Throughput-Optimal Relay Selection in Multiuser Cooperative Relaying Networks

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Abstract—The optimal relay selection problem in multiuser cooperative wireless networks is considered in this paper. A general discrete time model for such networks is introduced which takes into account the dynamic variations of the channel state as well as stochastic arrival of data packets into the system. The model consists of a set of mobile users, one destination node and R relay nodes which may be either mobile or fixed. The system uses the benefit of cooperative diversity by relaying in decode and forward or amplify and forward mode. We assume that each user either transmits its packets directly to the destination or selects a relay node to cooperatively transmit its packets. It is not however trivial whether a user at each time slot has to cooperate with any relay node or not and if so, which relay node should be selected for cooperation. We will propose a throughput optimal relay selection policy that can stabilize the system for all the arrival rate vectors strictly inside the stability region. Then, we show that the optimal policy is equivalent to finding the maximum weighted matching in a weighted bipartite graph at each time slot. We also use simulations to compare the performance of the throughput optimal relay selection strategy with an instantaneous throughput optimal policy as well as a non-cooperative policy in terms of average queue occupancy (or equivalently, queueing delay).

I. INTRODUCTION

Cooperative communication constitutes a rich body of research on the area of wireless communications. The main concept of cooperative communication comes from the idea of MIMO wireless systems. In MIMO wireless systems, it is demonstrated that utilizing multiple antennas on the communicating entities can lead to substantial improvements on the achievable data rates for reliable communication. However, due to space limitations and implementation costs, it is not feasible to equip handset wireless devices with multiple antennas. Cooperative communication is a promising approach to implement MIMO in the form of distributed single antenna nodes in a wireless system. In this type of communication, the source node employs one or more relay nodes to cooperatively transmit its information to the destination. It was shown that cooperation can lead to significant channel capacity improvements as well as providing diversity in the form of spatial diversity [1]-[5].

Other than information theoretic studies of cooperative wireless systems (such as the works in [1]-[6]), there is a large body of research in cooperative communication whose main goal is to devise efficient cooperative relaying protocols. In these types of works, the main problem is to find optimal resource (for example, power, channel, relay, etc.) allocation schemes according to an objective function as well as the constraints on the underlying model. Optimal relay selection is one of such problems which is of great importance in cooperative wireless networks.

Most of the works in this area focus on the physical layer issues and usually study the bit error rate, capacity and outage behaviour of the proposed schemes [7]-[13]. In [14]-[16], stochastic control of wireless cooperative networks is discussed. In [14], throughput optimal network control policies for single-source single destination cooperative networks are studied. The optimal policy takes into account the queue dynamics and it jointly optimizes routing, scheduling and resource allocation in the network. The work in [15] considers relay selection problem in cooperative networks from the stochastic control point of view. The proposed policy incorporates adaptive modulation and coding, as well as residual relay energy in the relay selection process to maximize the network life time. The authors in [16] formulate the relay selection problem in wireless cooperative networks as a stochastic control problem in a discounted Markov decision chain. The work in [16] investigates the optimal resource allocation policy for delay limited cooperative communication networks and develop dynamic cooperation strategies to achieve a target outage probability.

In this paper, we will consider the optimal relay selection problem in a multiuser cooperative wireless system. In particular, we will introduce a general model of multiuser cooperative system which takes into account the dynamic variations of channels as well as stochastic arrival of data packets into the system. In our model, there is a set of users as well as a set of relay nodes and a centralized controller that controls the relay assignment process. Each user may transmit directly to the destination (direct mode) or it can send its packets to the destination using the cooperation with a relay node according to a two phase cooperative protocol (cooperation mode). Therefore, at each time slot, the network controller has to address two questions about each user: whether it should work in the direct mode or cooperation mode; and if it has to cooperate, which relay node must be assigned to that user. We call any strategy that answers these two questions about each user a relay selection policy. We investigate the optimal policy for such a problem with the objective of maximizing the long run average throughput of the system. We will characterize the optimal policy as an integer programming (IP) problem. Then, we will show that the IP problem at each time slot is equivalent.
to finding the maximum weighted matching in a weighted bipartite graph. Simulations are conducted to compare the performance of the proposed policy with another cooperative policy as well as non-cooperative policy.

The rest of the paper is organized as follows. In section II, we will describe the model used in the paper and then we will have a brief review on the notions of stability, stability region and throughput optimal policies. In section III, we will introduce the throughput optimal relay selection policy. We also show that the optimal policy is equivalent to finding the maximum weighted matching in a bipartite graph at each time slot. Simulation results are brought in section IV. Section V summarizes the conclusions.

II. PROBLEM FORMULATION

A. Model Description

The cooperative model considered in this paper consists of the set of users $\mathcal{N}$, the set of relay nodes $\mathcal{R}$ and one destination node $d$. Assume that $|\mathcal{N}| = N$ and $|\mathcal{R}| = R$ where $|\cdot|$ is the cardinality of a set. Suppose that the system is working in the uplink mode. However, using similar modelling, the same results can be easily drawn for the downlink mode as well. Assume that there are $N$ orthogonal channels in the system and each user $n$ is equipped with one transceiver tuned on a separate channel $C_n$. The destination node $d$ is capable of receiving and decoding the information transmitted on different channels, simultaneously. The system is assumed to be time slotted with equal length intervals. Therefore, all the users can transmit at each time slot using their own channels.

There is also exogenous arrival process to each user $n$ at each time slot $t$ which is represented by $A_n(t)$. In fact, $A_n(t)$ represents the number of packets arrived for user $n$ exogenously during time slot $t$. For these processes, we assume that $E[A_n^2(t)] < \infty$ for all $t$ and all $n$. Suppose that we add the new arrivals to each queue at the end of each time slot. Let $X(t) = (X_1(t), \ldots, X_N(t))$ be the queue length process vector at the end of time slot $t$ after adding new arrivals to the queues. Assume that each arrival process $A_n(t)$ follows an i.i.d. process with mean $\lambda_n$. Figure 1 illustrates the model used in this paper.

Each user $n$ can transmit directly to $d$ or it can use one of the relay nodes to send its information cooperatively. In the former case, we say that the user is in direct mode and in the latter case we say that the user is in cooperative mode. When user $n$ is in direct mode, it uses all the time slot duration to transmit its information. However, when user $n$ is working in cooperative mode, it uses a two phase transmission protocol to transmit its information to $d$ (this is because the relay nodes are assumed to be half duplex). Specifically, it splits the time slot into two sub-slots. In the first sub-slot, it starts the first phase of transmission in which it broadcasts the information to the relay nodes and also node $d$. In the second sub-slot, a specific relay node $r$ (which is selected to cooperate with user $n$ according to a relay selection policy) cooperatively relays the information received from user $n$ to the destination node $d$. The relay node $r$ may operate in Decode and Forward (DF) mode or Amplify and Forward (AF) mode. In the DF mode, the relay node $r$ receives the signal and decodes it. Then it re-encodes the information and forwards it to $d$. In the AF mode, the relay node $r$ receives the signal but does not decode the signal. However, it amplifies the signal in such a way that its transmission power satisfies the relay’s maximum power constraint. In both cases of DF and AF, destination node $d$ uses the information received from direct link in the first sub-slot and the relayed information in the second sub-slot and combines them. Then, $d$ uses the combined signal to decode the information.

We represent the direct communication link between each user $n$, $n \in \mathcal{N}$ and node $d$ by $\ell_{n,d}$. The achievable rate corresponding to each link $\ell_{n,d}$ (which is using channel $C_n$) at time slot $t$ is denoted by $R_{n,d}(t)$. It is assumed that the achievable rates over different direct communication links may be correlated but vary over different time slots. The variation of communication links depends on various factors such as fading, mobility of the users, path loss, etc. We denote all the effects of such factors on each link $\ell_{n,d}$ by $H_{n,d}$ and we call it channel gain of direct link $\ell_{n,d}$. In other words, if $X_{n,d}$ and $Y_{n,d}$ represent the symbol transmitted and received on this link, respectively, then $\forall n \in \mathcal{N}$

$$Y_{n,d}(t) = H_{n,d}(t)X_{n,d}(t) + N_d(t)$$

in which $N_d(t)$ is the additive Gaussian noise at node $d$. Suppose that each user $n$ transmits its signals with fixed power $P_n$. Assuming that the bandwidth of the channel $C_n$ is $W_n$ and the PSD (Power Spectral Density) of the noise process $N_d$ is equal to $\frac{1}{2N}$, the maximum achievable transmission rate for reliable communication over each link $\ell_{n,d}$ is given by Shannon formula i.e.,

$$R_{n,d}(t) = W_n \log_2(1 + \frac{|H_{n,d}(t)|^2P_n}{N_0W_n}) \text{ bits/sec}$$

We denote the cooperative link consisting of user $n$, relay node $r$ and destination node $d$ by $\ell_{n,r}$. The achievable rate corresponding to the cooperative link $\ell_{n,r}$ at time slot $t$ is dependent to the cooperation mode (AF or DF) and is denoted by $R_{n,r}^{DF}(t)$ and $R_{n,r}^{AF}(t)$ for DF and AF, respectively. These rates depend on the channel gains of direct links between $n$ and $r$, the gain of direct link between $n$ and $d$ and the gain of direct link between $r$ and $d$ denoted by $H_{n,r}$, $H_{n,d}$.

![Diagram](image_url)
and $H_{r,d}$ respectively. More specifically, if each relay node $r$ has the maximum power limit of $P'_r$ for its transmissions, the achievable rates $R_{n,r}^{DF}(t)$ and $R_{n,r}^{AF}(t)$ can be calculated by the following equations [4].

$$R_{n,r}^{AF}(t) = \frac{W_n}{2} \log_2 \left( 1 + \frac{|H_{n,d}(t)|^2 P_n}{N_0 W_n} + f \left( \frac{|H_{r,d}(t)|^2 P'_r}{N_0 W_n} \right) \right)$$

$$R_{n,r}^{DF}(t) = \frac{W_n}{2} \min \{ \log_2 (1 + \frac{|H_{n,r}(t)|^2 P_n}{N_0 W_n}) \}$$

where

$$f(x,y) := \frac{xy}{x+y+1}. \quad (4)$$

Note that the achievable rate for DF in (3) is for the case where a repetition code is used at the relay node i.e., the relay node is using the same codebook as the source is using [4], [5].

Therefore, we can see that by having the channel gains of all one hop communication links, the achievable rates for all the direct links ($R_{n,d}(t), n = 1, 2, ..., N$) and cooperative links ($R_{n,r}^{DF}(t)$ or $R_{n,r}^{AF}(t) n = 1, 2, ..., N, r = 1, 2, ..., R$) are determined at each time slot. Henceforth, we assume that all the cooperative communications are in DF mode. As we explained before, the channel gains are assumed to be fixed during each time slot and are allowed to vary from time slot to time slot. This assumption is usually used in modelling of a slow Rayleigh fading wireless system. We represent the channel state of the system as the set of channel gains of all one hop links in the systems, i.e.,

$$CS(t) = \{H_{n,d}(t), H_{n,r}(t), H_{r,d}(t), \forall n \in N, \forall r \in R\}$$

Note that we allow the channel gains over different links at any time slot $t$ be arbitrarily correlated. However, it is assumed that the channel state $CS(t)$ evolves with time according to a finite state, irreducible Markov chain.

Packet are assumed to have the same length which is equal to $L$. Therefore, the number of packets that can be transmitted successfully through the direct link $\ell_{n,d}$ and the cooperative link $\ell_{n,r}^{DF}$ are equal to

$$w_{n,d}(t) = \left\lfloor \frac{R_{n,d}(t)}{L} \right\rfloor, \quad w_{n,r}^{DF}(t) = \left\lfloor \frac{R_{n,r}^{DF}}{L} \right\rfloor \quad (5)$$

respectively.

We assume that a centralized controller at each time slot determines each user’s mode of operation (direct or cooperation) and if it is in cooperation mode, which relay must be selected for cooperation such that the long-term throughput region of the system is maximised. This is accomplished based on the information about the channel state and also the queue length process $X(t)$.

### B. Stability, Stability Region and Throughput Optimal Policies

The notions of stability, stability region and throughput optimal policies in network stochastic control comes from the works [17]-[20]. We will start with the definition of strong stability in queueing networks [19]. Consider a discrete time single queue system with an arrival process $A(t)$ and service process $\mu(t)$. Let $X(t)$ represent the queue length process at time slot $t$. Obviously, it evolves with time according to the following rule:

$$X(t) = (X(t - 1) - \mu(t)) + A(t) \quad (6)$$

where $(-)^+$ outputs the term inside the brackets if it is non-negative and zero otherwise.

**Definition 1**: A queue satisfying the conditions above is called strongly stable if it has bounded time averaged expected backlog [19], i.e.

$$\lim_{t \to \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} E[X(\tau)] < \infty \quad (7)$$

Definition 1 can be extended to a queueing network as follows [19].

**Definition 2**: A queueing system is called to be strongly stable if all the queues in the system are strongly stable. Specifically, for a network consisting of $N$ queues, the system is strongly stable if the time averaged expected aggregated backlog in the network is bounded, i.e.

$$\lim_{t \to \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \sum_{n=1}^{N} E[X_n(\tau)] < \infty \quad (8)$$

Consider the queueing system in definition 2 with $N$ queues. Assume that the arrival rate to each queue $n$ is represented by $\lambda_n$ and therefore, the arrival rate vector is denoted by $\lambda = (\lambda_1, \lambda_2, ..., \lambda_N)$. A resource allocation (relay selection) policy $\pi$ is said to stabilize the system if by applying policy $\pi$ the system is strongly stable. Let $\Lambda_{\pi}$ represent the closure of the set of arrival rate vectors for which $\pi$ can stabilize the system. $\Lambda_{\pi}$ is called the stability region for policy $\pi$. Now, consider the union of the stability region of all the possible policies and let us denote it by $\Lambda$, i.e., $\Lambda = \bigcup_{\pi} \Lambda_{\pi}$. $\Lambda$ is called the network stability region (also called network layer capacity region in literature). In other words, the network stability region is the closure of the set of all arrival rate vectors for which there exists a policy that can stabilize the network. Note that the network stability region is independent of the resource allocation policy and in fact is a specific characteristic of any network. A resource allocation policy $\pi^*$ is called throughput optimal if it can stabilize the system for all the arrival rate vectors strictly inside the network stability region. In other words, $\pi^*$ is throughput optimal if its stability region coincides with the network stability region.

### III. Throughput Optimal Relay Selection Policy

In this section, we will introduce the throughput optimal relay selection policy for the model described in section II-A.
A. Optimal Policy

Let us denote the indicator variables \( I_{n,d}(t) \) and \( I_{n,r}(t) \) as the following:

\[
I_{n,d}(t) = \begin{cases} 
1 & \text{user } n \text{ transmits directly to } d \text{ at time } t \\
0 & \text{oth.}
\end{cases}
\]

\[
I_{n,r}(t) = \begin{cases} 
1 & \text{user } n \text{ selects relay node } r \text{ at time } t \\
0 & \text{for cooperation}
\end{cases}
\]

In fact, characterization of a relay selection policy is equivalent to determination of indicator variables \( I_{n,d}(t) \) and \( I_{n,r}(t) \) at each time slot \( t \). Consider the relay selection policy \( \Theta \) which determines the indicator variables \( I_{n,d}(t) \) and \( I_{n,r}(t) \) at each time slot \( t \) by solving the following optimization problem.

**Problem P:**

Maximize \[
\sum_{n=1}^{N} X_n(t) \left( w_{n,d}(t)I_{n,d}(t) + \sum_{r=1}^{R} w_{n,r}(t)I_{n,r}(t) \right) \]

s.t. \[
\sum_{n=1}^{N} I_{n,r} \leq 1 \quad \forall r = 1, 2, \ldots, R
\]

\[
I_{n,d} + \sum_{r=1}^{R} I_{n,r} \leq 1 \quad \forall n = 1, 2, \ldots, N
\]

\[
I_{n,r} \in \{0, 1\}, \quad I_{n,d} \in \{0, 1\} \quad \forall n \in \mathcal{N}, \forall r \in \mathcal{R}
\]

**Proposition 1:** The relay selection policy \( \Theta \) stabilizes the system for all the arrival rate vectors strictly inside the stability region \( \Lambda \). The proof is based on applying Lyapunov stability techniques and skipped here because of space limitation.

The above proposition states that the solution to the optimization problem \( \text{P} \) at each time slot determines the optimal decision variables \( I_{n,d}(t) \) and \( I_{n,r}(t) \) such that the stability of the system is guaranteed for all arrival rate vectors strictly inside the stability region.

B. Bipartite graph Representation of Policy \( \Theta \)

Problem \( \text{P} \) is an integer programming problem. In general, integer programming problems are NP-hard. However, the above problem has the structure of a maximum weighted matching problem in bipartite graphs [21]. Consider the weighted bipartite graph \( G(V_1, V_2, E) \) which consists of two sets of vertices \( V_1 \) and \( V_2 \) and a set of edges \( E \). \( V_1 \) is in fact, the set of all users and therefore \( |V_1| = N \). The set of vertices \( V_2 \) is \( V_2 = \mathcal{R} \cup D \) where \( D = \{d_1, d_2, \ldots, d_N\} \). Each \( d_n, 1 \leq n \leq N \) represents direct transmission from user \( n \) to node \( d \). Therefore, to each vertex \( d_n \), there is just one incident edge which is originated from vertex \( n \in V_1 \). However, other vertices in \( V_2 \) (i.e., vertices in \( \mathcal{R} \)) are connected to all the vertices of \( V_1 \) through different edges. The edges weights \( e \) are defined as the following:

- \( e_{n,d_n}(t) = X_n(t)w_{n,d}(t) \quad \forall n = 1, 2, \ldots, N \)
- \( e_{n,r}(t) = X_n(t)w_{n,r}(t) \quad \forall n = 1, 2, \ldots, N \quad \forall r = 1, 2, \ldots, R \)

Figure 2 illustrates the structure of the bipartite graph \( G \). We can easily verify that the optimal solution to problem \( \text{P} \) is equivalent to finding the maximum weighted matching in the weighted bipartite graph \( G \). Note that at each time slot, there may be more than one maximum weighted matching for graph \( G \). In those cases, ties are broken arbitrarily.

Fortunately, finding the maximum weighted matching in a bipartite graph is not NP-hard and has polynomial time algorithms. Hungarian algorithm is the most well known algorithm in this area [22]. The computational complexity of this algorithm is \( O((\min(|V_1|, |V_2|))(\max(|V_1|, |V_2|))^2) \). We used this algorithm to solve the optimization problem \( \text{P} \) in our simulations.

IV. SIMULATION RESULTS

In this section, we will compare the performance of the throughput optimal relay selection (ITORS) policy with the corresponding performance of two other policies using simulations. The other two policies are called iTORS (instantaneous Throughput Optimal Relay Selection) and NC (Non-Cooperative) policy. In the following, we will describe these two policies in detail.

At each time slot \( t \), iTORS policy assigns the relay nodes according to the solution of the following optimization problem.

**Problem \( \text{P}' \):**

Maximize \[
\sum_{n=1}^{N} w_{n,d}(t)I_{n,d}(t) + \sum_{n=1}^{N} \sum_{r=1}^{R} w_{n,r}(t)I_{n,r}(t)
\]

s.t. \[
\sum_{n=1}^{N} I_{n,r} \leq 1 \quad \forall r = 1, 2, \ldots, R
\]

\[
I_{n,d} + \sum_{r=1}^{R} I_{n,r} \leq 1 \quad \forall n = 1, 2, \ldots, N
\]

\[
I_{n,r} \in \{0, 1\}, \quad I_{n,d} \in \{0, 1\} \quad \forall n \in \mathcal{N}, \forall r \in \mathcal{R}
\]

Note that problem \( \text{P}' \) is very similar to the optimization problem \( \text{P} \) except that the queue length parameters \( X_n(t) \) were dropped. We call this policy as instantaneous Throughput Optimal Relay Selection (iTORS) since at each time slot, it attempts to maximize the instantaneous throughput of the current time slot without considering the queue lengths.

The other policy is the Non-Cooperative (NC) policy which does not use the relay nodes for transmission to \( d \). In other words, each user uses just the direct communication link to \( d \) in order to transmit its packets to \( d \).
In our simulations, we considered 12 users \( (N = 12) \) each having a separate orthogonal channel with the bandwidth of \( W = 100 KHz \) for its transmissions. There are also 8 relay nodes \( (R = 8) \) in the system with fixed locations. All the nodes (users and relay nodes) are located in a grid cell structure with the size of \( 11 \times 11 \) \(([-5, 5] \times [-5, 5]) \). The access point is located at \((0, 0)\). Figure 3 shows the cell structure used in the simulations.

The users are represented by black circles, the relay nodes by white circles and the access point is shown by a square in the middle. The users are initially distributed randomly on the grid but they can move with equal probabilities to the possible directions north, south, east and west at the beginning of each time slot. We do not allow a user to move to \((0,0)\) since the distance between the user and access point will be zero.

All the users and relay nodes transmit with the same level of power \( P \). We will set \( P_{\text{min}} = 20 \text{dB} \). The parameters \( H_{i,j}(t),\forall i \in N \cup R, \forall j \in R \cup d \) represent the effect of both location of users and relays as well as the shadowing and fading effects. Therefore, they can be written as

\[
H_{i,j}(t) = \frac{h_{i,j}(t)}{D_{i,j}^\alpha(t)}
\]

where \( D_{i,j} \) is the distance between nodes \( i \) and \( j \) and \( \alpha \) is the path loss exponent. The parameters \( h_{i,j}(t) \) denotes the effects of shadowing, fading, etc. at time slot \( t \). We used \( \alpha = 6 \), and modelled \( h_{i,j}(t) \) as i.i.d. multinomial random processes which takes the values \( \{0.05, 0.1, 0.2, 0.5\} \) with equal probabilities of 0.25. As we mentioned earlier, the relay nodes are fixed and located at the points \((i, j)\) where \( i, j \in \{-2, 0, 2\}\) except \((0,0)\). With the above setting, the channel state \( CS(t) \) evolves according to a finite state Markov chain. The arrival processes to all the queues at each time slot are assumed to follow a Poisson distribution and packet length is set to 1024 bits.

We considered four cases in which we change the arrival rates to the users and plot the average total queue length versus arrival rate. In the first case we simulated a symmetric system in which the arrival rates to all the users are the same. Figure 4 shows the average total queue occupancy versus arrival rate. In the second case, we considered asymmetric arrivals to the queues. More specifically, we increase the arrival rate to each user according to its index, i.e. if the arrival rate to user 1 is \( \lambda \), the arrival rate to user \( n \) is \( n \lambda \). Figure 5 depicts the average total queue occupancy versus \( \lambda \). In the third case, we assume that the arrival rates to all the queue are the same. However, we force users 9, 10, 11 and 12 to move on the border of the grid. Figure 6 reflects the average total queue occupancy versus arrival rate. The forth case is the mixture of cases two and three, i.e. we will consider asymmetric arrival to the users (like the second case, users arrival rates are proportional to their index) and also force users 9, 10, 11 and 12 to move just on the border of the cell. In this case, users 9, 10, 11 and 12 are not only very far from the access point, but also have very high arrival rates. Figure 7 illustrates the average total queue occupancy versus arrival rate \( \lambda \) for this case.

As we can observe from the figures, the stability region of TORS policy is larger than the iTORS policy and NC policy. Note that both the cooperative policies TORS and iTORS performs better than the NC policy. The reason is that by using the benefit of relaying, the cooperative policies TORS and iTORS provide higher transmission rates rather than what NC provides. More specifically, relaying helps the users very far from the base station to transmit their packets to the base station with higher rates. The cost of this rate improvement is to consume power at the relay nodes.

From the figures, we also observe that TORS has better performance than iTORS in terms of average queue occupancy and stability region. Equivalently, we can conclude that TORS performs better than iTORS in terms of long run average throughput. The reason to this fact is that iTORS does not consider the queue length process in the optimization \( P \). Therefore, although iTORS tries to maximize the instantaneous throughput of the system at each time slot, it is probable in iTORS to assign some relays to some empty queues or queues with few packets. This situations happens specially when a user is very close to some relay nodes or base station for a long time. Such a user has high service rate for its
we observed that the proposed throughput optimal policy outperforms the other two policies.

REFERENCES


Fig. 6: Average queue occupancy versus arrival rate in case 3

Fig. 7: Average queue occupancy versus arrival rate in case 4

V. CONCLUSIONS

In this paper, we introduced a throughput optimal relay selection policy for multiuser cooperative wireless networks. The proposed policy can stabilize the system for all the arrival rate vectors strictly inside the network stability region. We used simulations to compare the performance of the proposed policy with that of an instantaneous throughput optimal policy and a non-cooperative policy in terms of average backlog or equivalently average queueing delay. From the simulations