistic routing at relay nodes, the system resource consumption can be reduced. Our goal is to fully utilize the advantages of DTN and node mobility to exploit the possible DoF.

DTN combining node mobility forms new logical network architecture. This architecture utilizes potential node motions to lower the resource consumption and boost system capacity. The basic idea is to use the "store, carry and forward" mechanism in DTN, letting a relay node aid the propagation of data when distance is relatively long between source and destination. The example system we illustrate next shows the utilization of spatial and delay tolerance DoF specifically. Figure 8 shows a conventional DTN system. When a user requires some service and the nearby BS1 does not have it, the adjacent BS2 needs to send it to the user. Since the distance between BS2 and the user is rather long due to the sparse distribution of BSs, the link has poorer quality and more intermittent connectivity. Therefore, the resource consumption needed for successful transmission is large; the transmission delay is large, thereby achieving a quite low system capacity.

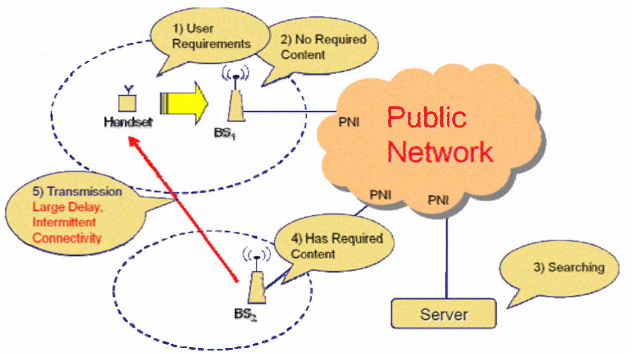

Figure 8. Data Delivery Without Utilizing Node Mobility

We now introduce two DoF into the system. The difference of systems from Figure 9 to Figure 8 is utilizing another user's mobility. This user R1 serves as a relay node between BS2 and the destination user, and it moves from BS2's nearby range to BS1's nearby range after the destination user requires the service. BS2 needs to be aware of R1's mobility model, so it knows it need to send the data to R1 and when to send it. R1 stores the data, carries it through the motion, and forwards it onto the destination user. Notice that R1 does the job in a "store, carry and forward" manner. Here it first brings the spatial DoF, which is induced by mobility of the relay node. A long-distance data transmission is replaced with two stages of short-distance data transmission and a carrying of data by the relay node. So the distance of communication links are shortened significantly, thereby the spectrum and power efficiencies are improved significantly. In the meantime, it introduces the delay tolerant DoF. By replacing the transmission delay with motion (data carrying) delay, the problem with poor link quality and intermittent connectivity is solved, and more resources could be saved and be used on other users and services, potentially increasing system capacity. Note that this relies on the inherent delay tolerance of services.

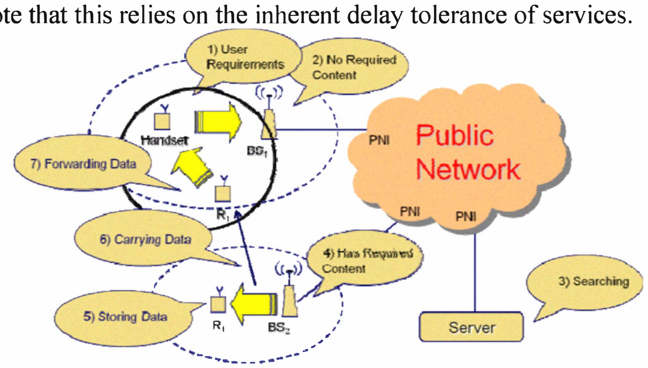

Figure 9. Data Delivery With Utilizing Node Mobility

We consider a two cell case with several destination users for performance evaluation. The distance between each destination user and BS_2 is 3km, and the distance between the relay node R_1 and BS_2 is 300m. A COST-WI propagation model is adopted with path loss indicated as $L(d) = 7.17 + 26.0\log_{10} d$, where d is distance in meters [11]. The power spectral density of AWGN noise is $-135\text{dB}\cdot\text{mW/Hz}$. Assume the transmit power from BS_2 to all users is 200mW. We only consider the bandwidth consumption from base station to relay node. As shown in Figure 10, the bandwidth consumption can be decreased by 70% in case of the percentage of destination users being aided by moving relay nodes increases from 10% to 30%.

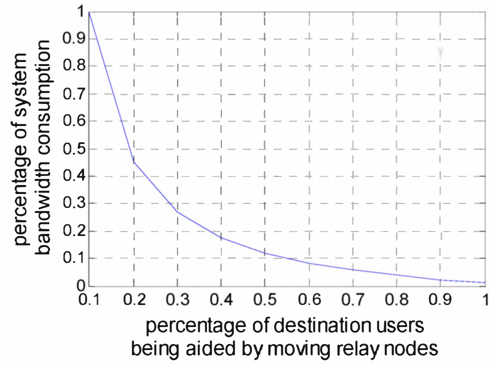

Figure 10. Ratio of bandwidth saving aided by node mobility

V. Conclusion

In this paper we provide a general architecture and research framework of wireless communication system with multi-domain collaboration. We also address three key technologies, which are creating DoF from physical and logical frameworks, logical reconfiguration, and collaboration between different DoF, under the general research framework. Performance evaluation and simulation results show that the bandwidth consumption of wireless communication system is dramatically reduced by means of multi-domain collaboration.

Acknowledgment

This work is supported by the National Basic Research Program of China (2007CB310601).

References

[1] P. Nicopolitidis, M. S. Obaidat, G. I. Papadimitriou, A. S. Pomportsis, Wireless networks, Chichester, Chichester: Wiley, 2003.

[2] ITU-R. Requirements related to technical system performance for IMT-Advanced radio interface(s).

[3] http://en.wikipedia.org/wiki/Diminishing_returns.

[4] http://www.973.gov.cn/English/Index.aspx.

[5] D. Zhang, X. Tao, Y. Wang, J. Lu, Multi-Domain Collaboration: Create and Exploit the Degrees of Freedom in Wireless Communication, submitted to Chinacom 2010, Aug. 25-27, 2010, Beijing, China.

[6] I. E. Telatar, "Capacity of multi-antenna gaussian channels," Europ. Trans. Telecommu., vol. 10, pp. 585-595, Nov./Dec. 1999.

[7] D. Tse and P. Viswanath, Fundamentals of Wireless Communication. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[8] V. Cadambe and S. Jafar, "Interference alignment and the degrees of freedom of the K user interference channel," IEEE Transactions on Information Theory, vol. 54, no. 8, pp. 3425-3441, Aug. 2008.

[9] A. R. Mishra, Fundamentals of cellular network planning and optimization: 2G/2.5G/3G- evolution to 4G, Chichester, Chichester: Wiley, 2004.

[10] R. Kraemer, M. D. Katz, Short-Range Wireless Communications: Emerging Technologies and Applications, Chichester, Chichester: Wiley, 2009.

[11] D. S. Baum, J. Hansen, J. Salo, G. Del Galdo, M. Milojevic, and P. Kyösti, "An Interim Channel Model for Beyond-3G Systems: Extending the 3GPP Spatial Channel Model," IEEE VTC, Spring, vol. 5, pp. 3132 – 3136, 2005.

[12] K. Fall, "A delay-tolerant network architecture for challenged internets", Proc. of the conf. on Applications, technologies, architectures, and protocols for computer communications, pp. 27 – 34, 2003.