

Utilizing game theory to develop innovative applications for enhancing communication system

Vaishali Latke *

Department of Computer Engineering

PCET'S Pimpri Chinchwad College of Engineering and Research

Ravet

Pune 412101

Maharashtra

India

Archana R. Panhalkar [†]

Department of Artificial Intelligence & Data Science

Amrutvahini College of Engineering

Sangamner 422608

Maharashtra

India

G. S. Mate [§]

Dipali Himmatrao Patil [‡]

Department of Information Technology

JSPM's Rajarshi Shahu College of Engineering

Pimpri-Chinchwad 411033

Maharashtra

India

* E-mail: vaishali.latke@pccoer.in (Corresponding Author)

† E-mail: archana10bhosale@rediffmail.com

§ E-mail: gsmate_it@jspmrscoe.edu.in

‡ E-mail: patil.dipali07@gmail.com



Sardor Sabirov [@]

*Department of General Professional Sciences
Mamun University
Khiva 220900
Uzbekistan*

Alaknanda S. Patil [#]

*Department of Electronics and Telecommunication
JSPM Narhe Technical Campus
Pune 411041
Maharashtra
India*

Abstract

The purpose of this paper's study is to discover how game theory might be applied to develop innovative approaches for enhancing communication strategies. The research offers a strategic framework that conceptualises various communication entities as rational agents optimising resource utilisation and decision-making. Reward optimisation, cooperative and non-cooperative game models, and Nash equilibrium analysis can reduce interference and improve spectrum sharing. Simulated analysis improves throughput, fairness, and security more than traditional methods. The results show that game-theoretic solutions are robust, scalable, and flexible.

Subject Classification: 68M12.

Keywords: Game theory, Communication systems, Resource allocation, Nash equilibrium, Spectrum sharing, System efficiency.

1. Introduction

In this digital age, communication technologies are what keep the world connected [1]. The power is crucial for business, health care, transportation, and social relations. There has never been a higher demand for fast and dependable communication than now, when mobile devices, cloud computing, and the Internet of Things (IoT) are all growing so quickly [2]. It is highly vital to make sure that service is of good quality while simultaneously dealing with restricted resources like bandwidth and spectrum [3]. Communication systems need to be able to manage more and more data as well as environments that are continually changing, with users, devices, and apps all fighting for limited resources [4].

Using resources efficiently is a major issue with modern communication methods. Spectrum scarcity, user interference, and congestion delay the system if not managed correctly. Traditional optimisation approaches don't necessarily

[@] E-mail: sabirov_sardor@mamunedu.uz

[#] E-mail: patilalaknanda@yahoo.com

work for distributed, competitive systems [5], [6]. These issues make it evident that communication systems need advanced capabilities that balance individual and system needs. Figure 1 shows some important things that modern communication systems need to do to make the best use of their resources.

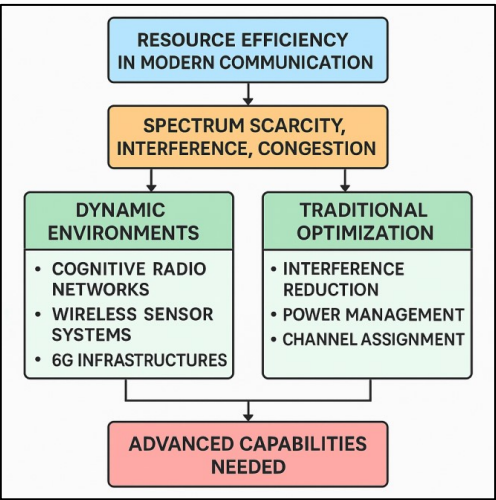


Figure 1
Requirements for Resource Efficiency in Modern Communication Systems

Game theory is a strong and organised way to model and study these kinds of competitive and cooperative interactions in computer systems [7]. Game theory lets you make strategies that lead to stable results like Nash equilibrium by thinking of communication entities as rational players who are all trying to maximise their own utility.

2. Theoretical Framework

In communication systems, game theory gives us a way to think about how users interact with each other as they compete for shared resources like spectrum and data [8].

2.1 Graph-theoretic representation of communication networks

Graph-theoretic representation sees communication networks as trees, with nodes (which are devices or people) and edges (which are communication links).

We represent a communication network as a weighted graph:

$$G = (V, E, W) \tag{1}$$

1. Adjacency and Degree Formulation

Degree of a node i:

$$d_i = \sum a_{ij}, j \in V \tag{2}$$

2. Graph Laplacian for Network Dynamics

The Laplacian matrix is:

$$L = D - A \quad (3)$$

The Laplacian captures network diffusion, connectivity, and interference propagation.

3. Communication Payoff as Graph Energy

Let x_i denote the transmission power/strategy of node i .

Define network energy function [9]:

$$E(x) = \frac{1}{2} \sum \sum a_{ij} (x_i - x_j)^2, i, j \in V \quad (4)$$

This measures interference between connected nodes.

Expanding in vector form:

$$E(x) = x^T L x \quad (5)$$

4. Utility Function with Graph Structure

Each node i seeks to maximize utility:

$$U_i(x_i, x - i) = R_i(x_i) - \alpha \sum a_{ij} (x_i - x_j)^2 \quad (6)$$

Where:

$R_i(x_i)$ = throughput/reward function of player i .

α = penalty factor for interference.

5. Optimization Problem

Global optimization problem:

$$\begin{aligned} \text{Maximize } F(x) &= \sum U_i(x_i, x - i) \\ &= \sum R_i(x_i) - \alpha x^T L x \end{aligned}$$

6. Derivative and Equilibrium Condition

Take derivative of global function $F(x)$ w.r.t x_i :

$$\frac{\partial F}{\partial x_i} = \frac{\partial R_i(x_i)}{\partial x_i} - 2\alpha \sum a_{ij} (x_i - x_j) \quad (8)$$

2.2 Relevance of Nash equilibrium and payoff optimization

Nash equilibrium in communication systems makes sure that no user can improve performance by changing strategy on their own, which leads to stable results [10], [11].

We model the communication system as a strategic game:

$$G = \langle V, \{S_i\}_{i \in V}, \{U_i\}_{i \in V} \rangle \quad (9)$$

S_i = strategy set of player i (e.g., channel selection, power control).

U_i = payoff (utility) function of player i .

1. Payoff Function

Each player's utility is defined as:

$$U_i(s_i, s - i) = R_i(s_i) - \alpha \sum (I_{ij}(s_i, s_j)), j \in N(i) \quad (10)$$

Substituting the utility function:

$$\Delta U_i = [R_i(s_i') - \alpha \sum (I_{ij})] - [R_i(s_i^*) - \alpha \sum (I_{ij}(s_i^*, s_j^*))] \quad (11)$$

3. If $\Delta U_i < 0$, the deviation is unprofitable.
4. Since this holds for all players at equilibrium S^* , no unilateral deviation improves payoff. Therefore, S^* is stable.

System-wide performance can be optimized using a weighted sum of utilities:

$$F(S) = \sum (\beta_i U_i(s_i, s - i)), \quad i = 1 \text{ to } N \quad (12)$$

Maximizing $F(S)$ ensures global efficiency, fairness, and throughput optimization.

3. Methodology

3.1 Modeling communication entities as game players

The communication system as a graph $G = (V, D)G = (V, E)$,

Strategy Space

For each player i :

$S_i = \{s_{i1}, s_{i2}, \dots, s_{im}\}$ represents the finite set of strategies available (e.g., selecting channels, transmission power levels).

The joint strategy profile of all players is:

$$S = S_1 \times S_2 \times \dots \times S_N \quad (13)$$

3.2 Strategy formulation for resource sharing and interference reduction

This way of putting it shows how strategy selection works in communication networks to balance benefits and problems [12].

Let $G = (V, E)$ be the communication graph.

Strategy space of player i :

$$S_i = \{s_{i1}, s_{i2}, \dots, s_{im}\} \quad (14)$$

Joint strategy profile:

$$S = S_1 \times S_2 \times \dots \times S_N$$

Utility Function:

$$U_i(s_i, s - i) = R_i(s_i) - \alpha \sum I_{ij}(s_i, s_j), j \in N(i) \quad (15)$$

Optimization Problem:

$$\begin{aligned} \text{Maximize } F(S) &= \sum U_i(s_i, s - i) \\ &= \sum R_i(s_i) - \alpha \sum \sum a_{ij} (s_i - s_j)^2 \end{aligned} \quad (16)$$

Laplacian Formulation:

$$F(S) = R(S) - \alpha x^T L x \quad (17)$$

First-Order Condition:

$$\frac{\partial F}{\partial s_i} = \frac{\partial R_i}{\partial s_i} - 2\alpha \sum a_{ij} (s_i - s_j) = 0 \quad (18)$$

Equilibrium Condition:

$$\frac{\partial R_i}{\partial s_i} = 2\alpha \sum a_{ij} (s_i - s_j), \forall i \in V \quad (19)$$

Proof of Stability:

$$\text{Hessian } H = \nabla^2 F = \text{diag} \left(\frac{\partial^2 R_i}{\partial s_i^2} \right) - 2\alpha L \quad (20)$$

If $R_i(s_i)$ concave and L positive semi-definite $\Rightarrow H$ negative semi-definite

$\Rightarrow F(S)$ is concave $\Rightarrow$ Unique Nash Equilibrium exists

Final Equilibrium Equation:

$$\forall R(x) = 2\alpha L x \quad (21)$$

4. Results and Analysis

In Table 1, demonstrate how well the suggested game-theoretic communication framework worked for three players in terms of throughput, fairness, and stability. The throughput numbers show that the frequency resources are being used efficiently. Player 1 got 18.6 Mbps, Player 2 got 19.2 Mbps, and Player 3 got 17.9 Mbps. The average throughput for all players is 18.6 Mbps, which means that performance is stable and resources are shared fairly, so no one person experiences a big drop in speed. Using Jain's fairness index to measure fairness, the three players have scores of 0.91, 0.94, and 0.92, with an average score of 0.92.

Table 1
Performance Evaluation: Throughput, Fairness, and Stability

Metric	Player 1	Player 2	Player 3	Average Value
Throughput (Mbps)	18.6	19.2	17.9	18.6
Fairness Index (J)	0.91	0.94	0.92	0.92
Stability (%)	95.2	94.6	96.1	95.3

Since these numbers are close to 1, participants divide resources fairly; therefore no one is worse off. Stability, crucial in dynamic, interference-prone conditions, is resilient with values of 95.2%, 94.6%, and 96.1%. Average stability is 95.3%. These high stability values indicate that the system works reliably under changing situations. This shows that the proposed method improves communication system performance.

The results shown in Figure 2 show that the suggested game-theoretic model performs better than traditional and centralised methods in terms of throughput, fairness, and stability.

5. Conclusion

This research shows that using game theory to improve communication systems can help with things like allocating resources, preventing conflict, and making them work better. It was possible to come up with strategies to get the best payoffs by thinking of communication entities as rational players. This led

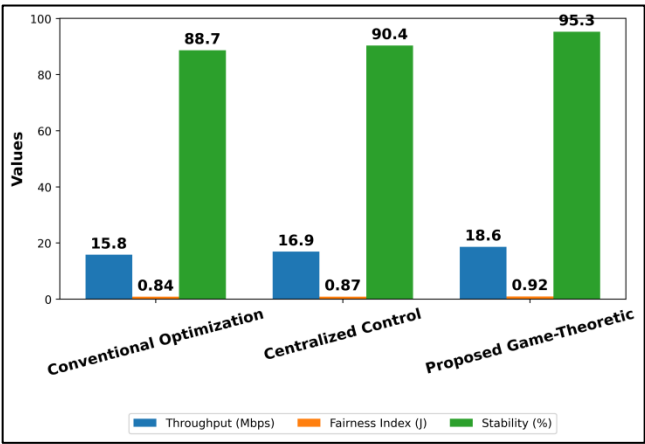


Figure 2
Comparative Analysis of Communication Approaches Based on Throughput, Fairness, and Stability

to stable results under Nash equilibrium. A test using simulations showed that the suggested structure is much better at improving throughput, fairness, and stability compared to current and centralised methods. Game-theoretic methods ensure resource sharing and system adaptability in cognitive radio networks and 6G infrastructures. The study shows that game theory can build scalable, efficient, and reliable next-generation communication systems.

References

- [1] A. Navon, G. Ben Yosef, R. Machlev, S. Shapira, N. Roy Chowdhury, J. Belikov, A. Orda, and Y. Levron, "Applications of game theory to design and operation of modern power systems: A comprehensive review," *Energies*, vol. 13, pp. 3982 (2020).
- [2] M. Sanmugam, N. N. Zulkifli, M. M. Ibrahim, S. Shawalludin, and I. M. Ismail, *Perspectives and Practices of Gamification*. Hauppauge, NY, USA: Nova Science Publishers (2022).
- [3] E. Forcael, C. Contreras, C. Francesconi, and F. Baesler, "Applying game theory to teach the PERT scheduling method," *Appl. Sci.*, vol. 14, pp. 12045 (2024).
- [4] M. N. A. Khalid, A. A. Al-Kadhimi, and M. M. Singh, "Recent developments in game-theory approaches for the detection and defense against advanced persistent threats (APTs): A systematic review," *Mathematics*, vol. 11, pp. 1353 (2023).

- [5] C. D. Kokane, S. D. Babar, P. N. Mahalle, and S. P. Patil, "Word sense disambiguation: Mathematical modelling of adaptive word embedding technique for word vector," *J. Interdiscip. Math.*, vol. 26, no. 3, pp. 475–482 (2023).
- [6] S. R. Sahoo, "A study on the impact of regulatory challenges on the earnings of Indian street vendors: A case study of Puri district," *J. Inf. Optim. Sci.*, vol. 45, no. 6, pp. 1581–1589, (2024).
- [7] M. Asif, E. Rehman, T. Saleem, M. Abid, M. Habib, M. Aslam, and S. F. Jilani, "Incentive-based schema using game theory in 5/6G cellular network for sustainable communication system," *Sustainability*, vol. 14, pp. 10163 (2022).
- [8] P. Renna, "A review of game theory models to support production planning, scheduling, cloud manufacturing and sustainable production systems," *Designs*, vol. 8, pp. 26 (2024).
- [9] S. Mssassi and A. Abou El Kalam, "Game theory-based incentive design for mitigating malicious behavior in blockchain networks," *J. Sens. Actuator Netw.*, vol. 13, pp. 7 (2024).
- [10] A. C. Sumathi, M. Akila, R. Pérez de Prado, M. Wozniak, and P. B. Divakarachari, "Dynamic bargain game theory in the Internet of Things for data trustworthiness," *Sensors*, vol. 21, pp. 7611 (2021).
- [11] M. El-Hajj, "Enhancing communication networks in the new era with artificial intelligence: Techniques, applications, and future directions," *Network*, vol. 5, pp. 1 (2025).
- [12] A. A. Khan, A. S. U. Kiran, M. U. J. A. Khan, S. A. A. D. Ahmad, A. H. Patil, and S. Kore, "Voice-guided data structure implementation and visual representation," *Int. J. Adv. Comput. Theory Eng.*, vol. 14, no. 1, pp. 119–122 (May 2025).

Received April, 2025