Distributed Spectrum Allocation of Delay-sensitive Users over Multi-user Multi-carrier Networks

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Abstract—**In this paper, we study the distributed spectrum allocation for autonomous users transmitting delay-sensitive information over a wireless multi-carrier network. Because there is no central moderator in the network, we propose a distributed information exchange protocol for users to exchange information, which considers their heterogeneous traffic and priorities. Based on this information exchange, we propose different prediction models that enable users to dynamically select the optimal channels for transmission. We consider two types of users – myopic and foresighted users. A myopic user selects channels passively based on the previous actions of other users, while a foresighted user applies the prediction models to select the channels in a foresighted manner. Depending on the composition of myopic users and foresighted users in the network, we define two operation modes – the homogeneous mode and the leader-follower mode. The performance of different prediction models is analyzed in each mode. Based on this analysis, we show that in the leader-follower mode, the most sophisticated model leads to the best performance. Nevertheless, in the homogeneous mode, the simplest prediction model leads to better performance. The analysis and simulation results show that in a competitive network, users should avoid adopting highly sophisticated models because this will prevent them from accurately learning each other's channel selection behavior. The proposed models and formulation can be extended to other multi-channel communications scenarios.**

Index Terms—**Distributed spectrum allocation, delay-sensitive users, multi-carrier networks, model-based prediction**

I. INTRODUCTION

Bandwidth-intensive multimedia applications, e.g. video conferencing and multimedia streaming, are proliferating in homes, offices, campuses, etc. A majority of these applications is delay-sensitive, i.e. undesirable quality degradation will result if packets are missing their delay deadlines. While numerous papers address the problem of efficient transmission of delay-sensitive applications [10][11], they do not often consider how to transmit such applications over multi-carrier networks. In this paper, we focus on the distributed spectrum allocation problem for delay-sensitive users over multi-user multi-carrier networks.

Conventionally, the spectrum is allocated by a central moderator (e.g. an access point or a base station) [8], which acquire information about all users. This centralized spectrum allocation becomes very complicated and potentially inefficient when the number of users and available channels becomes very large. The high computational complexity, distributed nature of information, and high delay associated with acquiring each user's information can prevent the moderator from computing the centralized solution accurately, in a timely manner. Thus, distributed solutions are necessary to deal with this limitation.

In this paper, we propose a new solution to perform distributed channel selection using a model-based spectrum allocation strategy. This differs from the related work in several ways. First, we assume that the users are cooperative as they do not deviate from pre-determined protocols [6]. Instead of jointly pursuing the global optimum of the overall utility [2], users autonomously select their channels to maximize their own utilities in a distributed manner. The interference problem in [3] is not considered by modeling a collision avoidance data transmission [6]. Without applying payoff-based strategies [4], users adopt different models to determine the impact of other users on the packet loss rate as the channel selection basis. By using these models, we show how users can predict the channel condition to approach the expected minimum packet loss rate.

In order to evaluate the impact from other users, we adopt a queuing analysis. In this analysis, the average packet loss rate is determined by all users' channel selection results (actions) and traffic specification [9]. Since users require each other's information to compute the packet loss rates, information exchange between users becomes essential. Hence, we provide an information exchange scheme where users can exchange the traffic specification and actions. Based on the information exchange, users can acquire sufficient information to calculate their packet loss rates. Moreover, based on this information, we propose models for users to model each other's strategies using different types of models.

We define two types of users. One type is the myopic users, who use the myopic model to assign the spectrum. The other type is the foresighted users. They adopt the predictive models for channel selection. Based on the composition of users' types, we define two *operation modes*, e.g. the *leader-follower mode* [1] (which consists of one foresighted and several myopic users) and the *homogeneous mode* [6] (where all the users are foresighted). In this paper, we focus our analysis on these two modes of operation to study various scenarios.

The paper is organized as follows. In Section II, we provide the adopted multi-carrier network model. The expected packet loss rates are quantified. Model-based spectrum allocation strategies are discussed in Section III. Different user operation modes are proposed and analyzed in Section IV. The centralized solution is provided as a comparison of the distributed strategies. The simulation results and discussions

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are presented in Section V and the conclusions are drawn in Section VI.

II. THE MULTI-CARRIER NETWORK MODEL

In this section, we model the generalized multi-carrier network. The concept of users' prioritization in [6] is adopted. Without losing generality, we classify the users as high priority users and normal users. We study the spectrum allocation problem of the normal users in the network because the channel selection strategies of those users can be adapted to users with any priority level in the network.

A. *Considered Network Settings*

The considered network consists of high priority and normal users accessing various frequency channels in a distributed manner.

- *High Priority Users*, e.g. licensed users, have the access right to specific channels without being interfered by other users [8]. We also assume that they do not change their assigned carrier frequencies.
- *Normal Users*, or simply called the *users* in this paper, can transmit packets in different channels by switching their carrier frequencies. They are only allowed to access a channel if high priority users do not actively transmit their packets using these channels. We assume that the traffic of high priority users can preempt the transmission for normal users.
- *Frequency Channels* include the control channels and the traffic channels. Traffic channels are used for data transmission, while users initiate their transmissions and exchange their information in separate control channels.

Our used model for the distributed spectrum allocation by the autonomous users is modeled as follows.

- *Users:* we assume that there are N normal users in the network. x_i is denoted as the i^{th} user and $\boldsymbol{x} = \{x_1, x_1, ... x_N\}$ is the set of all normal users. x_{-i} denotes all users except x_i .
- *Channels:* There are M traffic channels and several control channels in the network. The j^{th} traffic channel is denoted as f_j . Users are assumed to be able to transmit packets in all traffic channels.
- *Actions:* The actions are the channel selection results of users. The action $a_{ij} = 1$ denotes that x_i transmits its packets in f_j . Otherwise, $a_{ij} = 0$. $\boldsymbol{a}_i$ and $\boldsymbol{A}$ denote $[a_{i1}, a_{i2}, ..., a_{iM}]^T$ and $[\boldsymbol{a}_1, \boldsymbol{a}_2 ..., \boldsymbol{a}_N]$, respectively.

B. *Utility Definition*

The average packet loss rate is selected as the users' utilities, since we are focusing on the delay-sensitive applications, and the packet loss rate will account for packets missing their delay deadlines. The incoming rate of the delay-sensitive data depends on the source characteristics and it is assumed to be Poisson distributed as in [7] and [11]. The packets are assumed to be transmitted in virtual queues as in [6]. Hence, there is no interference between different users. The packet loss rate of a user is calculated as follows.

- *Normalized Loading from High Priority Users:*

We denote x_j^P as the high priority users in f_j . The first and second moment normalized loading in each channel is $\rho_{Pj} = \lambda_{Pj} \cdot E[X_{Pj}]$ and $\rho_{Pj}^2 = \lambda_{Pj} \cdot E[X_{Pj}^2]$. λ_{Pj} is the packet rate of x_j^P in f_j . $E[X_{Pj}]$ and $E[X_{Pj}^2]$ are their first and second order average service time.

- *Normalized Loading of Normal Users:*

The packet length and required bit rate of x_i is denoted as l_i and b_i . The packet rate is $\lambda_i = \dfrac{b_i}{l_i}$. x_i 's physical transmitting rate and packet error rate in f_j are T_{ij} and p_{ij} . We assume that user x_i repeatedly retransmit its packets if the packet is received erroneously [7]. Using this assumption, the transmitting time becomes the geometric random variable. Thus, the average packet service time for x_i in f_j is $E[X_{ij}] = \dfrac{l_i}{T_{ij}(1 - p_{ij})}$ and the second moment of service time is $E[X_{ij}^2] = \dfrac{l_i^2 (1 + p_{ij})}{T_{ij}^2 (1 - p_{ij})^2}$. The x_i 's first and second moment loading in f_j is defined as $\rho_{ij} = a_{ij} \cdot (\lambda_i \cdot E[X_{ij}])$ and $\rho_{ij}^2 = a_{ij} \cdot (\lambda_i \cdot E[X_{ij}^2])$.

- *Packet Loss Rate of the User:*

Based on the mean value analysis in [7], we derive the average waiting time $E[W_j]$ for x_i in f_j :

$$E[W_j] = \frac{\rho_{Pj}^2 + \sum_{n=1}^{N} \rho_{nj}^2}{2(1 - \rho_{Pj})(1 - \rho_{Pj} - \sum_{n=1}^{N} \rho_{nj})} \tag{1}$$

The corresponding average delay $E[D_{ij}]$ for x_i in f_j is the summation of the average waiting time in the channel and the average service time for x_i in the channel.

$$E[D_{ij}] = E[W_j] + E[X_{ij}] \tag{2}$$

For delay-sensitive users, the packets fall behind the delay deadline is worthless. Given the delay deadline d_i for x_i , the approximate packet loss rate of x_i in f_j is given here:

$$P_{ij} = \Pr(D_{ij} > d_i) = (\rho_{Pj} + \sum_{n=1}^{N} \rho_{nj}) \cdot \exp(-\frac{(\rho_{Pj} + \sum_{n=1}^{N} \rho_{nj}) \cdot d_i}{E[D_{ij}]}) \tag{3}$$

Note that P_{ij} indicates the packet loss rate while p_{ij} indicates the packet error rate. From above expression for ρ_{ij} and ρ_{ij}^2 , we know that P_{ij} is a function of $\boldsymbol{A}$. By introducing the notation $\boldsymbol{a}_{-i}$ where $\boldsymbol{a}_{-i} = [\boldsymbol{a}_1, ..., \boldsymbol{a}_{i-1}, \boldsymbol{a}_{i+1}, ..., \boldsymbol{a}_N]$. The packet error rate can be thus represented as $P_{ij}(\boldsymbol{a}_i, \boldsymbol{a}_{-i})$, to indicate de dependency on the user's actions, but also the competing users' actions in that particular channel. This coupling effect complicates the channel selection problem, because the channel selections of all the users are inter-related.

C. *Decentralized Spectrum Access Problem*

The target of spectrum allocation of delay-sensitive users is to minimize their own packet loss rate. The average packet loss rate of user x_i is $\sum_{m=1}^{M} a_{im} \cdot P_{im}(\boldsymbol{a}_i, \boldsymbol{a}_{-i})$. Hence, the optimal action for x_i is

$$\begin{aligned} \boldsymbol{a}_i^* &= \arg\min_{\boldsymbol{a}_i} \sum_{m=1}^{M} a_{im} \cdot P_{im}(\boldsymbol{a}_i, \boldsymbol{a}_{-i}) \\ &\text{s.t. } a_{im} \in \{0,1\},\ \forall \mathrm{m} \in \{1,2,...,M\},\ \sum_{m=1}^{M} a_{im} = 1 \end{aligned} \tag{4}$$

III. MODEL-BASED SPECTRUM ALLOCATION

In Section II, the packet loss rate of the user is derived. According to equations (1) to (4), the packet loss rate depends on other users' transmission parameters, including data type, bit rate, channel selection, etc. Without this information, x_i cannot model the traffic condition and optimally select a channel for transmission. Thus, we propose an information exchange scheme, where users exchange information. Using the exchanged information, users can build models of their competing users and implement the model-based spectrum allocation. Note that in this paper we assume that users are truthfully declaring their information.

A. Information Exchange

Information exchange is essential for users to build models about their competing users in the various channels, in order to be able to select the optimal channel access, which will minimize their experienced packet loss.

Based on equations (1) to (4), the overall information required from x_i to build the model includes required bandwidth (bit rate) b_i, average packet length l_i, physical transmission rate $\boldsymbol{T}_i = [T_{i1}, T_{i2}, ..., T_{iM}]^T$, average packet error rate $\boldsymbol{p}_i = [p_{i1}, p_{i2}, ..., p_{iM}]^T$, and channel selection $\boldsymbol{a}_i$. This information is divided into: the traffic specification and the channel selection.

♦ *Traffic Specification for* x_i

Users in our network setting should announce their traffic specifications to other users as in [9], which include the bandwidth (bit rate), packet length, physical transmission rate, and average packet error rate, denoted as $\boldsymbol{TS}_i = [b_i, l_i, \boldsymbol{T}_i, \boldsymbol{p}_i]$. Similarly, $\boldsymbol{TS}_{-i}$ and $\boldsymbol{TS}$ denote x_{-i} and $\boldsymbol{x}$'s traffic specifications. The parameters in $\boldsymbol{TS}_i$ can be separated into two types.

- *Source information:* The parameters b_i, l_i, and $\boldsymbol{T}_i$ are the source traffic specifications. These parameters can stay unchanged by deploying the scheduling techniques in [12].
- *Channel information:* Additionally, the packet error rate $\boldsymbol{p}_i$ is determined by the dynamic channel environment. We model the dynamic characteristic of f_j, p_{ij} as a random variable.

♦ *Channel Selection (action):*

In this paper, we will consider the channel selection as the actions (i.e. $\boldsymbol{a}_i$) available to the users in the multi-carrier network. Using their a priori knowledge about x_{-i}, x_i can construct different prediction models about its competitors' channel access and select the optimal channel $\boldsymbol{a}_i$. This is discussed next in detail.

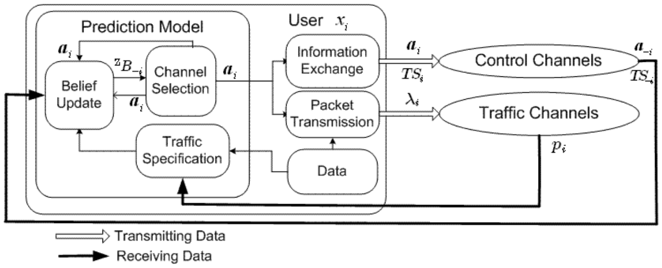

Fig. 1. The model-based channel selection with information exchange

B. Channel Selection Strategies

We assume that the users can change channels at each time slot. At time slot t, x_i's action is denoted as $\boldsymbol{a}_i^t$ and $\boldsymbol{x}$'s actins are denoted as $\boldsymbol{A}^t$.

The objective of a channel selection strategy for x_i at each time t is to find the optimum spectrum allocation $\boldsymbol{a}_i^{t*}$, which can minimize the average packet loss rate in equation (4). Unfortunately, at time $t-1$, other users' action $\boldsymbol{a}_{-i}^t$ are not available for x_i. Hence, x_i has to predict possible $\boldsymbol{a}_{-i}^t$ based on the available information, which includes the previous actions, $\boldsymbol{A}^{t-1}$,…, $\boldsymbol{A}^1$, and users' traffic specification $\boldsymbol{TS}$. The prediction is based on the models constructed by x_i. The prediction result is defined as x_i's *belief* in $\boldsymbol{a}_{-i}$, denoted as ${}^{\mathrm{Z}}\boldsymbol{B}_{-i}^{t-1}$, where Z is x_i's prediction model. Equation (4) can be reformulated as:

$$\begin{aligned} \widehat{\boldsymbol{a}}_i^{t*} &= \arg\min_{\boldsymbol{a}_i^t} \sum_{m=1}^{M} a_{im}^t \cdot P_{im}(\boldsymbol{a}_i^t, {}^{\mathrm{Z}}\boldsymbol{B}_{-i}^{t-1}) \\ &\text{s.t. } a_{im}^t \in \{0,1\},\ \forall \mathrm{m} \in \{1,2,...,M\},\ \sum_{m=1}^{M} a_{im}^t = 1 \end{aligned}, \tag{5}$$

where $\widehat{\boldsymbol{a}}_i^{t*}$ is the predicted optimum action for x_i. Equation (5) shows that the modeling results in ${}^{\mathrm{Z}}\boldsymbol{B}_{-i}^{t-1}$ plays the most important role in our study. The general algorithm for the model-based spectrum allocation is presented next.

```
Algorithm        Model-based Spectrum Allocation Strategy for $x_i$
Input            Deploy the traffic specification $\boldsymbol{TS}$ in eq. (5)
Initialization   Initiate the belief ${}^{\mathrm{Z}}\boldsymbol{B}_{-i}^0$
Repeat
    Step 1.      Use ${}^{\mathrm{Z}}\boldsymbol{B}_{-i}^{t-1}$ in eq. (5) to select the predicted best
                 action $\widehat{\boldsymbol{a}}_i^{t*}$.
    Step 2.      Transmit packets and exchange $\boldsymbol{a}_i^t$
    Step 3.      Update time $t := t + 1$
    Step 4.      Update ${}^{\mathrm{Z}}\boldsymbol{B}_{-i}^{t-1}$.
Until            If $\boldsymbol{TS}$ changes, exchange $\boldsymbol{TS}$ and go to Input.
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Below, we discuss how x_i selects the channels based on different models.

1. Myopic Model ($\mathrm{Z} = MP$)

The channel selection strategy using a myopic model is also called the *best response strategy*. In this case, x_i does not predict how other users will behave, but rather reacts on their previous actions $\boldsymbol{a}_{-i}^{t-1}$. Denote the myopic model as $Z = MP$. Then, the update of the model can be denoted as:

$${}^{MP}\boldsymbol{B}_{-i}^{t-1} = \boldsymbol{a}_{-i}^{t-1}.$$

2. *Empirical Frequency Model ($Z = EF$)*

The simplest method to predict the random actions is to compute the empirical frequency of actions in each channel. The concept empirical frequency is similar to the fictitious play in [5]. The probabilistic characteristics of $\boldsymbol{a}_{-i}^{t}$ is modeled as the arithmetic mean of $\boldsymbol{a}_{-i}$ from time 1 to time $t-1$:

$$\begin{aligned} {}^{EF}\boldsymbol{B}_{-i}^{t-1} &= \frac{1}{t-1}(\boldsymbol{a}_{-i}^{1} + \boldsymbol{a}_{-i}^{2} + \ldots + \boldsymbol{a}_{-i}^{t-1}) \\ &= \frac{1}{t-1}\cdot \boldsymbol{a}_{-i}^{t-1} + \frac{t-2}{t-1}\cdot {}^{EF}\boldsymbol{B}_{-i}^{t-2} \end{aligned} \tag{6}$$

Hence, the update of ${}^{EF}\boldsymbol{B}_{-i}^{t-1}$ can be computed from ${}^{EF}\boldsymbol{B}_{-i}^{t-2}$ directly. The empirical frequency model can be summarized in the following two steps:

Initiate ${}^{EF}\boldsymbol{B}_{-i}^{0}$.

Update ${}^{EF}\boldsymbol{B}_{-i}^{t-1}$ based on equation (6).

3. *Conditional Empirical Frequency Model ($Z = CE$)*

In the empirical frequency model, the update of the belief path is according to the empirical frequency. On top of the empirical frequency model, we can further exploit the structure of the queuing model to reflect the *coupling effect* we observed in Section II. According to equation (4), x_i's packet loss rate, and hence channel selection $\boldsymbol{a}_i$, are influenced by all the other users' actions $\boldsymbol{a}_{-i}$. Similarly, $\boldsymbol{a}_{-i}$ are also influenced by $\boldsymbol{a}_i$. Therefore, $\boldsymbol{a}_{-i}^{t}$ and its belief ${}^{CE}\boldsymbol{B}_{-i}^{t-1}$ is conditioned on $\boldsymbol{a}_{-i}^{t}$. Accordingly, we can denote ${}^{CE}\boldsymbol{B}_{-i}^{t-1}$ as ${}^{CE}\boldsymbol{B}_{-i}^{t-1}(\boldsymbol{a}_i^t)$.

Define $\boldsymbol{e}_j$, $j \in \{1,\ldots,M\}$ and $\boldsymbol{a}_i^t = \boldsymbol{e}_j$ represents that x_i select f_j at time t. Given $\boldsymbol{y} \in \{\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_M\}$, the update of ${}^{CE}\boldsymbol{B}_{-i}^{t-1}$ is:

$${}^{CE}\boldsymbol{B}_{-i}^{t-1}(\boldsymbol{y}) = \frac{I(\boldsymbol{a}_i^{t-1}, \boldsymbol{y})}{\sum_{t'=1}^{t-1} I(\boldsymbol{a}_i^{t'}, \boldsymbol{y})} + \frac{\sum_{t'=1}^{t-1} I(\boldsymbol{a}_i^{t'}, \boldsymbol{y}) - 1}{\sum_{t'=1}^{t-1} I(\boldsymbol{a}_i^{t'}, \boldsymbol{y})} {}^{CE}\boldsymbol{B}_{-i}^{t-2}(\boldsymbol{y}), \tag{7}$$
$$\boldsymbol{y} = \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_M$$

where I is the indicator function. $I(\boldsymbol{a}_i^t, \boldsymbol{y}) = 1$ means that $\boldsymbol{a}_i^t = \boldsymbol{y}$; otherwise, $I(\boldsymbol{a}_i^t, \boldsymbol{y}) = 0$. The conditional empirical frequency model considers both the empirical frequency calculation as well as the coupling effects among users and thus creates a more sophisticated model than the empirical frequency model. The conditional empirical frequency model can be expressed as:

Initiate ${}^{CE}\boldsymbol{B}_{-i}^{0}(\boldsymbol{a}_i^1 = \boldsymbol{y})$, $\boldsymbol{y} = \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_M$.

Update ${}^{CE}\boldsymbol{B}_{-i}^{t-1}(\boldsymbol{a}_i^t)$ based on equation (7).

IV. NETWORK OPERATION MODELS

In Section III, several channel selection strategies are proposed based on different levels of modeling. Different strategies chosen by each user will influence the channel selection behavior of other users. We classify the users as foresighted and myopic users. A foresighted user is the user who uses the predictive models to allocate the spectrum while a myopic user applies the myopic model to select the channel. Different compositions of users in the network result in different performances and thus, require further study. The composition of users in the network will determine *the operation modes*. We first discuss two operation modes and subsequently provide the centralized solution as a comparison.

A. Leader-Follower Mode

The leader-follower mode [1] consists of one foresighted and several myopic users. It evaluates the performance of the foresighted strategies in Section III. The leader applies a foresighted transmission action, while all the other users are taking myopic actions. By comparing the performance of different types of leaders, using different foresighted transmission strategies, we can know the prediction ability of different predictive models.

B. Homogeneous Mode

We also consider the homogeneous mode, where each user is competing for resources by using a similar decision process and using similar models.

C. Centralized Solution

We would like to compare the performance of our distributed solutions with a centralized solution, where a fully-informed moderator selects the channels for all the users, in such a way the overall packet loss rate in the network is minimized. The performance of his solution can provide us the lower bound for the overall packet loss rate over the network. The optimization problem solved by the network moderator is formulated as

$$\begin{aligned} &\text{minimize} && \sum_{n=1}^{N}\sum_{m=1}^{M} a_{nm}^{t} \cdot P_{nm}(\boldsymbol{a}_n^t, \boldsymbol{a}_{-n}^t) \\ &\text{subject to} && a_{nm}^t \in \{0,1\}, n = 1,\ldots,N, m = 1,\ldots,M \\ &&& \sum_{n=1}^{M} a_{nm}^t = 1, n = 1,\ldots,N \end{aligned} \tag{8}$$

V. SIMULATION

In this section, we examine the performance of the different spectrum allocation strategies. The strategies in the two different operation modes are compared. We provide the centralized solution as a comparison for the distributed solutions when the users and channels are few, since the complexity of computing the centralized solution grows exponentially with the numbers of users and channels.

A. Simulation Environment

We consider 25 network users and 15 available channels. However, as mentioned before, this network size is too large for the centralized solution. Hence, we provide an additional setting with 7 network users and 4 available channels in order to compare the proposed distributed solutions with the centralized solution. The traffic is selected to be heavy-loaded in these channels since channel selections in light-loaded network do not provide meaningful results of how good the various strategies are, since the performance is always relatively good. The simulation parameters are given in the next table.

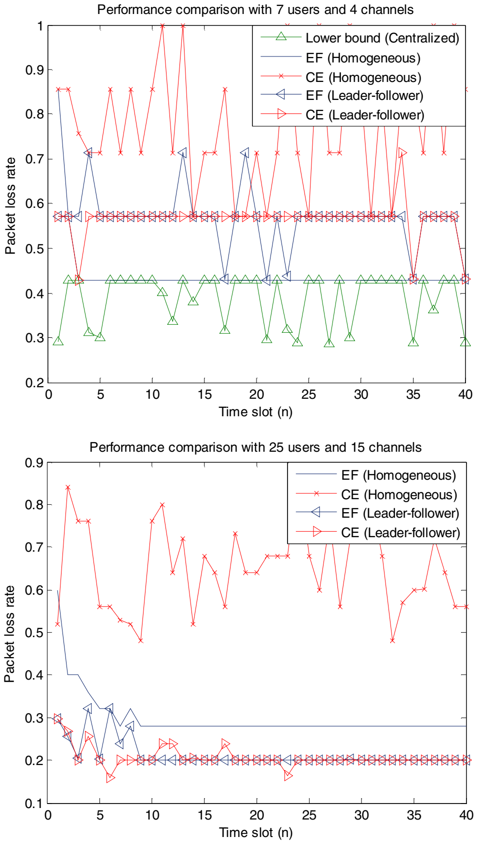
Table 1 Used parameters

Network users N	Available channels M	Transmission rate T_i	High priority user normalized loading ρ_{Pj}	Second order loading ρ_{Pj}^2
25 (7)	15 (4)	4 MHz	0.2~0.3,	10^{-4}

Initial value of belief $^{Z}B_{-i}^{0}$		Packet length L_i	Delay deadline d_i	Required bandwidth B_i
Conditional	Unconditional	1000 Bytes	0.5 Sec	1~2Mbps
1/15 $\forall f_j, \forall a_{ij}$	1/15 $\forall f_j$			

B. *Results*

The simulation result presented in Fig. 2 shows that the performance of the CF model performs slightly better than the EF model in the leader-follower mode. However, the CF model performs much worse than the EF model in the homogeneous mode. This is because when users are applying highly sophisticated models at the same time, it is harder for other users to predict each other's behavior.


Performance comparison with 7 users and 4 channels

Performance comparison with 25 users and 15 channels

Fig. 2 Resulting packet loss rates for various scenarios. The upper figure is a small scale network (includes the centralized solution) and the lower is a large scale network.

VI. CONCLUSION

In this paper, we address the problem of distributed channel selection by autonomous and delay-sensitive users in multi-carrier wireless networks. We propose a prioritized queuing model to model the channel access of delay-sensitive users in the network. Depending on the composition of myopic users and foresighted users in the network, we discuss two different user operation modes. The simulation results show that the performance of the conditional empirical frequency model is very poor in the homogeneous operation mode. Hence, we conclude that considering the prediction complexity and accuracy, the empirical frequency model is a good choice for channel selection in a both homogeneous and leader-follower network. For networks with only foresighted users, the performance is degraded because these foresighted users prevent each other from predicting their actions accurately, in a dynamic network setting. The remaining work of how users determine their channel selection models is further discussed in [13].

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