[Proposal] Network Selection with LTE-Unlicensed and WiFi: A Game Theoretic View

Nikhil Garg

I. Introduction

Network selection is a well-studied problem in which users (UEs) must decide to connect to one of several spatially co-located networks to maximize their data rate. As heterogeneous and multi-RAT networks become more common in the coming years, network selection by the user (as opposed to user association handled by the network) will play a role in optimizing wireless systems. In particular, when LTE-Unlicensed develops, it will often be co-located both in space and in frequency with WiFi networks, and UEs must decide to which network to connect.

The optimal network selection strategy for each user is a function of the network characteristics and the behaviors of other UEs because UEs must share resources if connected to the same network. This problem lends itself well to a game theoretic analysis, and many papers adopt such an approach [1].

In this project, we will analyze the network selection process for co-located LTE-U and WiFi networks as an infinitely repeated game between the UEs. We plan to make the following contributions

1) Find an optimal downlink network selection strategy for UE network selection for co-located WiFi and LTE-U, assuming no information about the strategies of other UEs or when there are no other UEs in the network.
2) Find a mixed strategy Nash Equilibrium for a base case network with 1 LTE-U BS, 1 WiFi BS, and 2 UEs equidistant to the two BSs, parametrized by the LTE-U coexistence mechanism and WiFi performance characteristics.
3) For each of the cases discussed in Section IV, evaluate the performance of different strategies against other UEs (including those following the same or other strategies) through simulation.

II. Related Work

Game theory for network selection, along with the general network selection problem, is well-studied in various contexts and assumptions, though little used in practice by consumer devices[1]. In [2], the authors present a reinforcement learning mechanism within an evolutionary game framework for users competing for bandwidth across multiple networks. The paper studies network dynamics and convergence time, the time after which users do not change their network choice. In [3], the authors study the general class of network selection games and find analytic bounds on the quality of the Nash Equilibria (in terms of the price of anarchy) for several selection cost functions. Many other works also study network selection through the context of games [1], [4].

This project is distinct from the existing game theoretic network selection literature in several ways. First, to the best of our knowledge, no literature looks at the case in which the networks themselves are also co-located in space and frequency. Thus, the optimal strategies are parametrized by the network coexistence mechanisms. Second, our approach integrates strategies in which the network selections do not "converge," but rather may keep changing indefinitely. Third, our project will characterize the performance beyond Nash Equilibria. In practice, UEs cannot force other nodes to follow the strategy that achieves the Nash Equilibrium because there may be constraints that prevent certain UEs from carrying out the optimal (Nash Equilibrium-wise) strategy. For example, certain UEs may not be able to connect to the LTE-U network because of either device limitations or economic reasons. Thus, the strategy that achieves the Nash Equilibrium will not maximize performance in practice.

III. Model

A. *Infinitely Repeated, Finite-size Game*

Players. UEs = $\{i | i \in \{1 \dots N_{UE}\}\}$

Actions. At time-step t, each UE chooses which BS to connect to.

Utilities. The utility function is the downlink rate received from the BS to which the player is connected at time t. Each player seeks to maximize its own time-averaged utility in the repeated game.

Strategies. Strategies to be examined include: best `SNR` association, pre-determined to a single network/BS, stochastic with distribution determined on network parameters, and various learning algorithms. An objective of this project is to characterize the performance of various strategies in this game. The goal is to determine whether naive or commonly used algorithms perform similarly to smarter methods.

[1] for example, the hightest rated WiFi selection app for Android utilizes only user-inputted priorities and signal strength thresholds (https://play.google.com/store/apps/details?id=com.pintacdesign.bestwifi&hl=en)

TABLE I
POSSIBLE DESIGN CHOICES FOR EACH NETWORK COMPONENT

LTE-U Coexistence	**BSs (Num & Location)**	**UEs (Num & Location)**	**WiFi Parameters**	**LTE-U Parameters**
Duty cycle with parameter K (synchronized or unsynchronized), as described in [5].	1 LTE-U, 1 WiFi BS at [-1, 0] and [1, 0], respectively	1 to 2 UEs at origin. For the base case ($N_{UE} = 1$), each strategies ability to learn the network is determined.	Channel Bandwidth = [20 MHz, 40 MHz, 80 MHz, 160 MHz]	Channel Bandwidth = [20 MHz, 40 MHz]
Always On	Poisson Point Process on grid with λ_{WiFi} and λ_{LTE-U}, respectively	N_{UE} UEs evenly spaced between [-1,0] and [1,0]	Path loss parameter α	Path loss parameter α
CSMA/Listen Before Talk (LBT)		Poisson Point Process on grid with λ_{UE}	Different MCS schemes, MIMO configurations, etc	

B. LTE-U Coexistence

The most contentious (and among the most important) open issues in the LTE-U standards and implementations is how (or whether) LTE-U will attempt to coexist with co-located WiFi (and other unlicensed) networks. Li et al. present and analyze three coexistence mechanisms: "Always On," "Duty Cycle with parameter K," and "Listen Before Talk with Random Backoff" [5]. The authors find that the coexistence mechanism in use significantly affects network performance.

This work will assume that the LTE-U nodes employ a duty cycle, parametrized by K, while the WiFi nodes use the standard CSMA/CSMA/LBT model. In this case, each LTE-U node at each time t transmits with probability K. WiFi nodes then transmit if the channel is locally clear (resolving conflicts within themselves through a pre-determined ordering). This model is used and justified in [5].

As a possible extension, other coexistence mechanisms will be considered.

C. Downlink Capacity

The simple path loss model with rayleigh fading will be used, with parameters determined to match an indoor network (such as a large office space floor with cubicles). Shannon capacity with frequency splitting will be used to determine downlink rates (agent utilities), though parameters may be fit to closely model the rates of various common WiFi configurations.

IV. SPECIFIC CASES TO BE STUDIED

Table I contains a few of the numerous network design choices that can be made, leading to an exponentially large set of networks to analyze. In this project, a subset of these possibilities will be analyzed.

For the primary goal, LTE-U will coexist using a duty cycle parametrized by K, and downlink rate will be determined using the freespace path loss model, Shannon capacity, and the bandwidths for each channel. Then, the following cases will be studied:

1) 1 WiFi and 1 LTE-U BS are placed at $[1, 0]$ and $[-1, 0]$, respectively. One UE at the origin determines which BS to connect to at each time step.
2) 1 WiFi and 1 LTE-U BS are placed at $[1, 0]$ and $[-1, 0]$, respectively. Two UEs at the origin determine which BS to connect to at each time step.
3) 1 WiFi and 1 LTE-U BS are placed at $[1, 0]$ and $[-1, 0]$, respectively. N UEs evenly spaced on the line between $[-1, 0]$ and $[1, 0]$ compete with various strategies.

Time permitting, some of the following extensions may be included:

1) WiFi and LTE-U BSs will be placed on the grid by Poisson Point Process (PPP) with λ_{WiFi} and λ_{LTE-U}, respectively, with WiFi using CSMA to coexist with itself. UEs placed by a PPP with λ_u will use various strategies.
2) In the base case, users pay no penalty for switching networks. In this extension, a cost function (in which a UE "sits out" some amount of time when it switches networks) will be added to reflect overhead/connection delay.
3) The network parameters (bandwidth, modulation schemes, predicted data rates, CSMA cutoffs, signal propagation, etc) will be detailed and chosen to closely match real networks or industrial simulations of LTE-U/WiFi networks.
4) Network selection strategies under different LTE-U coexistence mechanisms (such as LBT) and duty cycle parameter K will be studied.
5) (Long term) Build an Android application that uses a well-performing learning algorithm found in this work for network selection among different WiFi networks and, eventually, LTE-U and WiFi networks.

V. DELIVERABLES

The central goal for the project is to determine whether traditional network selection mechanisms (static selections, SINR based approaches, or even the mixed strategy that achieves the Nash Equilibrium) are effective in maximizing downlink data rates for co-located wireless networks. For the simple cases, explicit mixed strategies will be found. In all cases, each strategy's performance in a competitive setting will be evaluated through simulations. Time permitting, the sensitivity of strategy performance to network parameters will also be shown, along with performance in the cases listed as possible extensions above.

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