GateQuest: Game-Theoretic Gateway Selection in Cyber-Physical Systems

Game Theory (IT305) Report

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by

Saliq Gowhar Khan - 211AI043

Harshit Ravindra Gawade- 211AI019

under the guidance of

Dr. Bhawana Rudra

DEPARTMENT OF INFORMATION TECHNOLOGY

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, MANGALORE - 575025

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1 Abstract

In this paper, we explore the dynamics of Cyber-Physical Systems (CPSs) where diverse devices, employing various wireless technologies, interact within a shared environment. The communication among these devices and external networks is facilitated through gateways strategically positioned in the operational area. The coexistence of different device types in a CPS leads to a competitive scenario where devices vie for gateway bandwidth to optimize throughput and minimize transmission delays. We cast this gateway selection process as a noncooperative game and examine the strategic behaviors of devices as they switch gateways, influencing the overall outcome of their competition. To address this, we present a bandwidth allocation model for gateways and introduce a distributed algorithm enabling clients to select gateways strategically, thereby enhancing the total bandwidth for their respective device types. Additionally, we analyze the migration trends of clients within this game-theoretic framework, shedding light on the evolving landscape of gateway selection in CPS.

Keywords— Cyber-Physical Systems, Gateways, Non-Cooperative Games, Bandwidth, Nash Equilibrium

2 Introduction

In the realm of Cyber-Physical Systems (CPS), vital information about the physical world is gathered, and the environment is shaped through a diverse array of devices. Various sensors are deployed to observe targets, while different actuators exert influence upon them. Extracted knowledge from the data governs the behaviors of actuators within CPS. Seamless data exchange between devices within a CPS and between CPS devices and external networks is imperative for optimal functionality.CPS rely extensively on wireless communication for data transmission. Sensors and actuators typically leverage wireless technology to exchange information and maintain connectivity with external networks. Different sensor types are strategically placed to acquire comprehensive area information, transmitting data to external networks for in-depth analysis. Actuators in the vicinity require commands from external networks or sensors in other systems to execute appropriate actions.However, challenges arise when devices are equipped with diverse wireless communication technologies, preventing direct data transmission. The current landscape witnesses the prevalence of CPS with multiple wireless technologies coexisting. Devices with distinct wireless technologies typically communicate through gateways strategically positioned in the working area. This approach addresses compatibility issues, cost considerations, and privacy and safety concerns, preventing direct connections of each device to external networks. Gateways are strategically arranged to cover the entire working area, ensuring no subarea is overlooked. Intensive placement of gateways, with overlapping coverage areas, allows devices to choose among them, emphasizing the rationality of such choices. Extensive research has been devoted to determining the most suitable gateway selection methods.

The focus in this paper is on an approach to the gateway selection problem in Cyber-Physical Systems (CPS). We introduce a unique perspective by modeling the gateway selection as a non-cooperative game, wherein devices compete for limited resources, specifically bandwidth. This framework provides insights into the behaviors of devices when choosing gateways, shedding light on the dynamics of competition and cooperation among different kinds of devices within the CPS. This paper delves into the migration trends of devices, exploring under what circumstances devices decide to change their current gateways to maximize the collective benefit of their kind. The paper also investigates the convergence of this gateway selection game, demonstrating that it reaches a Nash Equilibrium under the condition where one kind of client is fixed. To validate the proposed methodology, we conduct simulations, offering a practical evaluation of the approach. The simulations serve to assess the effectiveness of the game-theoretic model in real-world scenarios, providing empirical evidence of its utility in guiding the behavior of devices in CPSs. The paper concludes with a comprehensive overview of related work, system models, assumptions, migration patterns, convergence analysis, and practical simulations, contributing to the ongoing discourse on efficient gateway selection in Cyber-Physical Systems.

3 Literature Review

Game theory has found extensive application in the examination of networking issues, as evidenced by previous studies. Tekin et al. [1], introduce and scrutinize a category of games, specifically atomic congestion games on graphs, leveraging game theory to investigate wireless network performance. Law et al. [2] focus on modeling the competitive dynamics of Secondary Users (SUs) in a cognitive radio network, employing singleton congestion games with varying preference constants. In a related context, Southwell et al. [3], conceptualise a scenario as a game, equivalent to a network congestion game following intricate transformations. Notably, Wang et al. [4] research stands out as the inaugural attempt to analyze the gateway selection problem in Cyber-Physical Systems (CPSs) through the lens of game theory.

The exploration of network selection has been approached through various game theory models, including noncooperative game and evolutionary game. Malanchini et al. [5], delve into the dynamics among end users and network operators during network selection and resource allocation, employing noncooperative game theory to model competition among multiple end users accessing shared wireless networks. Aryafar et al. [6] investigated the network selection dynamics in heterogeneous wireless networks, while Monsef et al. [7] focus on analyzing the convergence properties of network selection dynamics in such environments. While these contributions significantly advance the understanding of the network selection problem using game theory, it is important to note that these studies do not account for cooperation within the same group or the competition between different groups.

Khan et al. [8] embrace Evolutionary game theory as a solution framework for addressing challenges in wireless communications and networking. This study not only applies evolutionary coalitional game theory to resolve diverse issues in wireless networking but also elucidates the existing gaps and emerging trends in this domain. Srinivas et al. [9], propose a distributed mechanism leveraging reinforcement learning for strategy and payoff learning in wireless networks, with a focus on the stability of the learning algorithm based on evolutionary game dynamics. The problem of network selection in environments with multiple available networks is tackled using an evolutionary game theory-based approach by Niyato et al. [10] . Zhu et al. [11]

employ evolutionary game theory to model and analyze service selection in small cell networks, while Semasinghe et al. [12] introduce a distributed subcarrier and power allocation scheme based on evolutionary game theory for downlink transmission in small cell networks operating under a macrocellular network. It is worth noting that evolutionary games typically assume a vast number of clients, where the influence of a single client is minimal on others. In contrast, our problem scenario involves situations where the decisions of a single client can significantly impact the choices made by other users.

4 Problem Statement

To solve the gateway selection problem in a Cyber-Physical system by formulating the situation as a combination of a non cooperative game (lack of controller) and a cooperative game, and modelling it as a single non-cooperative game.

5 Objectives

1. Investigate the dynamics of strategic decision-making among players within the noncooperative game, providing detailed insights into the factors influencing their choices regarding accessible gateways and their strategic pursuit of collective bandwidth optimization.

2. Conduct a detailed analysis of the convergence patterns inherent in the gateway selection game, scrutinizing the mechanisms driving the system towards Nash Equilibrium in pure strategies and elucidating the stability implications associated with reaching this equilibrium state.

3. Refine the methodology for calculating payoffs, introducing enhancements to ensure a robust evaluation of the benefits associated with different gateway selections.

6 Background

We have utilised various game-theoretic concepts in our work, and an overview for each of the concepts utilised is given in this section.

6.1 Game Theory

Game theory is a branch of mathematics and economics that provides a systematic framework for analyzing strategic interactions among rational decision-makers [13]. It seeks to model situations where the outcomes of individual choices are interdependent, and participants, referred to as players, make decisions based on their rational expectations of others' actions. The central concept in game theory is the Nash Equilibrium, a state in which no player has an incentive to unilaterally deviate from their chosen strategy, signifying a stable solution to the strategic interactions. Game theory encompasses both cooperative and noncooperative scenarios, where players may either form coalitions to achieve mutual benefits or act independently to optimize their outcomes. Widely applicable across various disciplines, game theory offers insights into decision-making processes in complex and dynamic environments, making it a valuable analytical tool in understanding strategic behaviors and outcomes.

6.2 Non-Cooperative Games

Non-cooperative games are a subset of game theory that focuses on strategic interactions where independent decision-makers, termed players, pursue their individual objectives without forming explicit coalitions or agreements [14]. In these games, each player makes decisions based solely on their preferences, anticipating the potential responses of other players, but without formal collaboration. The fundamental concept in non-cooperative games is the Nash Equilibrium, a state in which no player has the incentive to unilaterally change their strategy, given the strategies chosen by others. Non-cooperative games provide a powerful framework for studying competitive scenarios, such as those found in economic markets, military conflicts, and various real-world situations where entities make strategic decisions without explicit cooperation. The analysis of non-cooperative games contributes to understanding the dynamics of self-interested decision-making and predicting outcomes in scenarios where individual actors pursue their interests independently.

6.3 Cooperative Games

Cooperative games form a branch of game theory that focuses on strategic interactions where participants, known as players, have the ability to form coalitions and collaborate to achieve mutual goals [15]. In these games, players can negotiate, make binding agreements, and coordinate their actions in pursuit of outcomes that benefit the collective. Cooperative games explore scenarios where the synergy of joint efforts may lead to more favorable outcomes compared to individual actions. The core concept in cooperative games is the formation of stable coalitions, typically analyzed through solution concepts like the core or Shapley value. This branch of game theory finds applications in various fields, including economics, political science, and operations research, providing insights into situations where collaboration and joint decision-making play a pivotal role in achieving optimal results.

6.4 Our Assumptions

We have made use of several assumptions in our work for modelling the situation as a non cooperative game, which are given as under.

- Each device must be connect to one and only one gateway at a time.
- Each gateway has the same bandwidth W.
- Devices do not have a minimum bandwidth requirement.
- Each device has to be in the range of at least one gateway.
- Devices are divided into two groups according to their wireless communication technology.
- The devices of the same group can exchange information mutually.
- The bandwidth of a gateway is equally distributed among the connected devices.
- Each device chooses a gateway to maximise its obtained bandwidth.

- It is a perfect information model.

7 Methodology and System Design

The model specifications for our work is given in this section, which is further divided into multiple subsections including Network Model, Bandwidth allocation model and Gateway Selection Model.

7.1 Network Model

In our analysis, we examine a system featuring three distinct categories of nodes coexisting within the operational area, devoid of a central controller. One category consists of gateway nodes denoted by G = (g1, g2,...,gk). The remaining entities comprise two sets of client nodes, namely A = (a1, a2,...,an) and B = (b1, b2,...,bm). Each client node necessitates a connection to a gateway for data exchange with external networks, and clients of the same type can mutually exchange data. The strategic placement of gateways ensures comprehensive coverage across the entire area, guaranteeing that every client node can connect to at least one gateway. Client nodes are randomly distributed in this area, and each client can connect to a subset of gateways. Different types of client nodes are equipped with distinct wireless communication technologies, assuming interference-free conditions achieved through spectrum separation among clients using different technologies and frequency separation or orthogonal channels between gateways and similar types of clients. Every client is limited to maintaining a wireless connection with a single gateway at a time. Clients can access information about nearby gateways through gateway broadcasts, which includes the number and type of clients connected to each gateway. Based on this information, clients can calculate the potential bandwidth they would obtain by switching from their current gateway to another. Consequently, clients actively seek to connect to alternative gateways if such a switch offers advantages in terms of improved bandwidth.

7.2 Bandwidth Allocation Model

Even though clients A and B utilize distinct wireless communication technologies, they share a common type of gateway bandwidth. This sharing mechanism can be conceptualized as the gateways' capability for data transmission with external networks. The total bandwidth of a gateway, denoted as W, is allocated to clients A and B as Wai and Wbi, where Wai + Wbi equals W . Clients of the same type evenly divide the bandwidth allocated to them, signified by wa = Wai/ni, wb = Wbi/mi, with wa and wb representing the bandwidth obtained by clients A and B, respectively. Here, ni represents the number of clients A connected to gateway gi, and mi represents the number of clients B connected to the same gateway. Clients A and B sharing a common gateway engage in bandwidth competition, where the obtained bandwidth is contingent on their respective numbers: more connected clients result in proportionally more bandwidth for that type of client. In this paper, we assume a fair distribution, expressing it as Wai : Wbi = ni : mi. Consequently, the bandwidth allocated to clients A and B by gateway gi is calculated as:

$$w_a = \frac{n_i \left[W/\left(n_i + m_i\right)\right]}{n_i} = \frac{W}{n_i + m_i} \tag{1}$$

$$w_b = \frac{m_i \left[W/\left(n_i + m_i\right)\right]}{m_i} = \frac{W}{n_i + m_i} \tag{2}$$

7.3 Gateway Selection Model

As previously mentioned, clients seek to optimize their benefits by changing gateways, triggering a competition for gateway bandwidth among different client types. Clients derive advantages from an increased bandwidth shared among their entire group, facilitating data forwarding within the same client type. Consequently, a client will transition to another gateway if such a move enhances the overall bandwidth for its client type. To formalize this dynamic, we model the gateway selection process as a non-cooperative game, where clients independently choose gateways to augment the collective bandwidth of their respective client types.

Players: The participants in this game are clients A and clients B capable of connecting to multiple gateways within the working area. Clients restricted to a single gateway are not considered players in this context.

Strategy: The strategy set comprises the available gateways within the area denoted as G ¯(g1, g2,...,gk). Each player's strategy set encompasses the gateways it can access. Player i's chosen strategy is denoted as si, and the overall strategy profile for all players is represented by s = (s1, s2,...,sn), where N is the total number of players.

Payoff: The payoff for a client is the bandwidth it obtains. Unlike traditional games where players aim to maximize their own payoff, in this scenario, players choose strategies to enhance the total payoff of their population.

Population: Players belonging to the same client type constitute a population. In this game, two populations exist: one comprises players from clients A (denoted as PA), and the other includes players from clients B (denoted as PB).

Nash Equilibrium: A strategy profile is deemed a Nash Equilibrium if no player can increase its population's payoff by switching to another strategy, given that other players maintain their current choices.

7.4 Migration of Client

In this section, we explore the conditions under which a client decides to switch its gateway and examine the migration tendencies of clients.

Initially, we analyze the circumstances under which a client opts to change its current gateway. As previously mentioned, a client undergoes migration when the shift enhances the overall payoff of its population. Let's consider client Ai as an illustration. Assuming Ai can connect to gateways g1 and g2, currently maintaining a connection with g1, and there are n1 clients of type A and m1 clients of type B connecting to g1, as well as n2 clients of type A and m2 clients of type B connecting to g2. Here, we assume that n1+m1 $\bar{2}$ and n2+m2 $\bar{1}$.

The increment in PA's payoff is given by(3):

$$\Delta W_a = \left[(n_1 - 1)\frac{W}{n_1+m_1-1} + (n_2+1)\frac{W}{n_2+m_2+1}\right] - \left(n_1\frac{W}{n_1+m_1} + n_2\frac{W}{n_2+m_2}\right) \tag{3}$$

From (3), it is evident that the migration of client Ai only impacts the payoff of clients connected to g1 and g2. When $DEL(W)$ $\leq$0 , client Ai refrains from changing its gateway from g1 to g2, as such migration yields no benefit to its population. Conversely, if $DEL(W) \geq 0$, indicating an increased total payoff for PA, client Ai opts to switch its gateway from g1 to g2.

7.5 Migration Convergence

In the context of our gateway selection game, the attainment of a Nash equilibrium is not assured in every instance. Therefore, it becomes imperative to introduce a termination condition to cease the game, such as a predefined number of iterations or the satisfaction of a minimum error threshold. According to the theorem outlined in the foundational paper [4], the game is guaranteed to reach a Nash equilibrium only when one specific type of client is capable of modifying its strategies. This critical condition underscores the necessity of incorporating a well-defined stopping criterion, ensuring the practicality and termination of the game execution under varying circumstances.

7.6 Flowchart of Algorithm

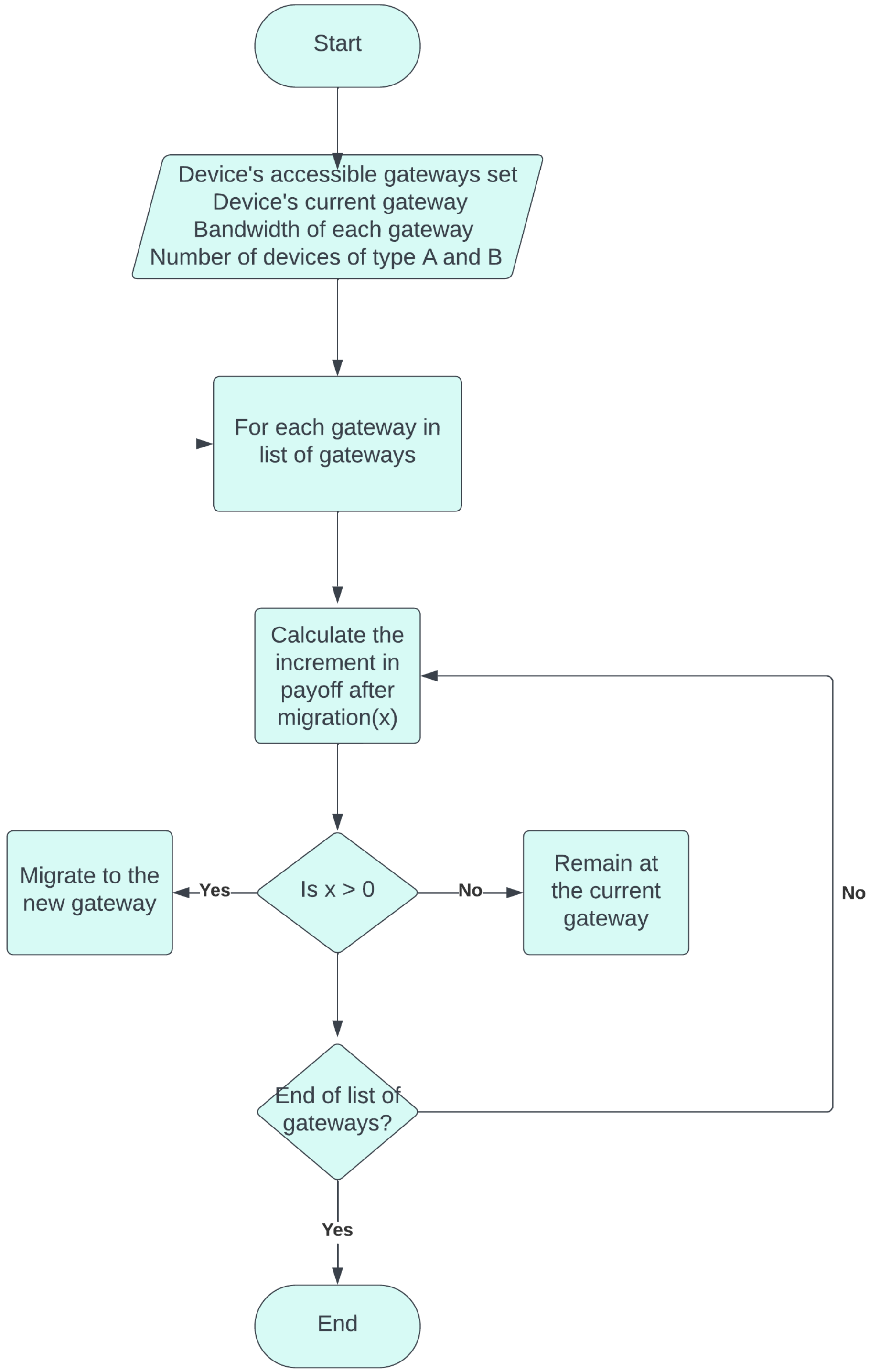

Figure 7.1: Flowchart of GS Algorithm

8 Simulations

We created the GUI using Tkinter and performed simulations using different input values. The input fields include Height, Width, Bandwidth, Number of A devices, Number of B devices, Strategy employed and Radius of each gateway. An example of the simulation is given for the input listed below.

- Bandwidth: 100 MBps
- Height and Wdith: 12m
- Gateways: 3
- Radius: 5m
- Number of A and B devices: 3 and 2
- Strategy: Both can migrate

Output: Allocation of devices to each gateway is given in Figure 1,2 and 3.

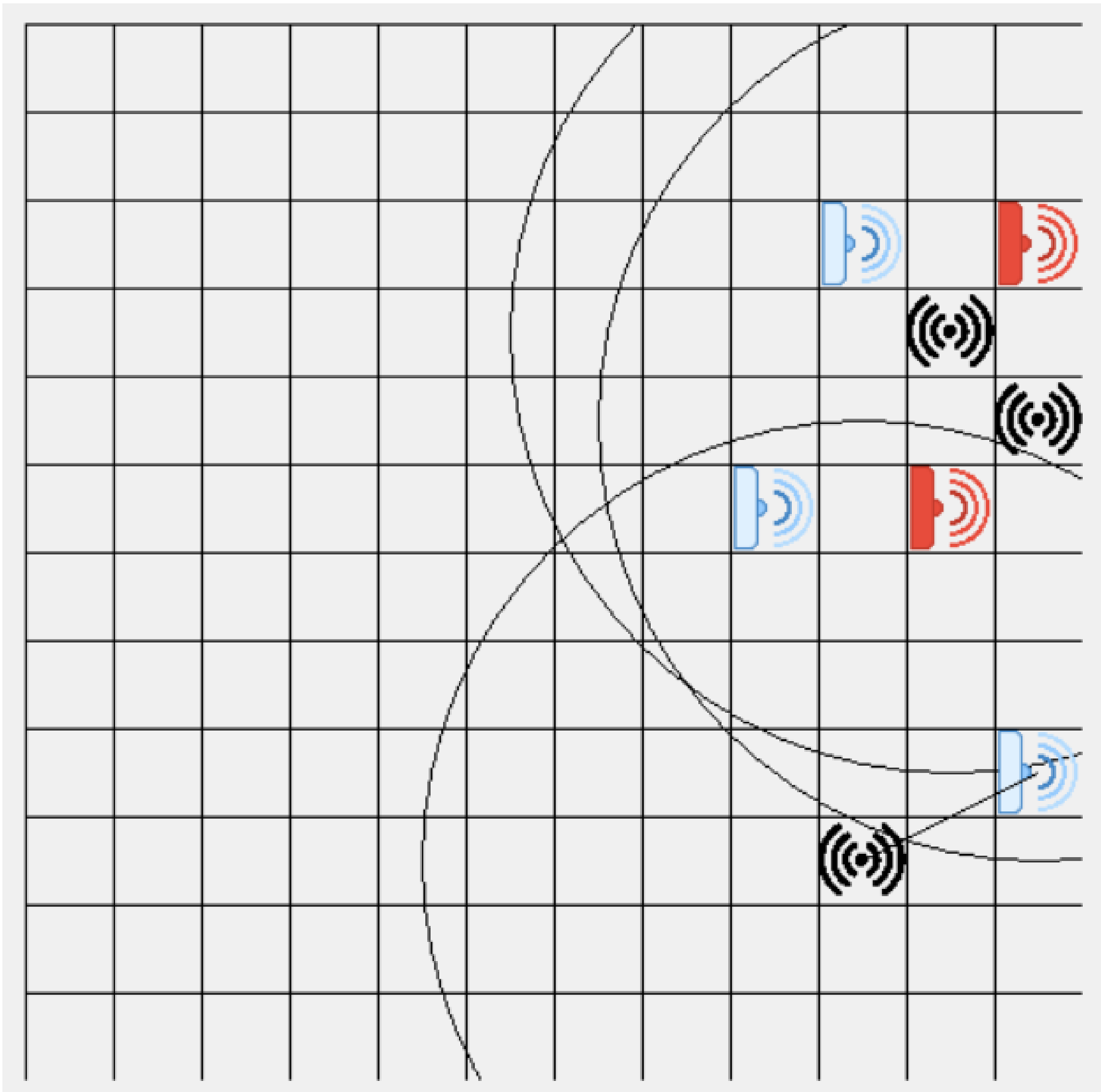

Figure 8.1: Allocation of gateway 1

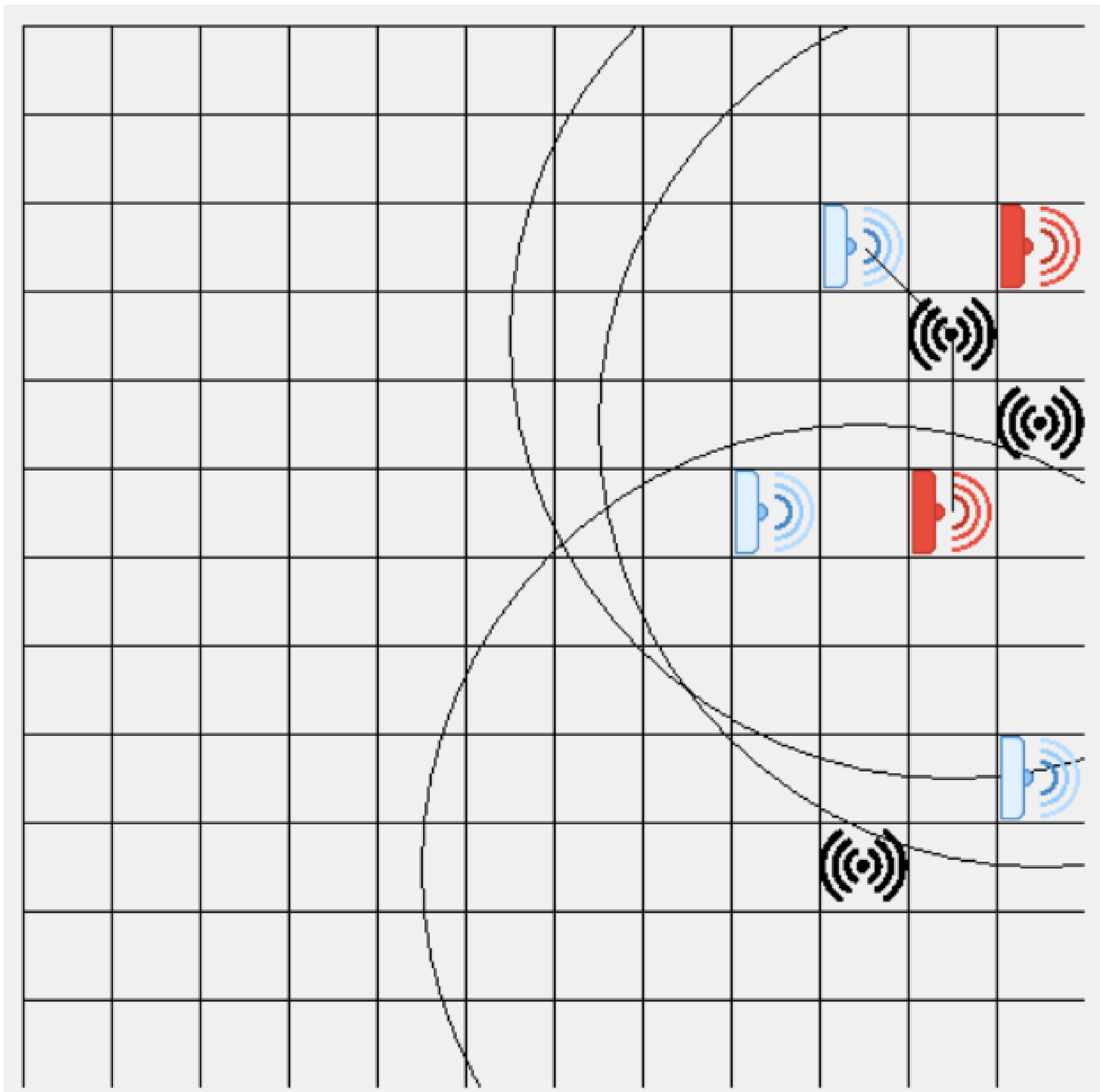

Figure 8.2: Allocation of gateway 2

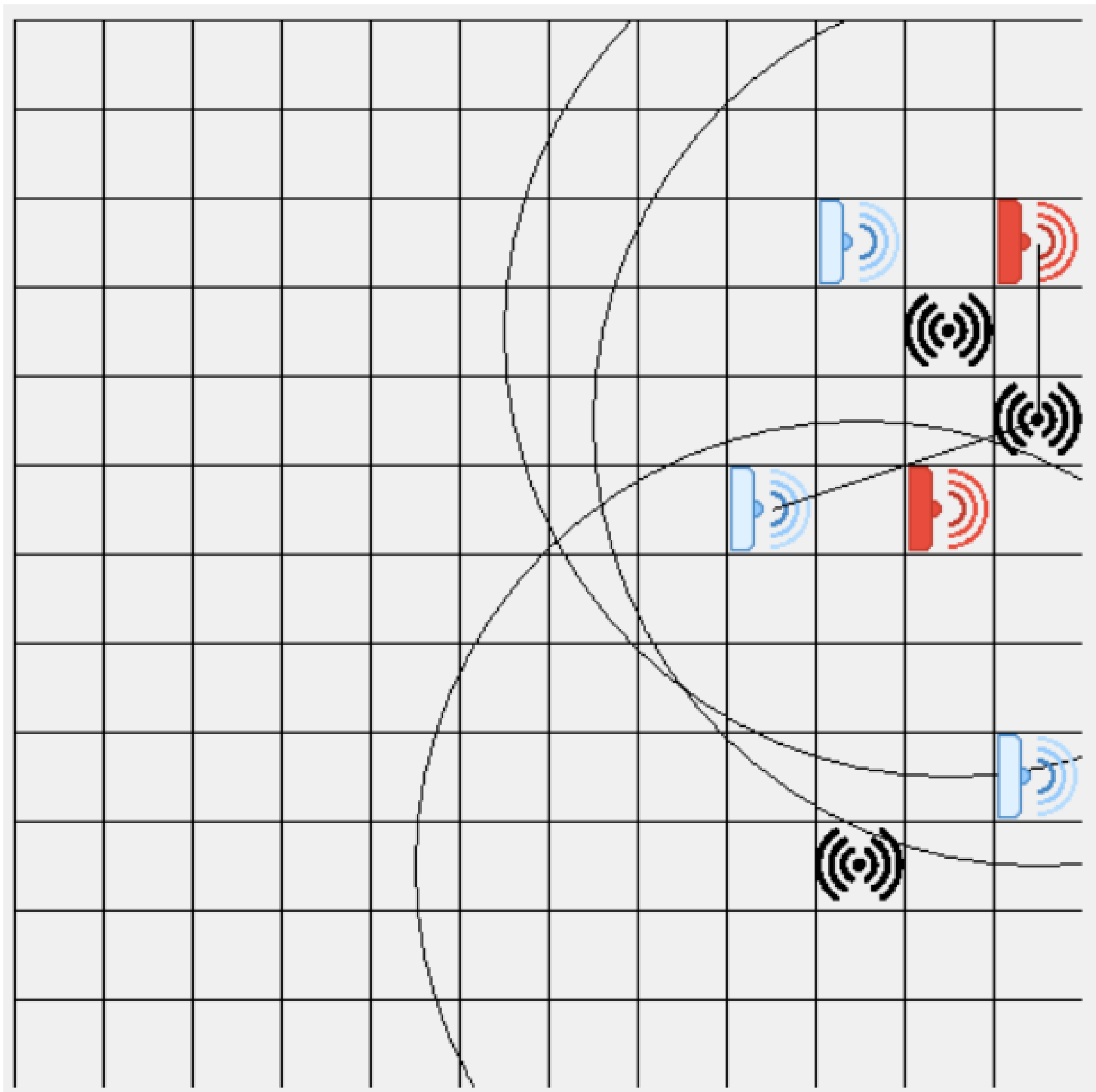

Figure 8.3: Allocation of gateway 3

9 Conclusion and Future Work

9.1 Conclusion

This paper delves into the gateway selection game involving two distinct client types vying for increased bandwidth allocation within their respective domains. We modelled the algorithm initially as a mix of non-cooperative and cooperative games, reducing it to a model entirely based on non-cooperative games by clustering the clients together as a unit. Our investigation encompasses the analysis of clients migration trends and the convergence patterns within this competitive game. Subsequently, extensive simulations are conducted to scrutinize the outcomes of the gateway selection game under diverse conditions. The simulations underscore the efficacy of the gateway selection game in enhancing the overall bandwidth for clients.

9.2 Future Work

As part of our future work, we plan to model situations where a client can bind to multiple gateways, as well as situations were gateways have an enormous radius using Evolutionary Game Theory. Furthermore, extending the scope of our research to encompass the integration of machine learning techniques could enhance the adaptability and intelligence of client decisions in the gateway selection process. This could involve developing predictive models or reinforcement learning algorithms to optimize client strategies over time. Additionally, considering the security aspects of gateway selection in CPS is crucial. Future research could delve into the vulnerabilities and potential adversarial strategies within the context of the gateway selection game.

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