FYT Progress Report

Design of Multiuser Non-Cooperative Communication Systems via Game Theory

DP2a-08

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I. Chapter One – Project Review

i) Introduction

This project considers the maximization of mutual information on each link in the multiuser non-cooperative communication system given the constraints on the transmit power. In principle, the multi-objective optimization of the transceivers requires a centralized solution, which has high complexity, heavy signaling and the coordination among the users. This project focuses on a fully distributed fashion with no centralized control and the system can be designed in a game theoretical approach [1]. The basic idea is that users in the system can be modeled as several players having different objectives, say maximizing their own mutual information, and behave selfishly without cooperation. Therefore, the original multi-objective optimization problem is converted into a set of mutually coupled single-objective optimization problems. The optimal solution to this approach is the achievement of Nash equilibrium (NE). The existence and uniqueness of the NE [2] have been studied in some works together with several iterative and distributed algorithms [3] that converge to NE points.

A general system model is represented by

$$y_q = H_{qq}x_q + \sum_{r \neq q} H_{rq}x_q + n_q \, , \tag{1}$$

where x_q is the vector transmitted by source q; H_{qq} is the direct channel of link q; H_{rq} is the cross-channel matrix between source r and destination q; y_q is the vector received by destination q; and n_q is the noise vector. $\sum_{r \neq q} H_{rq}x_q$ represents the multi-user interference (MUI) received by the q-th destination and caused by other links. Using game theoretical approach, each user competes against the others in this strategic non-cooperative game by choosing his power allocation (i.e. strategy) to maximize his own information rate (i.e. payoff). Reformulating the system within the framework of game theory [4-6], the strategic non-cooperative game has the following structure:

$$\begin{aligned} &\text{maximize } R_q(Q_q, Q_{-q}) \\ &\text{subject to } Q_q \in \Phi_q \, , \\ &\forall q \in \Omega \, , \end{aligned} \tag{2}$$

where Ω is the set of players; Φ_q is the set of admissible strategies for player q; $R_q(Q_q, Q_{-q})$ is the payoff function of player q.

The aim of this project is to design alternative distributed algorithms to solve the strategic non-cooperative game (2) and mathematically prove the convergence of the algorithm to the NE points. Numerical simulations will also be developed for the comparison of the proposed approach with the existing ones. The alternative algorithms should be either more efficient or be able to be applied to more practical or general cases.

ii) System Block Diagrams

The multiuser non-cooperative communication system can be a single-input single-output system (SISO), e.g. multiuser SISO wireless communication system (Figure 1).

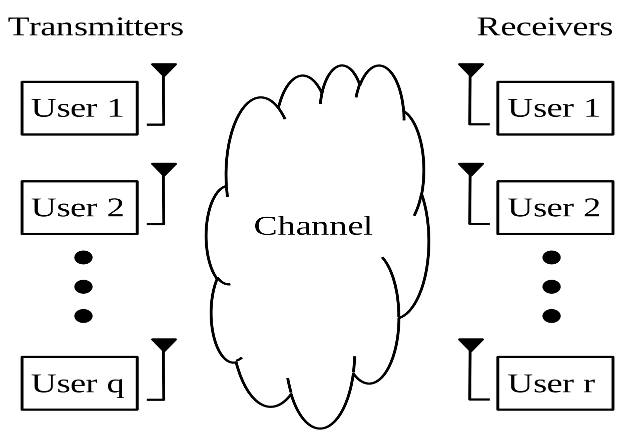

Figure 1- Multiuser SISO Wireless Communication System

It can be extended to multiple-input multiple-output system (MIMO), e.g. multiuser MIMO wireless communication system (Figure 2).

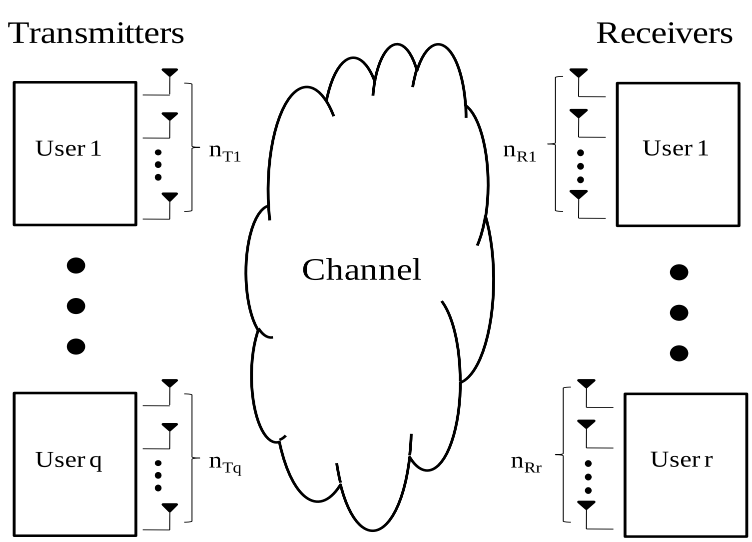

Figure 2- Multiuser MIMO Wireless Communication System

The transceivers may have perfect channel state information (CSI) or imperfect CSI, which strongly determines the transmission techniques we can use.

iii) Design Specification

This project involves no real implementation. Matlab simulation on the computer is the only requirement on the hardware and the software.

iv) Report Outline

This progress report is organized as follows. Chapter Two gives the background of this project and the existing approaches are stated. In Chapter Three, detailed knowledge and plan are discussed. Chapter IV reports the accomplishment on this project so far.

II. Chapter Two – Background

From communication system view, several communication systems with different requirements and constraints have been studied. For SISO, current work in the field can be divided in three large classes, according to the kind of games dealt with: scalar, vector and matrix-valued power control games. Users in scalar games have one degree of freedom to optimize their transmit power or rate. Based on the standard function proposed in [7], solutions have been provided in [8-12]. This kind of problem can also be recast as convex optimization problems [13]. For vector games, it is more complicated as each user has several degrees of freedom to maximize, e.g. power allocation across frequency bins. Since the seminal paper [14] studying the maximization of the information rate of two users in DSL system, a number of works have been done for the case of SISO frequency-selective channels [15-19]. In [5, 6], the problem was extended to matrix-valued games together with spectral mask constraints. It is proved that complicated matrix-valued problems can be converted into unified vector power control game with no performance penalty. For more general MIMO cases, two-user MISO channel was studied [20]. Rate maximization game in MIMO interference channels was studied in [21-24]. Mutual information maximization in MIMO Gaussian interference channel was studied in [4] together with the conditions that guarantee the uniqueness of the NE of the MIMO game and the convergence of the proposed distributed algorithms.

From distributed algorithm view, three major schemes of the distributed algorithm have been considered according to the kinds of updating schedule [3]: Gauss-Seidel scheme (i.e. synchronous sequential) [14-19], Jacobi Scheme (i.e. synchronous simultaneously) [6, 25, 26] and totally asynchronous scheme [27, 28]. Two iterative and distributed algorithms have been applied based on those three kinds of updating schemes, namely water-filling based algorithms [6, 14-19, 25-28] and gradient-projection based algorithms [6].

III. Chapter Three – Methodology

i) Knowledge needed

- Communication system
- Game theory [1]
- Convex optimization theory [29]
- Distributed algorithm theory [3]
- Matrix analysis [30]

Matrix analysis is the base of all the previous knowledge. Figure 3 illustrates the relations between the knowledge needed and the problems.

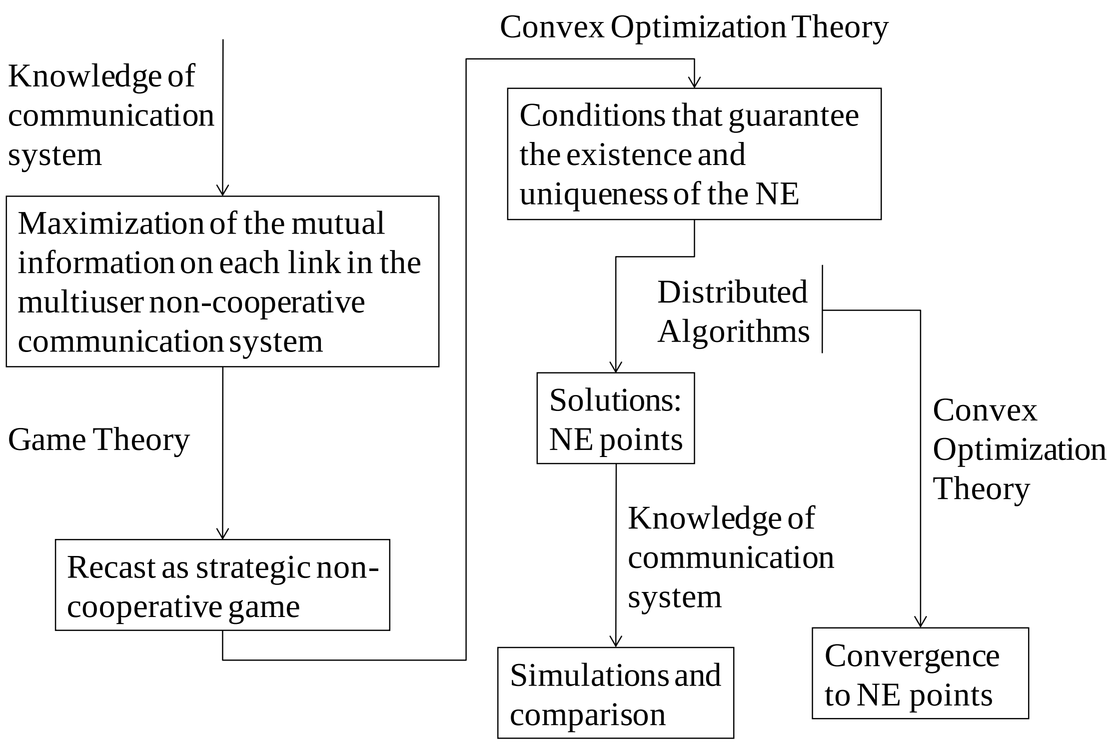

Figure 3 - Relations between the Knowledge Needed and the Problems

ii) Existing Approaches and Possible Extension

From communication system view, SISO and MIMO communication systems with perfect channel state information (CSI) have been studied in a number of works (as discussed in Chapter Two - Background). However, communication system with imperfect CSI has not been discussed in a game theoretic approach. Space-time coding with knowledge of the channel statistics, pre-coding techniques robust to channel uncertainty or the combination of previous two methods are the major ways dealing with communication systems with imperfect CSI [31, 32]. Using robust design of the transmitter, the channel H in (1) becomes

$$H = \hat{H} + \Delta \tag{3}$$

where $\hat{H}$ is the estimate of the imperfect channel and Δ is the error in the estimation. In reality, channel knowledge is generally imperfect and the game theoretical approach on imperfect CSI systems is a possible extension.

From distributed algorithm view, existing approaches are listed as follows.

a. water-filling based algorithms
    - Gauss-Seidel scheme [14-19]
    - Jacobi scheme [6, 25, 26]
    - Totally asynchronous scheme [27, 28]

b. gradient-projection based algorithms [6]
    - Gauss-Seidel scheme
    - Jacobi scheme

Water-filling based algorithms are very popular in related works. However, gradient-projection based algorithms have been shown to have approximately the same convergence speed and computational complexity of the water-filling based algorithms and thus it can be a valid alternative [6]. Jacobi scheme of the distributed algorithms has been shown to converge faster to the NE points than the Gauss-Seidel scheme [6]. Totally asynchronous scheme is a generalization of the Gauss-Seidel and Jacobi schemes as no rigid scheduling in the updates of the users is required and the coordination requirements among the users is relaxed significantly [28]. The problem of totally asynchronous scheme is that it can tolerate arbitrarily large communication and computation delays, which leads to the use of the outdated measurements of the received interference. Partially asynchronous scheme [3] imposes certain time bounds on the delays and it can be an extension to the current works. Asynchronous schemes for gradient-projection based algorithms or other new distributed algorithms can be other extensions.

From game theory view, solutions at NE points can be obtained by several distributed algorithms. However, NE is generally not Pareto-efficient [33]. Comparisons of NE with Pareto optimality are studied in [5, 20]. It is shown that Pareto-optimal solutions can be achieved as an NE of the game in selfish but cooperating systems, which have significant increase of signaling and coordination among the users and it exceeds the scope of this project, i.e. non-cooperative communication system.

iii) Challenges and Merits

Challenges of this project are the proofs of the existence and uniqueness of the NE points and the convergence of the distributed algorithms, which require thorough understanding of the communication system, convex optimization theory and distributed algorithm theory. Studying related knowledge and previous works will definitely help me on solving those problems.

Accomplishment of this project will either extend the current system to more practical and general communication systems or provide alternative algorithms based on discussed systems but with similar or better performance.

iv) Deliverables

- Alternative distributed algorithms with mathematical proof of its convergence to NE points
- Numerical simulations of the distributed algorithms compared with existing approaches

v) Schedule of Responsibilities

November: Study the existence and uniqueness of the NE for the strategic non-cooperative game

December: Study the convergence of water-filling based algorithm

January: Study the convergence of gradient-projection based algorithm

February: Develop alternative distributed algorithm and prove its convergence

March: Simulate the algorithms

April: Further extension and project presentation

vi) Budget

As this project involves no real implementation and Matlab simulation on the computer is the only requirement on the hardware and the software, printing fee on the papers of current works and related materials is the only cost in this project. The budget is hard to estimate right now.

IV. Chapter Four – Accomplishments

What I have done so far is list as follows.

- Review of game theory
- Study of the communication system
- Study of convex optimization theory and matrix analysis
- Literature search on the related papers and the basic survey of the current state of the art
- Thinking on possible extensions and alternative distributed algorithms

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