Multi-Domain Collaboration: Create and Exploit the Degrees of Freedom in Wireless Communication

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***Abstract*—The fundamental limit of wireless communication is the tradeoff between efficiency and reliability. In order to improve system efficiency and reliability simultaneously, we have to create and explore new degrees of freedom. Multi-domain collaboration can be regarded as a systematic approach to solve this issue. From a broader and higher perspective, *multi-domain* is utilized to *create* the degrees of freedom, and *collaboration* is adopted to *exploit* the benefit of new degrees of freedom. In this paper, we illustrate this essential idea with three scenarios of link, multiuser and network. To provide an overview of the core idea of of multi-domain collaboration, we also summarize some of our recent works under the general framework from a new perspective of degrees of freedom.**

I. INTRODUCTION

As a pillar industry of the world high-tech, wireless communication has maintained a strong momentum of development over the last two decades. However, existing and upcoming system is still can not resolve the conflict between limited spectrum resources and the rapidly growing service needs, thus resulting increasingly prominent bottleneck in wireless communications.

The key to solve this bottleneck is to fundamentally improve wireless spectrum utilization efficiency. The framework of traditional wireless communication system is mainly based on independent resource optimization and scheduling and has gradually been limited by "boundary effect". Therefore, in order to fundamentally improve wireless spectrum efficiency, we need to create a new type of wireless communication system framework, and make breakthrough in effective radio resource usage and multiuser resource sharing mechanism.

Multi-domain collaboration can be regarded as a systematic approach to solve this issue. National 973 Project "Fundamental Research on Multi-Domain Collaboration for Broadband Wireless Communications" started in 2007. This project focuses on the development need of the National S&T Major ProgramNew Generation Broadband Wireless Communication Networks, exploring fundamental theory to improve the effectiveness of spectrum utilization while achieving innovations in broadband wireless communication architecture and key technologies. Focusing on the fundamental issue of wireless communication to satisfy ever-increasing service demand under the resource constraint, this project studies the framework for the wireless communication system and addresses three basis issues: theories of effective application of wireless spectrum resources, methods of efficient wireless communications transmission, mechanisms of multi-user resource sharing and optimization.

In order to achieve this goal, we have to create and explore new degrees of freedom in wireless systems. From a broader and higher perspective, *multi-domain* is utilized to *create* the degrees of freedom, and *collaboration* is adopted to *exploit* the benefit of new degrees of freedom. In this paper, we show that classic techniques can actually be viewed as methods to handle degrees of freedom from different perspectives of link, multiuser and network. we also summarize some of our resent works under the general framework to illustrate this core idea.

The rest of this paper is organized as follows. Section II shows the The essential idea of multi-domain collaboration and provide three perspectives of the degrees of freedom. Section III summarize some of our resent works of adopting multi-domain collaboration to create and exploit the degrees of freedom in wireless network. Finally, we conclude the paper in Section IV.

II. DEGREE OF FREEDOM: THREE PERSPECTIVES

The essential idea of multi-domain collaboration can be illustrate by MIMO transmission schemes. The multiple antennas in effect increase the number of degrees of freedom in the system and allow spatial separation of the signals from the different users. Under suitable channel fading conditions, having both multiple transmit and multiple receive antennas provides an additional spatial dimension for communication and yields a degree-of-freedom gain. These additional degrees of freedom can be exploited by spatially multiplexing several data streams onto the MIMO channel, and lead to an increase in the capacity: the capacity of such a MIMO channel with N transmit and receive antennas is proportional to N [1].

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

We can reformulate the equation as

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

where C can be defined as the system capacity and N is the degrees of freedom achieved by the algorithm.

The evolution of MIMO systems reveals a two-step innovation. First, we realize that a new degree of freedom is created by the system, which is the space dimension, and through increasing the degrees of freedom available for communication

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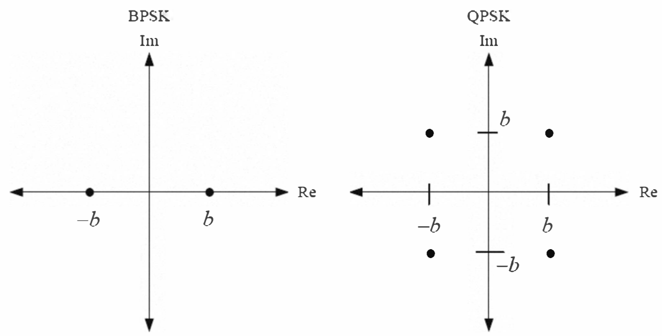

Fig. 1. Modulation: BPSK vs. QPSK

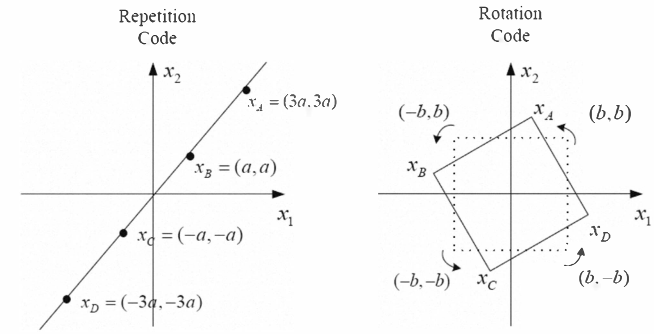

Fig. 2. Code design: Repetition Code vs. Rotation Code

fading can in fact be beneficial. Therefore, a door is opened for substantial improvement of system performance. Second, several schemes are then proposed to exploit the degrees of freedom (for example, the vertical Bell Labs space-time architecture (V-BLAST) [2]).

The essential idea of multi-domain collaboration can also similarly characterized, where multi-domain is utilized to create the degrees of freedom from various domains like time domain, frequency domain, code domain, space domain, power domain, service domain, user domain, etc., and collaboration is adopted to exploit the benefit of new degrees of freedom. We will further illustrate this idea from following three perspectives.

A. Link

At the link level, the ultimate goal of transmission design is to fully utilize the degrees of freedom of the channel, which can be defined as the dimension of the received signal space [3]. Take modulation as an example. BPSK modulation uses only the real dimension (the I channel), while in QPSK modulation, both the I and Q channels are used simultaneously, and an extra bit can be transmitted, increasing spectral efficiency (Fig. 1).

The same methodology applies to code design as well. The repetition code is the simplest possible code. Although it achieves a diversity gain, it does not exploit the degrees of freedom available in the channel effectively because it simply repeats the same symbol over all the symbol times. For more sophisticated schemes (e.g., rotation code, Fig 2), a coding gain can also be obtained beyond the diversity gain. This is achieved by utilizing the available degrees of freedom better than in the repetition schemes.

B. Multiuser

The problem of multiuser communication is first visited from information theory area. Motivated by the Shannon's pioneer work of point-to-point channel capacity, a lot effort has been made to extend the result to analyze the fundamental limits of multiuser communication. The first breakthrough was made in the earlier 1970s, when Ahlswede [4] and Liao [5] independently provided a single-letter characterization of the capacity region of the multiple access channel. This result is rather general in the sense that it holds for arbitrary number of users as well as arbitrary channel statistics. However, there have been essentially no other network information theory results of such generality since then. Most of the other results, for example, hold for only two users or for specific class of channel or source statistics. Even these results are few in number. So despite almost forty years of effort, we are still very far from solving the general network information theory problem [6].

Although obtain exact results from information theory is rather hard, it is still possible to derive interesting results and gain some insight if we turn to the perspective of the degrees of freedom. Take interference channel as an example. For the fully connected K user wireless interference channel where the channel coefficients are time-varying and are drawn from a continuous distribution, recent results based on the idea of interference alignment [7] has shown the sum capacity is characterized as $C(\text{SNR}) = \frac{K}{2}\log(\text{SNR}) + o(\log(\text{SNR}))$. Thus, the K user time-varying interference channel almost surely has $K/2$ degrees of freedom 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. At first sight, the conclusion that everyone gets half a cake seems to directly violate a basic intuition. However, the apparent contradiction is resolved by correctly accounting for the total number of signaling dimensions. Again, interference alignment is in effect a method to exploit the degrees of freedom already exist in the system.

Another example is opportunistic communication [8]. Opportunistic communication maximizes the spectral efficiency by measuring when and where the channel is good and only transmits in those degrees of freedom. In this context, channel fading is beneficial in the sense that the fluctuation of the channel across the degrees of freedom ensures that there will be some degrees of freedom where the channel is very good.

C. Network

Since DoF (2) is initially defined at link level, we can directly generalize the idea to the network level as follows

$$N = \frac{C_{sum}}{\text{basic unit}} \tag{3}$$

where *basic unit* in single user transmission is link, and is node or user in general communication network.

The evolution of cellular network presents a vivid picture about the basic idea. From frequency reuse to cellular design, from narrow band to wide band, from TDMA, FDMA, to CDMA, OFDM, what we do is actually discover or create new degrees of freedom and then find a way to fully exploit the freedom in the context of proper multiple access and interference management.

In recent years there has been significant and increasing interest in a more general network like ad hoc wireless networks. The design, analysis and deployment of such wireless networks necessitate a fundamental understanding of how much information transfer they can support, as well as what the appropriate architectures and protocols are for operating them. To address this question, we are confronted with several problems. First, we have no exact formula for the capacity of networks. Second, unlike in the point-to-point case, there is no single received SNR parameter in a network. One approach to get around the problems is through the scaling law formulation. Pioneered by Gupta and Kumar [9], this approach seeks not the exact capacity of the network but only how it scales with the number of nodes in the network and the number of source-destination pairs. Recall the equation (2) we mentioned above, if we substitute link element $\log_2(1+\text{SNR})$ with network basic resource element, the number of nodes n, the analysis of the scaling law of the network is actually discovering and exploiting the degrees of freedom within the network.

Gupta and Kumar [9] first show the capacity of such network can scale with $\sqrt{n}$ and simple multihop protocol can achieve this scaling. This innovative work inspires many research along this line. Another breakthrough is made in [10], Özgür, Lévêque and Tse prove that The total degrees of freedom in the network is n, and in regimes where power is not a limiting factor, the capacity can scale almost linearly with n. They propose an intelligent cooperation architecture where nodes form distributed MIMO arrays, thus the capacity can be significantly improved and achieve linear scaling. However, Franceschetti et al. [11] argue that there is a degrees of freedom limitation which is due to the laws of physics. Total degrees of freedom in the network is not n but is actually upper bounded by $\sqrt{n}$ due to the spatial constraints imposed by the physical channel. These two seemingly diametrically opposite results are base on two different channel models and have no mathematical contradiction. Is there a way to reconcile the two sets of results? The answer is yes. Recent work [12] investigates the role of cooperation in wireless networks subject to a spatial degrees of freedom limitation, the degrees of freedom of the network is limited by $\max\left(\sqrt{n}, \min(n, \frac{\sqrt{A}}{\lambda})\right)$, where A is the area of the network and λ is the carrier frequency.

III. Multi-domain Collaboration

In this section, we summarize some of our resent works under the general framework of multi-domain collaboration from a new perspective of degrees of freedom.

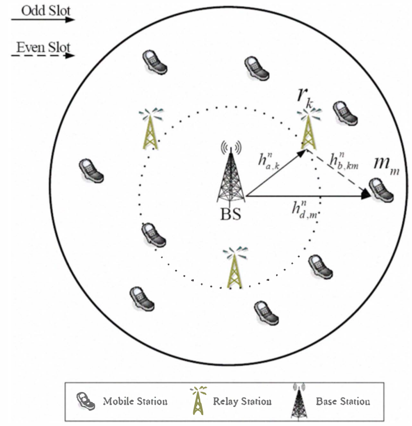

Fig. 3. The system model of cooperative OFDMA networks

A. Cooperative Communication

Cooperative relaying has recently emerged as a promising technology to achieve virtual spatial diversity in wireless communication networks [13]. Combined with orthogonal frequency division multiple access (OFDMA), cooperative OFDMA systems are strong candidates for future 4th Generation (4G) wireless communication and are currently under standardization by the IEEE 802.16j task group [14].

Since the cooperative OFDMA system provides various degrees of freedom from spatial domain, frequency domain and cooperation domain, the performance of cooperative OFDMA systems heavily depends on resource allocation and protocol design is critical in exploiting the degrees of freedom. In [15] and [16], we propose a general framework for utilizing these multi-domain degrees of freedom.

In the following we briefly summarize the main results in these works. Suppose there are one base station (BS), K relay stations (RS) denoted $\mathcal{R} = \{r_1, \dots, r_k, \dots, r_K\}$ and M mobile stations (MS) denoted $\mathcal{M} = \{m_1, \dots, m_m, \dots, m_M\}$ sharing a total number of N subcarriers in the cell. For the nth subcarrier, the channel coefficients between BS and mth MS, BS and kth RS, kth RS and mth MS are denoted by $h^n_{d,m}$, $h^n_{a,k}$, $h^n_{b,km}$, respectively (Fig. 3).

The BS can communicate with MSs either in cooperative mode or non-cooperative mode. For the cooperative mode, we consider two typical types of relay schemes: amplify-and-forward (AF), decode-and-forward (DF) [13].The instantaneous rate of relay-mobile pair (k,m) on the nth subcarrier is therefore given by

$$c^n_{km,AF} = \frac{1}{2}\log(1 + P^n_{s,k}d^n_m + \frac{P^n_{s,k}a^n_k \cdot P^n_{r,km}b^n_{km}}{1+P^n_{s,k}a^n_k + P^n_{r,km}b^n_{km}}) \quad (4)$$

$$c^n_{km,DF} = \frac{1}{2}\log(1 + \min\{P^n_{s,k}a^n_k, P^n_{s,k}d^n_m + P^n_{r,km}b^n_{km}\}) \quad (5)$$

where $a^n_k = |h^n_{a,k}|^2/\sigma^2_r$, $b^n_{km} = |h^n_{b,km}|^2/\sigma^2_m$, and $d^n_m = |h^n_{d,m}|^2/\sigma^2_m$. When the BS works in non-cooperative mode, it transmits directly to the mobile station over two time slots. Assume the BS transmits with power $P^n_{s,0m}$ to s_m on subcarrier n, the instantaneous rate can be written as

$$c^n_{0m} = \log(1 + P^n_{s,0m}d^n_m) \quad (6)$$

We can represent the relay selection and subcarrier allocation in a compact form by binary assignment variables x^n_{km} with $x^n_{km} = 1$ indicating that the base communicates with s_m with the help of relay r_k utilizing subcarrier n and $x^n_{km} = 0$ otherwise.

Two scenarios exploiting the degrees of freedom in the systems are considered in this paper. The first scenario is each MS cooperating with one RS on a single selected subcarrier. It is the case for flexible multiple-access where subcarriers are remained to the fairness of potential users. We also consider the scenario where each MS can utilize multiple subcarriers to cooperate with one RS which enjoy an even better performance. With the two strategies, the resource allocation problem in cooperative OFDMA networks can be formulated as follows.

Problem I:

$$
\begin{aligned}
\max_{\mathbf{X},\mathbf{P}} \quad & \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M} c^n_{mk} x^n_{mk} \\
\text{s.t.} \quad & \sum_{m=1}^{M}\sum_{k=1}^{K} x^n_{mk} \le 1, \quad \forall n \\
& \sum_{k=1}^{K}\sum_{n=1}^{N} x^n_{mk} = 1, \quad \forall m \\
& x^n_{mk} \in \{0,1\}, \quad \forall m,k,n \\
& \mathbf{P} \in \mathcal{P}
\end{aligned}
\tag{7}
$$

Problem II:

$$
\begin{aligned}
\max_{\mathbf{X},\mathbf{P}} \quad & \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M} c^n_{mk} x^n_{mk} \\
\text{s.t.} \quad & \sum_{m=1}^{M}\sum_{k=1}^{K} x^n_{mk} \le 1, \quad \forall n \\
& \sum_{k=1}^{K} y_{mk} = 1, \quad \forall m \\
& x^n_{mk} \le y_{mk} \\
& x^n_{mk}, y^n_{mk} \in \{0,1\}, \quad \forall m,k,n \\
& \mathbf{P} \in \mathcal{P}
\end{aligned}
\tag{8}
$$

To exploit the degrees of freedom and solve the problems, we propose a genetic-base RSSA algorithm in [15] and a dual-based JOSRA algorithm in [16]. We can compare average rate of our cooperative schemes and no relay schemes by varying the transmission power in Fig. 4. It can be observed that the performance is significantly enhanced by exploiting spatial, frequency and cooperation domain degrees of freedom in the system.

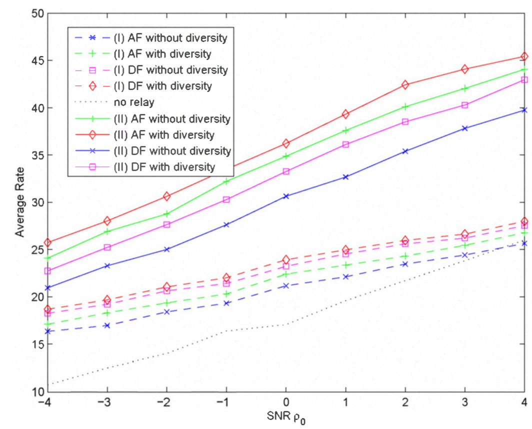

Fig. 4. Average Rate vs. SNR ρ_0 for two problems with four relay schemes and no relay schemes; $M = 8$, $K = 3$, $N = 16$, $r_2 = 500$m

B. Service Differentiation

Most existing works on resource allocation in cooperative OFDMA systems have focused on homogeneous users with same service and demand. However, service dimension is actually another degree of freedom in communication system and QoS guarantees play an important role in the future mobile wireless networks. It is a challenging task to meet the diverse QoS requirements imposed by current and envisioned services. With various practical applications, QoS requirements can be modeled in many ways including e.g., minimum transmission rates, maximum tolerable error rates, maximum delay bounds.

In [17] and [18], we add another degree of freedom, service domain, in cooperative OFDMA systems and consider two classes of services,*best-effort* (BE) services and *rate-constrained* (RC) services which are typical in wireless standards [19]. BE services are applications such as e-mail and http webbrowsing. They come with a prescribed maximum allowable bit-error rate (BER) but pose no requirements on rate guarantees. RC services are for mission-critical and rate-constraint applications such as file transfers (ftp). Users in the system can be classified into M_1 BE users with the set of $\mathcal{M}_1$ and M_2 RC users with the set of $\mathcal{M}_2$. For RC users, the QoS requirements can be described as

$$
\sum_{k=0}^{K}\sum_{n=1}^{N} c^n_{km} x^n_{km} \ge \bar{c}_m, \quad \forall m \in \mathcal{M}_2 \tag{9}
$$

where $\bar{c}_m$ is the minimum rate requirement for RC user m.

Fig. 5 shows QoS satisfaction results of our algorithm. To evaluate the performance of algorithm supporting differentiated services, we propose a new metric *Satisfaction Index* (SI) [18], which can be defined as SI $= \frac{1}{M_2}\sum_{m\in\mathcal{M}_2} \min\left(\frac{c_m}{\bar{c}_m}, 1\right)$ where SI is a number between zero and one. Intuitively, SI $= 1$ represents QoS requirements of all RC users are satisfied and the larger the value, the larger proportions are met. It can be observed our QAS algorithm has significantly improved satisfaction index by 178% compared with nQAS algorithm and 40.5% compared with algorithm in [20].

From traditional view, service satisfaction is a requirement consuming resource and degrading system performance. However, service dimension is actually another degree of freedom to be exploited. In [21], we propose an architecture supports aggregate broadcasting of services according to user behavior

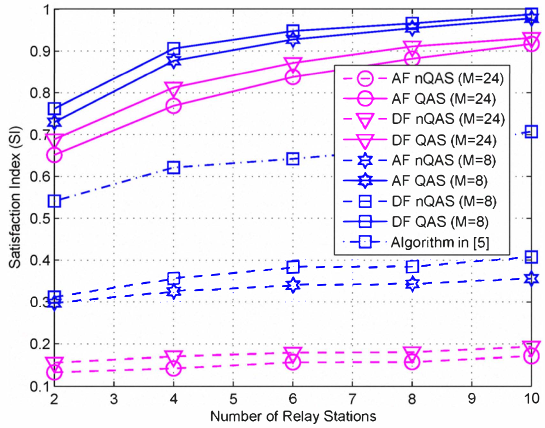

Fig. 5. Satisfaction Index (SI) vs. number of relay stations, $M = 8$ and 24, $N = 64$;

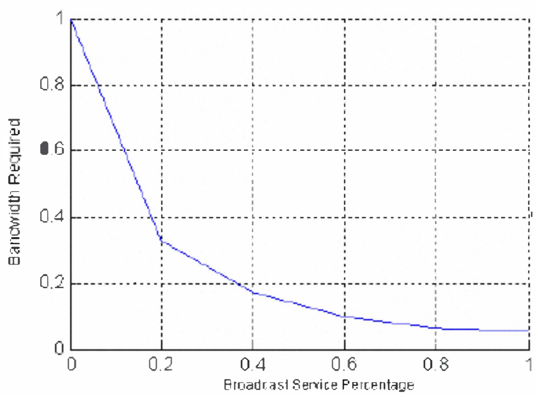

Fig. 6. Required Bandwidth vs. Broadcast Service Percentage

in cellular networks. These services are the enhanced version of Multimedia Broadcast and Multicast Services (MBMS), and they sufficiently utilize the similarity of service requirements among various users. This idea can be illustrated by the following example. Suppose we have 5 different messages with same size, and the frequency each message visited by users within one minute is $64, 16, 8, 4, 2$. If we utilize the degrees of freedom in services and sending "hot" messages in multicast way instead of unicast, significant performance improvement can be achieved (Fig. 6).

IV. Conclusion

In this paper we show the idea of multi-domain collaboration from the viewpoint of the degrees of freedom. Our core statement is that *multi-domain* is about creating the degrees of freedom, and *collaboration* is about exploiting the benefit of the degrees of freedom. This idea is shown from perspectives of link, multiuser and network. We also summarize some of our recent works under the general framework of multi-domain collaboration from a new perspective of degrees of freedom.

Acknowledgment

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