Chapter 10
A Non-cooperative TV White Space Broadband Market Model for Rural Entrepreneurs

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10.1 Introduction

Access to broadband Internet services for rural households and businesses in the world over has generally been truly lacking. Broadband internet according to the United Nations [17] delivers access to the sum of human knowledge as it opens doors to the future. It helps lift the world's poorest out of poverty, brings the benefits of education and health care closer to rural and remote populations, and delivers social and economic benefits to all. However, from the service providerss (rural entrepreneurs) perspective [5], there have traditionally been few incentives to provide access to low-income customers, who are presumed to have limited demand for new services, and to rural and remote regions, where the cost of extending or upgrading facilities and services is assumed to be higher than expected revenues. To this end, wireless technologies have generally proved to be a far more cost effective option for serving remote and rural areas, the core challenges are (a) the scarcity and cost of spectrum licenses, and (b) base station infrastructure deployment and operational expenses. However, technological innovations, many of which were initially designed for other applications, are now creating opportunities to reduce costs and/or increase revenues in these populations. A notable innovation in this regard,is that of Wireless Mesh Networks (WMNs) which have been touted as a candidate technology set for the ubiquitous connectivity of the end user. The WMNs basically comprise of wireless mesh routers and mesh clients as well as an endowed capability to dynamically self organize as well as self configure to the degree that the network nodes are able to establish and maintain connectivity among themselves. The WMN are characterized by low-upfront costs, ease of maintenance, robustness as well as reliable service coverage. WMN have found suitable application solutions spanning

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in the range of broadband home networking, community and neighborhood networks, enterprise networking, community, building automation, public safety etc. In spite of the numerous applications, the growth, performance and spread of WMN has been hampered by several limitations such as limited spectrum availability [23]. Limited spectrum availability is a consequence of the adoption of the Industrial, Scientific and medical (ISM) band for backbone communications. The adoption in turn leads to a scenario of devices existent in this particular band affecting the WMN with the case in point being nearby WLANS and bluetooth devices. Consequently the limited spectrum in this particular band cannot cope with the limited network applications leading to artificially high spectrum prices. Pursuant to understanding the high spectrum prices, findings on the empirical spectrum measurements have revealed a gross underutilization of licensed spectrum, called White Space. Moreover with the transition from analog to digital Television has also led to the release of large chunks of spectrum referred to as TV White Space (TVWS). Certainly, overcoming spectrum scarcity of the WMNs and enhancing the performance of these networks requires the full harnessing and exploitation of TVWS. TVWS exploitation can however be made feasible by leveraging on the technological development in Smart Radio (SM). Smart radio (SM) has the ability to observe, learn, optimize, and adapt transmission parameters according to the ambient environment. Moreover, the flexibility of this device renders feasible spectrum sharing between licensed (Primary Users-PUs) and unlicensed (Secondary Users-SU) services. Consequently Dynamic spectrum Access (DSA) is made possible when secondary users are permitted to opportunistically access licensed spectrum. DSA is thus a promising approach for reusing the underutilized spectrum as the spectrum is shared among the PUs and SUs improving flexibility and efficiency in the process [9]. Moreover, studies on SM based networks have revealed spectrum marketing as an effective way to realize spectrum sharing with economic modeling being among the main fundamental issues [1]. In tackling economic modeling where a scarce resource such as spectrum is concerned, game theory has often been adopted to model the behaviors of rational and self interested entities [19]. AQ1

10.2 Motivation, Contribution and Organization of Chapter

Game theory is widely regarded as a useful tool implorable in the analysis of resource allocation as well as mathematical models of conflict and cooperation among rationally intelligent decision makers from a microeconomic perspective. Specifically, this tool is applicable in scenario of dynamic spectrum sharing, particularly with regards to the planning and decision making in a smart radio based System. The system environment comprises multiple entities that objectively interact to achieve self interests. Game theory thus provides the conflict resolution mechanism so as to satisfy all concerned entities.

In this chapter, we investigate the problem of spectrum sharing and pricing within the context of a smart mesh wireless network using a game theoretic oligopoly framework from microeconomics. The oligopoly is contextual defined as a market scenario in which a small number of enterprise producers independently compete with each other in their quest to maximize profits either through controlling and varying the quantity or via price setting. The quantity/price offered by a particular enterprise producer will in general, likely impact on the profit of other enterprise producers. Guided by the law of supply and demand in economics, if a single enterprise producer offers increased quantities of its commodity, the market price drops and subsequently reduces the profits of other enterprise producers. Specifically a Bertrand game model is used to maximize the payoff of individual enterprise producers.

In applying this Bertrand model of competition to spectrum sharing and pricing in Smart mesh wireless network system, we analytically model several licensed telecommunication enterprises competing with each other to offer services to unlicensed enterprise systems so as to maximize profits under Quality of Service (QoS), constraints of licensed users. The QoS in question is a composite metric assembled from a combination of delay [13] and throughput QoS performance metrics. The spectrum demand of the secondary routers is derived from a quadratic utility function dependant on quality of transmission in the available spectrum as well as substitutability. The substitutability depicts the flexibility with which the secondary router is able to switch to different frequency spectra offered by various licensed enterprises. Ultimately a numerical analysis is carried out so as to evaluate our analytic model's performance in allocating TV White space. The rest of the chapter is organized as follows. Section 10.3 presents the related work in the literature. The general characteristics of the Bertrand oligopoly model. The Bertrand game model for spectrum sharing under competition is presented in Sect. 10.4. Numerical analysis of the model is carried out in Sects. 10.5 and 10.6 concludes the chapter.

10.3 Related Work

A number of studies regarding pricing in networking issues have been presented in the last few years. The efforts have concentrated largely on characterizing quality of service parameters (QoS), such as delay, jitter, packet loss and throughput on the operating point of a wireless network system. Moreover these efforts have attempted to demonstrate how the operating point can be set a priori by appropriately choosing the parameter. However, with the advent of smart radios and subsequent emergence of wireless mesh networks as an economical solution to support broadband services, efforts have intensified in the quest for efficient resource utilization. An important development in pursuit of the efficient spectrum utilization has been the introduction of Authorized Shared Access (ASA) as an enabler to unlock access to additional frequency bands for mobile broadband under individual licensed regimes. The ASA approach has been extended as Licensed Shared Access (LSA) to involve license holders authorizing secondary usage of spare spectrum within their licensed bands but under tight controls to prevent any disruption. The approach was conceived with a view to supporting business cases for the build-out of mobile broadband network infrastructure, where it is both economically and technically feasible [4, 7]. A major benefit of LSA is the guarantee of controlled as well as predictable Quality of Service (QoS) for both incumbent spectrum users and the LSA licensees by considering a couple of entities involved in the sharing agreement. Moreover the LSA notion provides an effective and harmonized way to utilize existing assets and achieve economies of scale by making International Mobile Communications (IMT) bands available worldwide with existing user equipment and minimal modifications to the infrastructure [11]. A successful trial with a live Long Term Evolution (LTE) network in the 2.3 GHz shared band has been achieved in Finland in April 2013. A major drawback of this technology is that it excludes concepts such as opportunistic spectrum access, secondary use or secondary service where the applicant has no protection from the primary users. Clearly the opportunistic spectrum access (OSA) approach is an alternative to the ASA/LSA approach which also contributes significantly to the efficient use of spectrum. According to [8] Opportunistic and dynamic spectrum access is a novel access model designed to extract unused spectrum from allocated but underutilized spectrum, supporting newcomer traffic without affecting existing owners. The approach implores the use of smart radios to identify unused portions of licensed spectrum, and utilize that spectrum without adverse impact on the primary user licensees. This approach renders feasible an abundantly higher level of spectrum utilization and near zero-deployment time [16] in cooperative and non-cooperative wireless network systems with coexistence of Primary and Secondary users.

To this end, both cooperative [15] and non-cooperative network systems have been scrutinized. Non cooperative networks systems characterize competition both among licensed (PUs) spectrum holders and between non-license holders (SUs). The authors in [22] explain network throughput as a more important concern for the emerging multi-hop wireless networks such as wireless mesh networks. These efforts are complimented in [21] in which throughput maximization using a negotiation based algorithm is extended to a non-cooperative scenario. Alternative QoS parameters such as delay, have also been considered [24] when the authors assert that, supporting delay sensitive real-time traffic such as video and voice over wireless mesh networks is a challenging and attractive task [18]. Considers both parameters and acknowledges the spectrum allocation problem as requiring maximization of throughput and also a minimization of the delay. To this end, dynamic mesh network systems need to consider the trade-off between immediate costly transmission and low cost but delayed transmission [6]. The idea of a trade-off between throughput and delay has been studied in [9] for an ad-hoc mesh network. Clearly the concept needs to be considered for smart wireless mesh network scenario which are a future generation network candidate solution.

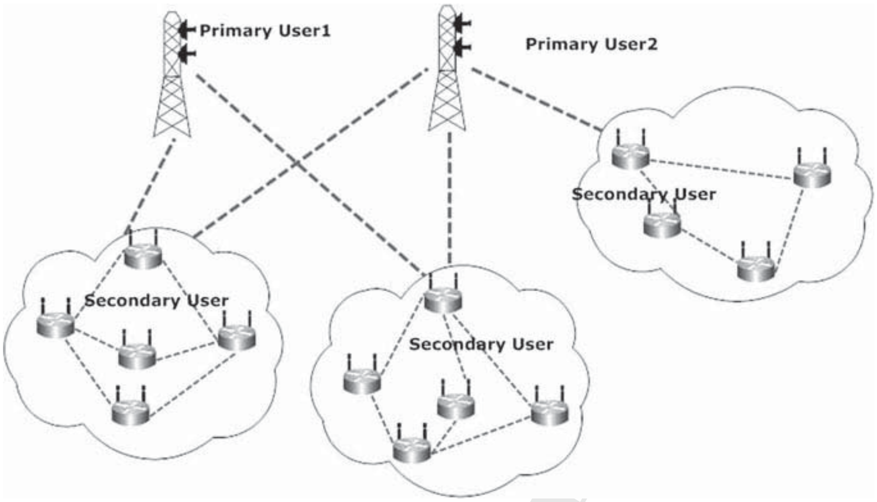

Fig. 10.1 Smart mesh network

10.4 TV White Space Market Pricing Model

We consider a system of non-cooperative Mesh routers within the context of spectrum management wherein licensed routers which are called primary users, compete to offer services to an unlicensed system of routers called secondary users. From a primary user's point of view, the cost of offering a service to a secondary user is modeled as a function of QoS degradation. This interaction between the primary and secondary users as well as the outcome can best be understood using game theory by generalizing it as a game. The solution of the game is obtained by imploring John Nash's concept of a 'Nash Equilibrium' (NE) [12] which is an organizing concept in game theory. This concept represents the optimal solution in such interactive games.

10.4.1 System Model

Our system model envisages the existence of N primary users (Fig. 10.1 (where N = 2)) operating on different frequency spectra and a multitude of secondary users aspiring to share the precious spectrum resource with the primary users in question. To this end, we introduce P_i as the tariff/pricing policy and QoS guaranteed by primary user i with all other symbols defined in Table 10.1. Then each of the secondary users is motivated to subscribe at this given tariff so as to attain a QoS sufficient to satisfy individual needs. In the process, the secondary users make use of adaptive modulation for transmissions by exploiting channel state information. With this type of modulation, transmission rate is influenced by channel quality while the

Table 10.1 Notation summary

Symbols	Description
λ_i	Arrival rate
Q_i	Spectrum size (secondary user)
W_i	Spectrum size (primary user)
$P^{(i)}$	Price
P_j	Price
$k_i(p)$	Spectral efficiency (primary users)
$k_i(s)$	Spectral efficiency (secondary users)
C_i^D	Cost function (delay)
C_i^T	Cost function (throughput)
d_i	Constant (elasticity)
D_i	Delay
ζ	Composite metric
ε	Constant = 0.5
Λ	Constant = 0.5
ψ	Utility
W_i	Primary user spectrum
Δ	Substitutability
$\phi_i(T)$	Profit (throughput)
$\phi_i(D)$	Profit (delay)
$\phi_i(TD)$	Profit (composite)
y_i	Channel quality (player i)
y_j	Channel quality (player j)
T_i	Throughput
n	Number of users
β	Constant

bit error rate must be maintained at target levels. Consequently, the spectral efficiency of transmission for a secondary user i is according to [3] given by:

$$k_i = log2(1 + Ky_i) \tag{10.1}$$

where

$$K = \frac{1.5}{ln(\frac{0.2}{BER_i^{tar}})} \tag{10.2}$$

On being allocated the spectrum, the secondary user i transmits with spectral efficiency k_i with its demand being a function of transmission rate in the allocated frequency spectrum as well as price charged by the allocating primary user.

10.4.2 QoS Measure and Cost

In the Next generation telecommunications industry, systems are required where cost is dependent on QoS. Subsequently in our system model, the QoS performance of a primary user is degraded when spectrum is shared with the secondary user. This translates to cost function being considerate of the QoS performance of the primary user. Ultimately, we consider the use of a composite QoS performance metric derived from a combination of the delay and Throughput QoS metrics. Moreover we define and introduce the individual QoS Performance measures metrics and then finally combine them into a single composite QoS measure. We begin with the average delay QoS measure obtained from [14] and defined as:

$$D_i(Q_i) = \frac{1}{2}\frac{\lambda_i}{(k_i^{(p)}(W_i - Q_i)^2 - \lambda_i k_i^{(p)}(W_i - Q_i)} \tag{10.3}$$

with the symbols meaning as given in the Table 10.1, it is worth to note that $k_i^{(p)}$ $(W_i - Q_i)$, denotes the service rate. Thus the average delay is a function of the total spectrum due to the primary user, the spectrum demand from the secondary user, the arrival rate and most importantly the spectral efficiency which subsequently leads to channel quality. The cost function is defined as:

$$C_i^D = dD_i(Q_i) \tag{10.4}$$

Intuitively, the cost function is a function of the average delay QoS measure and given its dependence on channel quality the cost can thus be subsequently varied through the channel quality parameter. Furthermore conscious and cognizant of the coexistence between the primary and secondary networks we focus on throughput as an alternative QoS measure. The achievable throughput in a secondary network system is given by [10] as:

$$T(Q_i) = \sum_{i=1}^{N} \frac{\beta Q_i}{\sqrt{nlogn}} \tag{10.5}$$

The throughput measure thus is a function of the spectrum demand by the secondary and the number of nodes. The spectrum demand is also dependent on spectral efficiency which in turn is a function of channel quality. Consequently the cost due to the throughput measure is expressed as:

$$C_i^T = dT_i(Q_i) \tag{10.6}$$

The implication of this cost function is that, the cost can again be made to vary with channel quality. We proceed to bring together the average delay and throughput to form a composite metric which we conveniently refer to as the composite QoS metric. The Composite QoS Measure is expressed as:

$$\zeta(Q_i) = \varepsilon(D(Q_i) + \Lambda(T(Q_i) \tag{10.7}$$

The relation between Λ and ε is given by:

$$\Lambda = 1 - \varepsilon$$

Consequently, the cost due to this composite QoS metric is

$$C_i^{\zeta} = d\zeta(Q_i) \tag{10.8}$$

Since both metrics forming the composite metric are dependent on the channel quality, this Composite QoS parameter can also be varied by correspondingly varying the channel quality. To this end, we conveniently defer this exercise to Sect. 10.5.

10.4.3 Quadratic Utility Function

The utility gained by the secondary users makes it possible to ascertain the level of spectrum demand. A quadratic utility function defined as in [20]:

$$\Psi(\mathbb{Q}) = \sum_{i=1}^{M} Q_i {k_i}^s - \frac{1}{2}\left(\sum_{i=1}^{M} Q_i^2 + 2\Delta \sum_{i=1}^{M} Q_i Q_j\right) + J \tag{10.9}$$

where

$$\mathbb{Q} = Q_1, \ldots, Q_i, \ldots, Q_M \tag{10.10}$$

and J is given by:

$$J = -\sum_{i=1}^{M} P_i Q_i \tag{10.11}$$

The spectrum substitutability is included in the utility function by way of parameter ∇. This parameter permits the secondary users to switch between frequencies depending on the offered price. The demand function of the secondary user is obtainable from differentiating the utility function w.r.t Q_i as follows:

$$\frac{d\psi(\mathbb{Q})}{dQ_i} = 0 \tag{10.12}$$

The demand function is the size of shared spectrum that maximizes the utility of the secondary user given the prices offered by the primary service

Table 10.2 Bertrand game formulation

Entity	Description
$Players$	Primary users
$Strategies$	Price per unit of spectrum (P_i)
$Payoffs$	The payoff for each player is the profit of primary user

$$Q_i = \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} \tag{10.13}$$

The revenue generated from the demand function is a function of the demand function and the relevant price.

$$R_i = Q_i P_i \tag{10.14}$$

10.4.4 Bertrand Game Model

The Bertrand oligopoly is formulated as in Table 10.2.

The profit due to the composite metric is obtainable from the revenue less the cost of the TV white space. Thus Profit

$$profit(\phi_i^{TD}) = Revenue(Eqn\ 10.14) - Cost(Eqn\ 10.18) \tag{10.15}$$

$$\begin{aligned}\phi_i^{TD} &= Q_i P_i - d(\varepsilon(D(Q_i) + \Lambda(T(Q_i)) \\ &= \frac{P_i k_i^s - P_i^2 - P_i \delta(k_j^s - P_j)}{1 - \Delta^2} - d(\varepsilon(D(Q_i) + \Lambda(T(Q_i))\end{aligned} \tag{10.16}$$

To obtain Nash Equilibrium (NE), the equation

$$\frac{d\phi_i^{TD}}{dP_i} = 0 \tag{10.17}$$

for all i. Therefore

$$\begin{aligned}\phi_i^{TD} = \frac{P_i k_i^s - P_i^2 - P_i \delta(k_j^s - P_j)}{1 - \Delta^2} - (\frac{d\lambda_i}{(2W_i - Q_i)^2 - 4\lambda(W_i - Q_i)} \\ + \frac{dk_i^s - P_i - \Delta(k_j^s - P_j)}{(1 - \Delta^2)(\sqrt{nlogn}}\end{aligned} \tag{10.18}$$

Table 10.3 System parameters

Parameter	Value
$Primaryuserspectrum$	5 (MHz)
BER	10^{-4}
$Trafficarrivalrate$	1 (Mbps)
d	1
$Channelqualityspan$	10–20 (dB)
λ_i	4
y_1	15
y_2	18
Δ	0.4
P_2	1
$Primaryusers$	2

AQ2 The derivative thus becomes

$$0 = \frac{k_i^s - 2P_i - \Delta(k_j^s - P_j)}{1-\Delta^2} + \frac{\frac{d\lambda_i(4Q_i-\lambda_i)}{1-\Delta^2}}{(2Q_i^2 - 2Q_i\lambda_i)^2} - \frac{1}{(1-\Delta^2)\sqrt{nlogn}} \tag{10.19}$$

where

$$Q_i = W_i - \frac{k_i^s - P_i - \Delta(k_j^s - P_j)}{1-\Delta^2} \tag{10.20}$$

10.5 Performance Evaluation

10.5.1 Parameter Setting

The parameters are set as in Table 10.3.

10.5.2 Numerical Analysis

In this section, we present numerical results to validate the efficacy of our TVWS broadband market model developed within the context of low cost Smart wireless Mesh network.

Figure 10.2 depicts the demand function of the secondary user, the revenue, cost and profit of the primary user under various pricing options. As the first primary user increases its price, the secondary user responsively demands a small amount of spectrum owing to a decrease in the utility of the allocated spectrum. This is

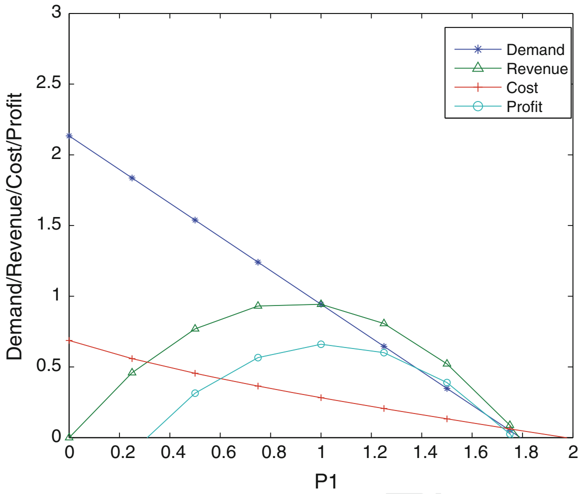

Fig. 10.2 Demand-revenue-cost and profit

clearly shown by the negative gradient line which represents the demand function of the secondary user. However, this demand function behavior impacts on the cost for the primary user. This is to say, the cost for the primary user decreases with a decrease in the demand function this therefore translates to a larger amount of residual spectrum corresponding to smaller delay. The revenue and profit functions of the primary user are all traversing a parabolic path as depicted on the same graph. Clearly both functions in question initially increase with an increase in price up to the optimal point where both functions begin to show a decline in both the revenue and profit. To this end, the primary user is able to sell a larger amount of spectrum to the secondary user at a smaller price thereby giving an increase in revenue as well as profit. Conversely, when the price increases, a small amount of spectrum is sold due to a decrease in the level of demand by the secondary user ultimately resulting in dwindling profit. Certainly an optimal price exists upon which the profit is maximized and this denotes an apparent best response for the corresponding primary user. This best response is further investigated wherein the best responses of the two primary users are analyzed. In Fig. 10.3, we analyze the best response functions of the two primary users under variable channel quality for the secondary user. When the channel quality increases, the spectrum demand correspondingly increases. The individual primary user then consequently offers a higher price. However, the best response function graphs intersect at some point called Nash Equilibrium. We analyze this Nash equilibrium under varied channel quality. Figure 10.4 depicts a scenario in which the Nash equilibrium is higher for higher channel quality, this emanates from an increased demand of spectrum by the secondary user. Moreover, we realize that the channel quality offered by one individual primary user impacts on the other individual primary user. This is to say, channel quality offered by one primary user

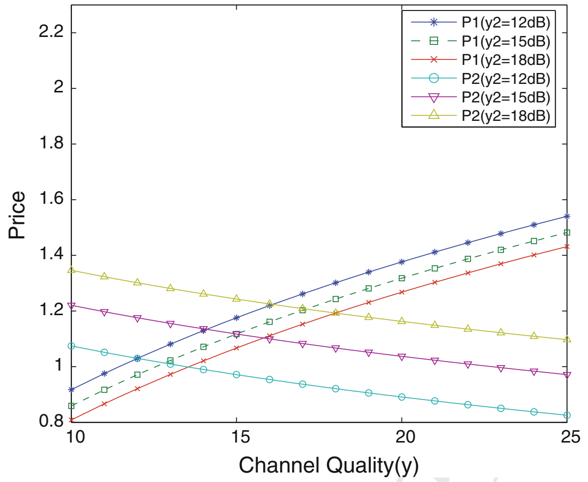

Fig. 10.3 Channel quality

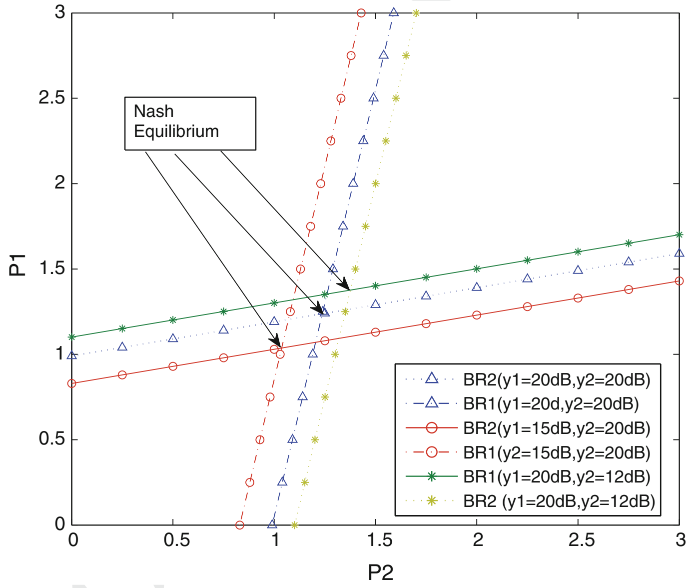

Fig. 10.4 Best response

impacts the strategy adopted by the other primary user. Consequently when the demand for spectrum from an individual player is varied, the other player adapts the price so as to maximize profit.

10.6 Conclusion

In this chapter a non cooperative TVWS analytic business model for rural telecommunications entrepreneurs for broadband internet provision has been developed. The analytic model is based on a proposed composite QoS performance constraint which is assembled from the Delay and Throughput QoS constraints. The performance of the analytic model is evaluated within the context of a smart wireless mesh network wherein routers that have licensed spectrum lease out the spectrum to unlicensed routers/clients. The interaction of these licensed routers with unlicensed client routers is modeled as a bertrand oligopoly. In the oligopoly the licensed routers compete to sell their spectrum to clients using price as the strategy. The optimal responses of the routers (PUs) are analyzed as well the dependence on variable channel quality. When the channel quality increases spectrum demand from SUs also increases triggering an increase in price. Further planned efforts in this regard will involve extension of these efforts from networking engineering to traffic engineering as in [2]. This approach could possible help in simultaneous routing of delay sensitive and real-time traffic.

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