A Game Theoretic Analysis of Fixed Channel Allocation for Multiple Radios in Multihop Wireless Networks

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Abstract

Cellular communications become increasingly popular and mobile subscribers are expected to rise heavily. Besides cellular communications. Ad hoc networking is another type of wireless communication technology. Traditional cellular networks and mobile ad hoc networks both have their respective advantages and drawbacks. Traditional cellular networks have mature technology support for reliable performance. However, building and expanding their necessary infrastructure is costly. Multihop wireless networks, on the other hand, are simple to deploy and easily expandable. In wireless communication the wireless medium is shared by the different user through the multiple access techniques. The total available bandwidth is divided permanently into a number of distinct subbands named as channels. Commonly, we refer to the assignment of radio transceivers to these channels as the channel allocation problem. An efficient channel allocation is essential for the design of wireless networks. Various channel allocation methods has been developed in past. static noncooperative game and Nash Equilibrium (NE) channel allocation scheme has developed in past it is not suitable for the multihop wireless networks and the conventional methods were not achieving the good through put and these not satisfying the good session data rates. To overcome the above problems a hybrid approach is to be developed. It is involving both cooperative and noncooperative Schemes and to achieve good data rates of multihop sessions and the throughput of the network is improved.

Keywords

Cellular Communication, MANETS, Multihop Communication, Nash Equilibrium

I. Introduction

New challenges in wireless network design refer to a more efficient bandwidth utilization and the use of new networking paradigms. The former goal is related to the growing bandwidth demand and the scarcity of available spectrum. The latter refers to the need for flexible and easy deployment, self configuration and adaptation to the working condition. Multi-hop wireless networks have been identified as a valuable networking paradigm able to fulfill the previous requirements. Examples of multi-hop wireless networks include ad hoc networks and mesh networks. Practical interest in multi-hop wireless networks is confirmed by the recent development of standards which explicitly encompass the mesh paradigm, where the backhaul network is organized in an ad hoc topology. The IEEE 802.16 standard is one example. In the context of 802.11 networks a special working group is dedicated to the mesh extension, which is referred to as 802.11s. Other standardization efforts are focusing on the introduction of mesh-like support in their network architecture, such as 802.15.3/4, where the network architecture implicitly supports a mesh-like structure, and 802.15.5, which is working to define a mesh structure for personal area networks. It is clear that a deep understanding and the ability to optimize the performance of multi-hop wireless networks will benefit significantly in these contexts. With the motivation of improving performance of multi-hop wireless networks, in the last few years great attention has been devoted to networks where each node is provided with multiple radio interfaces and can operate on multiple channels. This new degree of freedom has been proved to potentially allow for increased capacity with respect to single-channel single interface networks. This approach is particularly interesting Research reported here is supported in part by U.S. National Science Foundation award CNS 06-27074, U.S. Army Research Office grant W911NF- 05-1-0246 and "Ing. Aldo Gini" Foundation, Padova, Italy. Any opinions, findings, and conclusions or recommendations expressed here are those of the authors and do not necessarily reflect the views of the funding agencies. if applied to 802.11 networks, since multiple channels are already available and devices provided with multiple wireless networking cards are being designed and already exist in some test beds.

A lot of effort has also been spent in the last few years to understand the challenges related to resource allocation in such networks, where the increased number of variables to be jointly optimized has represented a big issue. The problem has been approached from different perspectives, ranging from heuristic and protocol oriented solutions whose performance is far from being exactly defined, to the determination of theoretical bounds whose practical implementation is not straightforward. It is thus worth investigating an approach aiming at the design of practical algorithms based on a solid theoretical background, which can be analytically proved to guarantee some performance bounds. In this paper, we consider the problem of joint congestion control, channel allocation and scheduling for multi-hop wireless networks in a general communication and interference scenario. The problem is formulated as a joint optimization, which is then solved by a dynamic algorithm and is potentially able to achieve the optimum solution under certain assumptions.

II. Scheduling and Error Control in Cellular Wireless Networks

A cellular wireless network is a wide area network, which divides the entire service area into several sub-areas called cells (circles in fig. 1). A base station controls each cell. Major responsibilities of a base station include controlling resources within its jurisdiction and coordinating with other base stations to setup connections as well as to handle mobiles' mobility. This dissertation focuses on scheduling and error control mechanisms1 of a base station in a particular cell.

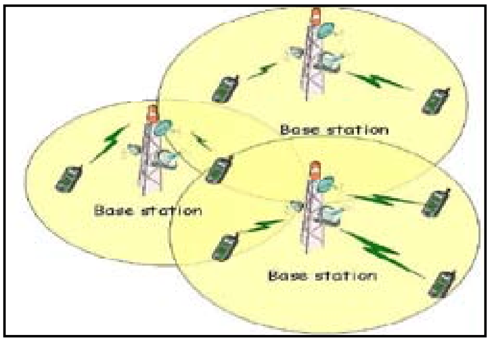

Fig. 1: A Cellular Wireless Network

One of the most important aspects in a cellular wireless network is resource sharing. Resource sharing (also known as channel access) defines a set of rules for each mobile to use the resource without incurring unacceptably high interference to other active mobiles. Conventionally, there are three resource sharing mechanisms:

A. Time Division Multiple Access (TDMA)

Each mobile is granted a channel access at different time. Since there is only one active mobiles, the interference is minimal. This dissertation focuses on this type of channel access.

Frequency Division Multiple Access (FDMA): Several mobiles are allowed to access the channel simultaneously. Different mobiles use non-interfering frequency bands.

B. Code Division Multiple Access (CDMA)

Several transmissions in the same frequency band can occur concurrently. Each mobile is identified by a particular Psudo-Noise (PN) code sequence. At the receiver, a multi-user detection technique uses the code sequence to extract information of the corresponding mobile. To a particular flow, transmissions from other flows acts as noise. Therefore, the power control in CDMA is very critical. In practice, a TDMA system divides time domain into logical units called time slots. During each time slot, the base station allows only one mobile to access the channel. The functionality of a base station to decide which mobile is allowed to access the channel in each time slot is known as scheduling. For example, a Round Robin scheduler allows each of the backlogged mobiles to transmit in order. Although we mainly focus on a TDMA-based system, which are also applicable for some advanced versions of CDMA systems. For example, implemented under a CDMA system, a Code Division Multiple Access with High Data Rate (CDMA-HDR) scheduler transmits data to only one mobile. A base station in a CDMA-HDR system obtains channel state information by using the following approach. The base station broadcasts so-called pilot signal periodically. Intercepting the pilot signal, each mobile determines the current received SINR, looks up the SINR-to-rate mapping table, and requests for corresponding data rate via the reverse link data rate request channel. Based on the received request, the scheduler selects only one mobile to access the channel. Due to time-varying nature of a wireless channel, this opportunistic scheduling exploits so-called multi-user diversity and yields higher throughput than a conventional CDMA system does. In a wireless network, a scheduler needs to be aware of channel variation. For example, to maximize overall throughput (number of transmitted packets over a certain period of time), a channel-quality-based opportunistic scheduling principle allows only a mobile with the best channel condition to access the channel. Alternatively, fair scheduling algorithms aims at fairly allocating resources among all mobiles. In a wired network, fair scheduling algorithms are generally derived from the Generalized Processor Sharing (GPS) algorithm. GPS generally allocates re- sources (e.g., channel bandwidth) among all data flows in proportion to their weights. In particular, the scheduler allocates $X_i(t_1; t_2)$ and $X_j(t_1; t_2)$ amount of resources to mobiles i and j (with weights w_i and w_j , respectively) in the interval from t_1 to t_2 such that, given that flow i is backlogged, the allocation satisfies

$$\frac{X_i(t_1,t_2)}{X_j(t_1,t_2)} \leqslant \frac{w_i}{w_j}, \qquad \forall i,j,$$

where the equality holds when both flow i and j are backlogged at the same time. The location-dependent and bursty channel errors make the original notion of GPS unsuitable for wireless networks. Fair queuing algorithms, such as Wireless Packet Scheduling (WPS) [9], Channel Independent Fair Queuing (CIF-Q), and Wireless Fair Service Algorithm (WFS), have been proposed to alleviate this problem. In general, a mobile perceiving a bad channel (i.e., low received Signal-to-Interference plus Noise Ratio (SINR) at the receiver) should defer the transmission and let another mobile with a good channel (i.e., high received SINR) transmit data. The scheduler should compensate for that when the channel of the deferred mobile becomes good again. The mobile deferring the transmission is considered to be lagging, while the mobile receiving extra allocation is considered to be leading. Most of the wireless fair queuing algorithms in the literature consist of five main components

1. The error-free service model allocates resources among all data flows in absence of error.
2. The lead and lag model determines which data flows are leading and lagging.
3. The compensation model specifies how lagging data flows can be compensated.
4. Slot queues and packet queues classify different types of data flows(e.g., delay sensitive flows, error sensitive flows).
5. Channel monitoring and prediction provide measurement and estimation of the channel state.

With multi-rate transmission capability, a mobile can dynamically adjusts transmission rate based on the current channel condition. Therefore, the number of transmitted packets in each allocated time slot might be different. The notion of fairness under multi-rate transmission can have different implications.

Another important issues in a wireless network is error control mechanism, which can largely be categorized into Forward Error Correction (FEC) and Automatic Re- peat request (ARQ) schemes. FEC inserts redundancy bits into a data frame before each transmission. When a received data frame is in error, the receiver uses these redundancy bits to correct the corrupted data frame. ARQ, on the other hand, combats an error-prone wireless channel by means of data retransmission. While able to correct the corrupted data with low latency, FEC could lead to inefficiency in resource usage, due to redundant bits in each data frame. ARQ, on the other hand, is more adaptive to channel variation but requires more latency (due to retransmission) to correct the error. In general, FEC is more suitable to real-time traffic, while ARQ is more appropriate for non-real-time data transmission.

III. Multi-Hop Wireless Networks

A multi-hop wireless network is characterized by the absence of a direct communication link between source and destination nodes. Data transmission in this case must first be transmitted to nearby relay nodes, which in turn forward data to the destination node. This class of networks has a wide range of applications such as wireless ad hoc networks, wireless mesh networks, wireless sensor networks, and multi-hop cellular networks. A multi-hop wireless network enables short-range communication while preserving broad service coverage. Short-range communications leads to higher received SINR. Therefore, transmitting power can be reduced without compromising packet error probability. The reduction in power requirement implies longer battery lifetime, and smaller interfering region which could result in an increase in spatial reuse. Alternatively, with fixed transmission power, short-range communications leads to decreased packet error probability, hence allowing higher modulation order transmission which is more susceptible to noise. Short-range communication not only improves aver- age throughput, but also helps distribute

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services fairly among mobiles with poorer channel condition. An example of multi-hop wireless networks is illustrated in fig. 2, where Mobiles 1 and 2 are close to the base station, and therefore their SINR levels are expected to be comparatively high. Mobile 3, on the other hand, is far from the base station and obstructed by a building, and therefore the link between Mobile 3 and the base station experiences high path loss and shadowing, leading to low SINR. Although increasing transmitting power can solve this problem, it might lead to more interference and inefficient energy usage. Another solution is to transmit data to Mobile 3 via a relay node. Transmission in a multi-hop manner could
Lead to better throughput.

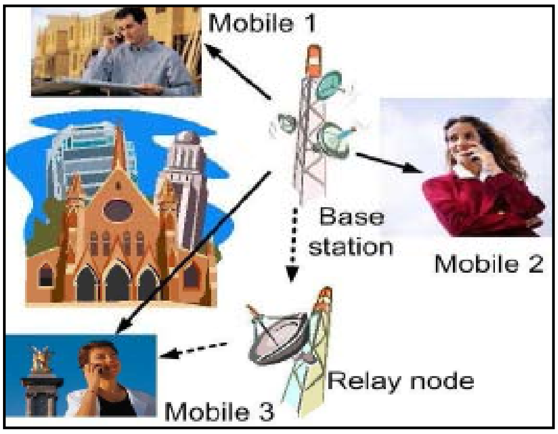

Fig. 2. A Multi-Hop Cellular Network

Due to the lack of any central controller, problems in a multi-hop wireless network are generally more challenging than those in a cellular wireless network. In a multi- hop wireless network, each mobile coordinates with each other to keep the network up and running. Scheduling could be difficult, since most algorithms for multi-hop networks are usually in a distributed manner. Error control on the other hand could be conducted in the same way as it is in a cellular wireless network. For a multi-hop wireless network, this dissertation models and analyzes the impact of a class of ARQ protocols on the performance of in a multi-hop wireless data network. The analysis is divided into two parts. The first part models the number of transmissions for successful delivery of a packet across a multi-hop path. The second part studies the performance of batch transmission in a multi-hop wireless network only with a small number of hops (e.g., two hops). The novelty of these models is that the probability mass function (pmf) for the number of transmissions required for end-to-end delivery of a packet or a batch of packets can be obtained under different hop-level error control policies. Therefore, the trade-off between reliability and latency can be analyzed. Scheduling is one of the most important components of radio link design for cellular wireless networks. In the literature, it was shown that a channel-quality-based opportunistic scheduling can be used to maximize resource usage (system throughput). However, the impact of Adaptive Modulation and Coding (AMC), ARQ, and channel variation on this scheduling algorithm was not thoroughly investigated. This work derives complete statistics (i.e., probability density function (pdf)/probability mass function (pmf)) for the delay and throughput of this type of scheduling. The statistics can be used to adjust the network parameters such as the level of Quality of Service (QoS), radio link layer parameter settings, and the number of admissible connections so that the radio link performance can be optimized. Another type of scheduling, namely, fair scheduling aims at allocating resources among customers in proportion to their weights. This type of scheduling algorithm would be useful to classify customers based on their levels of subscription. For example, premium-class customers should acquire larger portions of service than regular- class customers. This dissertation proposes two fair scheduling algorithms for cellular networks under single-rate and multi-rate transmissions. Both algorithms show im- proved performance over the algorithms in the literature. As cellular networks evolve towards the next-generation wireless networks, in- corporation of multi-hop communications into the cellular network seems to be in- evitable. This dissertation presents two performance analysis models for multi-hop packet transmissions which reveal the trade-o® between latency and reliability under different error control (i.e., retransmission) policies. In particular, ARQ with higher level of persistence provides higher reliability at the expenses of increased latency. For real-time traffic, data packets might become useless after some time. Therefore, the use of infinite-persistence ARQ may not be appropriate. The analytical model would be useful for engineering the network for provisioning required QoS for the different types of service in a multi-hop wireless setup.

IV. System Design

In this paper, we present a game-theoretic analysis of fixed channel allocation strategies of devices that use multiple radios in the multihop wireless networks. Static noncooperative game is a novel approach to solve the channel allocation problem in single-hop networks, and Nash Equilibrium (NE) provides an efficient criterion to evaluate a given channel allocation. In multihop networks, however, noncooperative game results in low achieved data rate for multihop sessions and low throughput for whole networks due to the reasons
Hence, we introduce a hybrid game involving both cooperative game and noncooperative game into our system in which the players within a communication session are cooperative, and among sessions, they are noncooperative. We first define the Min-Max Coalition-Proof Nash Equilibrium (MMCPNE) in this hybrid game, which is aiming to achieve the maximal data rate of all sessions (including single-hop sessions and multihop sessions). We also define three other equilibria schemes that approximate to MMCPNE, named as Minimal Coalition-Proof Nash Equilibrium (MCPNE), Average Coalition-Proof Nash Equilibrium (ACPNE), and I Coalition-Proof Nash Equilibrium (ICPNE), respectively. Then, we study the existence of MMCPNE in this game and our main result, Theorem 2, shows the necessary conditions for the existence of MMCPNE. Furthermore, we propose the MMCP algorithm which enables the selfish players to converge to MMCPNE from an arbitrary initial configuration and the DCP-x algorithms which enable the players converge to approximated MMCPNE states (e.g., MCPNE, ACPNE, and ICPNE). Finally, we present the simulation results of the proposed algorithms, which show that MMCPNE outperforms NE and Coalition-Proof Nash Equilibrium (CPNE) channel allocation schemes in terms of the achieved data rates of multihop sessions and the throughput of whole networks due to cooperative gain.

V. Related Work

There has been a considerable amount of research on channel allocation in wireless networks, especially in cellular networks. Three major categories of channel allocation schemes are always used in cellular networks: fixed channel allocation (FCA), Dynamic Channel Allocation (DCA), and Hybrid Channel Allocation (HCA) which is a combination of both FCA and DCA techniques. In FCA schemes, a set of channels is permanently allocated to each cell in the network. In general, graph coloring/labeling technique provides an efficient way to solve the problems of fixed channel allocation. FCA method can achieve satisfactory performance under a heavy traffic load; however, it cannot adapt to the change of traffic conditions or user distributions. To overcome the inflexibility of FCA, many researchers propose dynamic channel allocation methods. In DCA schemes, in contrast, there is no constant relationship between the cells and their respective channels. All channels are potentially available to all cells and are assigned dynamically to cells as new calls arrive in. Because of its dynamic property, the DCA method can adapt to the change of traffic demand. However, when the traffic load is heavy, DCA method performs worse than FCA due to some cost brought by adaptation. Hybrid channel allocation schemes are the combination of both FCA and DCA techniques. In HCA schemes, the total number of available channels are divided into fixed and dynamic sets. The fixed set contains a number of nominal channels that are assigned to the cells as in the FCA schemes, whereas the dynamic set is shared by all users in the system to increase flexibility.

Recently, channel allocation problem is becoming a focus of research again due to the appearance of new communication technologies, e.g., Wireless Local Area Networks (WLANs), Wireless Mesh Networks (WMNs), and wireless sensor networks (WSNs). Using weighted graph coloring method, Mishra et al. propose a channel allocation method for WLANsin. InWMNs,manyresearchers have considered devices using multiple radios. Equipping multiple with radios in the devices in WMNs, especially the devices acting as wireless routers, can improve the capacity by transmitting over multiple radios simultaneously using orthogonal channels. In the multiradio communication context, channel allocation and access are also considered as the vital topics. By joint considering the channel assignment and routing problem, Alicherry et al. propose an algorithm to optimize the overall throughput of WMNs . In the above cited work, the authors make the assumption that the devices cooperate with the purpose of the achievement of high system performance. However, this assumption might not hold for the following two reasons. In one hand, players are usually selfish who would like to maximize their own performance without considering the other players' objective. In the other hand, the full cooperation of arbitrary devices is difficult to achieve due

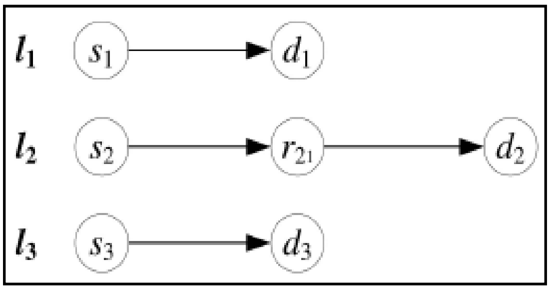

Fig. 3: An Example of Three Communication Sessions

to the transmission distance limitation and transmission interference of neighboring devices.

Game theory provides a straightforward tool to study channel allocation problems in competitive wireless networks. As far as know, game theory has been applied to the CSMA/CA protocol, to the Aloha protocol and the Peer-To-Peer (P2P) system. Furthermore, on the basis of graph coloring, Halldorsson et al. use game theory to solve a fixed channel allocation problem. Unfortunately, their model does not apply to multiradio devices. In Wireless Ad-Hoc Networks (WANETs), using a static noncooperative game, Felegyhazi et al. analyze the channel allocation strategies of devices that use multiple radios. However, their results can be only applied to single-hop wireless networks without considering multihop networks.

VI. Nash Equilibria

A. Noncooperative Game NE

In single-hop networks, the payoff of player i is equivalent to its utility Ri and the multiradio channel allocation problem can be formulated as a static noncooperative game. In order to study the strategic interaction of the players in such a game, we first introduce the concepts of Nash equilibrium.

B. Cooperative Game CPNE

It is worth noting that noncooperative game is not suitable for multihop networks due to the following two reasons. On one hand, the payoff of any player in multihop session is not equivalent to its utility. In fact, the payoff (achieved data rate) of player i is not only determined by the utility itself, but also by the utilities of other players within the

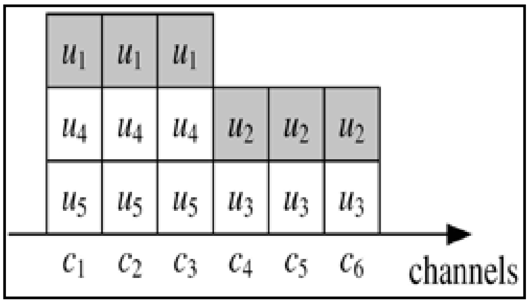

Fig. 4: An Example of CPNE Channel Allocation, Where, u_1 and u_2 Formulate a Coalition

same session. On the other hand, it is possible that the players in the same session cooperatively choose their strategies for the purpose of high payoff. Hence, we formulate the problem in multihop networks as a hybrid game involving both cooperative game and noncooperative game. In detail, the players within a coalition (session) are cooperative, and among coalitions, they are noncooperative. In order to study the strategic interaction of the coalitions in cooperative game, we introduce the concept of classical coalition-proof Nash equilibrium

VII. Results

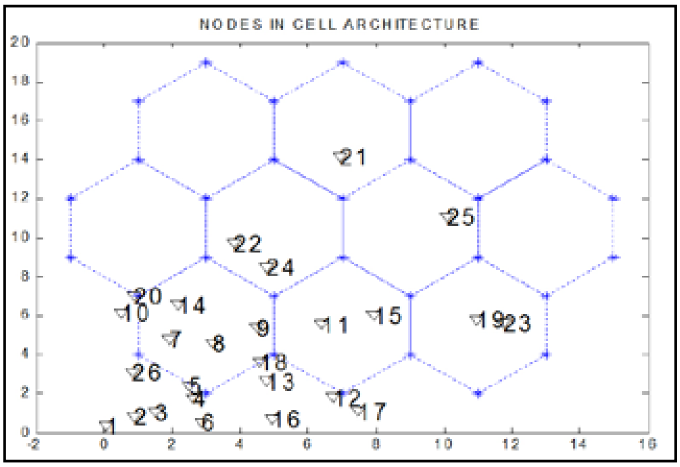

Fig. 5:

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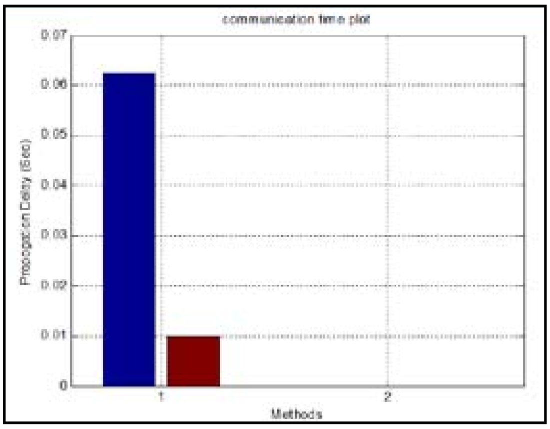

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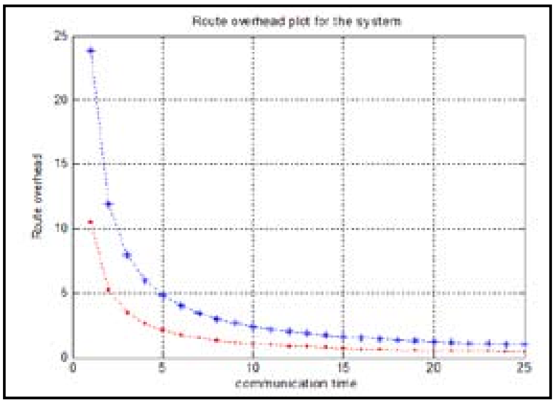

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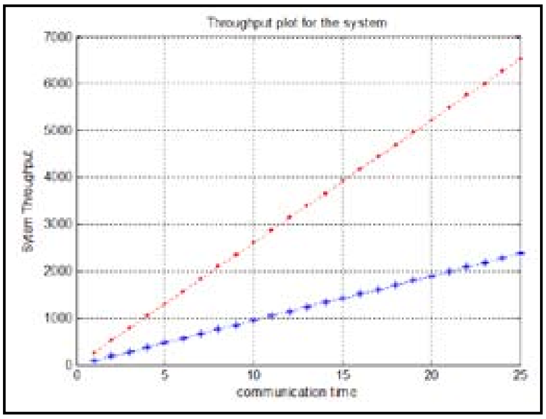

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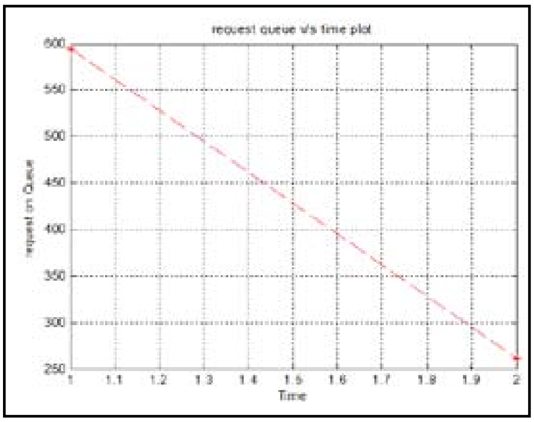

Fig. 9:

VIII. Conclusion

WIRELESS communication system is often assigned a certain range of communication medium (e.g., frequency and). Usually, this medium is shared by different users through multiple access techniques. Frequency Division Multiple Access (FDMA), which enables more than one users to share a given frequency band, is one of the extensively used techniques in wireless networks In order to meet the demands of multi-rate multimedia communications, next-generation cellular systems must employ advanced algorithms and techniques that not only increase the data rate, but also enable the system to guarantee the quality of service (QoS) desired by the various media classes. In this work we have investigated a novel approach called nash equilibrium for channel estimation and proper communication between nodes in different topologies

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