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ABSTRACT

Leveraging on recent TV white space communications developments in regulations, standards initiatives and technology, this paper considers a suitable next generation network comprising of two primary users (PUs) that compete to offer a service to a group of secondary users (SUs) in the form of mesh routers that belong to different entrepreneurs participating in a non-cooperative TV white space trading. From a game theoretic perspective the non-cooperative interaction of the PUs is viewed as a pricing problem wherein each PU strives to maximize its own profit. Subsequently the problem is formulated as a Bertrand game in an oligopolistic market where the PUs are players who are responsible for selling TV white spectrum in the market while the SUs are the players who are the buyers of the TV white spectrum. The PUs strategise by way of price adjustment, so much such that SUs tend to favour the lowest price when buying. The inter-operator agreements are based on the delay and throughput QoS performance metrics respectively. A performance evaluation of both models is comparatively performed with regards to parameters such as cost, generated revenue, profit, best response in price adjustments and channel quality. The throughput based analytic model fares better in terms of providing channel quality as it has a better strategy which is a decreased price value.

Keywords — White Spaces, Smart Radio, Non-cooperative Game Theory, Broadband Market, Traffic Engineering.

1. INTRODUCTION

Entrepreneurs and entrepreneurship are increasingly playing a vital transformative role in the rural telecommunications economy. Modern developmental trends in wireless technologies are not only providing various opportunities for entrepreneurs, but also overhauling the character of entrepreneurship by pioneering new business models. A welcome development in technology advancement has been that of wireless mesh networks. Increasingly Wireless Mesh Networks (WMNs) have indisputably and justifiably been touted as

a candidate technology that is set to facilitate ubiquitous connectivity to the end user. The WMNs comprise wireless routers and clients as well as an endowed ability to dynamically self organize, self configure to the extent of nodes in the network being able to establish and maintain connectivity among themselves. The candidature of this technology justifiably emanates from its characteristic low upfront cost, ease of maintenance, robustness as well as reliable service coverage. Indisputably, WMNs have found applications ranging from broadband home networking, community and neighbourhood networks, enterprise networking, building automation and other public safety areas etc. However, while the currently deployed WMNs provide flexible and convenient services to the clients, the performance, growth and spread of WMNs is still constrained by several limitations [2] such as limited usable frequency resource. This emanates from a scenario of WMNs in which the unlicensed Industrial, Scientific and Medical (ISM) band has mostly been adopted for backbone communications. A consequence of this adoption is that the WMN is affected by all other devices in this particular ISM band eg. nearby WLANs and Bluetooth devices. Ultimately, the limited bandwidth of the unlicensed bands cannot cope with the evolving network applications and this has led to artificially high spectrum prices. To this end, empirical occupancy measurements have revealed a gross under utilization of licensed spectrum, called white space, while on the other hand, the analog to digital Television transition has made available large chunks of spectrum called TV White Space. Clearly, the urge to exploit white spaces is irresistible as it provides an opportunity to significantly enhance the performance of WMNs. Pursuant to this cause, Smart Radio (SM) a device that has the capability to sense the environment and automatically adjust the configuration parameters is proposed as a viable solution to the frequency reuse problem. Moreover a fundamental application of SM is that of Dynamic Spectrum Access (DSA) whose technique allow SM radio to operate in the best available channel. Specifically, the SM radio technology will enable the users to [3](i) determine which portions of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (ii) select the best available channel (spectrum management), (iii) coordinate access to this channel with other users (spectrum sharing), and (iv) vacate the channel when a licensed user is detected (spectrum mobility). A second constraint to the spread and growth of WMNs has been a case of many rural areas being still not deemed economically viable by operators. Service providers claim this is a result of dispersed populations, cost of roll-out and lack of power infrastructure remains a hindrance to the efforts of service providers [5]. Ultimately dynamic spectrum access (DSA) wireless technology enables rural broadband internet service

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providers to access lower-frequency spectrum, reducing the cost of network deployment and operation. This will translate to service providers, for the first time being able to implement profitable business models and will provide consumers and businesses in rural areas with affordable and sustainable service [4]. According to [6], a combined decrease in the cost and increasing pervasiveness of access will have a positive social and economic impact in rural and remote areas. Moreover with SWMN holding the key to the last mile, the challenge is that of catalysing both decreased costs and increased access. An approach to this challenge involves leveraging on the common knowledge that telecommunications networks profit from network effects. The bigger the market the higher value it holds giving the incumbent (primary user) telecoms operator a massive strategic advantage. Essentially, the limited spectrum available to mobile services translates to a constrained number of competitors in the market. To this end, in many areas the effect has been a stagnation of competition and undesirably high telecommunications costs. Thus increasing spectrum availability, in particular to new entrants is likely to lead to more competition and healthier markets. In this paper, we concentrate our efforts on modelling the competition in the rural telecommunication market in which the spectrum sharing technique is employed within the context of a low cost Smart Wireless Mesh Network (SWMN) for the provision of broadband internet services. More specifically, we extend our efforts in [7], to a non-cooperative scenario in which network nodes belonging to different licensed wireless providers (PUs) engage in spectrum trade while competing to offer services to a secondary service and simultaneously striving to maximize profits. Thus our contribution is as follows: (i) we develop an analytic model for the design of a SWMN from a game theoretic perspective. Our SWMN is formulated as a Bertrand duopoly market in which two PUs from varied wireless service providers compete with each other with regards to their prices so as to offer services to a secondary service. In the process the PUs are aiming to maximize their profits under quality of service (QoS) constraints. (ii) adapt to TV white space the model [15] (iii) model the cost of sharing spectrum as a function of QoS degradation with the throughput as QoS performance measure. (iv) Comparative evaluate the models in terms of the profit, cost, revenue, price strategy and channel quality. The rest of the paper is organized as follows. Section II, presents the related work which subsequently leads to a TV white space market pricing model in section III. Performance evaluation of the models is presented in section IV and the conclusion as well as further work in section V.

2. RELATED WORK

From a competitive market perspective, Niyato et al. [1] acknowledge the important role pricing plays in the trading of any resource or service. Basically the objective of trading is to provide benefits both to sellers and buyers. Thus the choice of a price must be motivated by the desire to simultaneously maximize revenue for the sellers (service providers) and satisfaction for the buyers (users). Pricing rules should

be developed over open platforms that guarantee not only interoperability among the service providers, which would facilitate their cooperation, but also the implementation of their individual business strategies [2]. The choice of a price is influenced by the user demand and competition among service providers. Within the context of Cognitive radio networks, pricing of spectrum resources has been addressed in numerous works [8], [9], [10]. In [8], a framework to facilitate dynamic spectrum access by way of an optimization problem approach formulated for the purpose of maximizing the revenue for the spectrum provider through pricing and spectrum assignment is presented. A scheme for competitive spectrum sharing wherein multiple self-interested spectrum providers operating with different technologies and costs compete for potential customers is presented in [9] as a non-cooperative game. A stochastic learning algorithm is employed to determine the Nash equilibrium which is itself a solution to this game. However, the authors did not consider the dynamics of a multi-hop cognitive wireless mesh network as well as the issue of resource allocation in this kind of network. However efforts involving multi-hop networks concentrate on spectrum sharing with interference aware transmission mechanism for each relay mechanism. In [11], a Media Access Control (MAC) layer scheduling algorithm was proposed for a multi-hop wireless network. An integer linear programming model was formulated to obtain the optimal schedule in terms of time slot and channel to be accessed by the cognitive radio nodes. The problem of spectrum pricing and competition among primary users (or primary services) and interactions among the cognitive radios in a multi-hop mesh network were not considered in this work. Initiatives to focus on competitive spectrum sharing and pricing in cognitive wireless networks are recorded in [12]. The initiative involves two levels of competition the first being among primary users and the second among secondary users for spectrum usage to choose the source rate to maximize their utilities. Non-cooperative games are formulated for these competitions with the Nash equilibrium being considered as the solution. Clearly, these efforts are not enough and can still be extended. Fang et al. [13] affirm that in addition to networking technologies, additional factors that determine the success of wireless mesh networks is whether there exists viable business models. There is limited research on this problem. In wireless mesh networks, wireless nodes are required to forward traffic for both itself and its neighbours. If the nodes are controlled by self-interested users, they may not efficiently share their capacity to route traffic for other nodes. Such possibility undermines the performance and feasibility of wireless mesh networks, therefore effective pricing mechanisms need to be developed before mesh technologies are commercialized.

3. TV WHITE SPACE MARKET PRICING MODEL

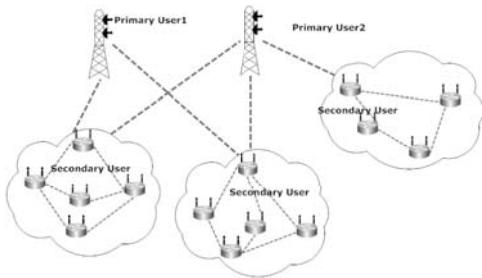
3.1 System Model

We present a competitive scenario within the context of spectrum management wherein licensed users of spectrum called primary users compete to offer services to an unlicensed

TABLE 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
ψ	Utility
(Q)	Set of available spectrum size
Δ	Substitutability
$\phi_i^{(T)}$	Profit(Throughput)
$\phi_i^{(D)}$	Profit(Delay)
y_i	Channel quality(player i)
y_j	Channel quality(player j)
T	Throughput
n	number of users
β	constant

users called secondary users. From a primary user perspective, the cost of providing a service to a secondary service is modelled as a function of QoS degradation. This being a game, Nash equilibrium is considered to be the optimal solution. Bertrand model generally depicts competition for an oligopoly market scenario comprising a homogeneous product with static and non discriminatory prices. In the classical case, this model fits well for a case of two firms bidding in a project in which the winner subsequently takes the entire project. Alternatively two firms may attempt to dominate a market and each one of the firms has sufficient manufacturing capacity to make all the product. Ultimately the lowest bidder gets the business. We however adapt the model to deal with the spectrum market scenarios within the context of a SWMN as shown in Fig 1. To begin with, a summary of the notation to be used in the ensuing analysis is presented in Table 1.


Figure 1: Smart Mesh Network

We consider the existence of N primary users operating on dissimilar frequency spectrum and a grouping of secondary users desiring to share the spectrum with the concerned primary users. If P_i is the tariff/pricing policy and the QoS guaranteed by primary user i then each of the secondary subscribers strives to subscribe at the given tariff so as to attain

a QoS sufficient to satisfy individual needs. The secondary users implore adaptive modulation for transmissions in the allocated spectrum in a time-slotted manner. In this kind of modulation, transmission rate is a function of channel quality. In this type of modulation, bit error rate must be maintained at specified target levels. Accordingly, the spectral efficiency of transmission for secondary user i can be expressed as in Equation 1:

$$k_i = \log_2(1 + Ky_i) \quad (1)$$

where

$$K = \frac{1.5}{\ln\left(\frac{0.2}{BER_i^{tar}}\right)}$$

The secondary user i transmits with spectral efficiency k_i to the extent that the demand of the secondary users is a function of transmission rate in the allocated frequency spectrum as well as the price charged by the primary users.

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3.2 QoS Measure and Cost

The QoS performance of a primary user is degraded in the event of some portion being shared with the secondary user. Thus cost function must be considerate of the QoS performance of the primary user .On this basis we consider a two pronged QoS measure in as follows:

- (i) Average delay as a QoS measure obtained for the transmissions at the primary user based on an M/D/1 queueing model [15].
- (ii) Throughput Measure

With regards to the delay QoS measure , Equation 2 defines the parameter as:

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

with the symbols meaning as given in the table. It is worth to note that $k_i^{(p)}(W_i - Q_i)$ denotes the service rate. The cost function is defined as in Equation 3 while that due to throughput (Equation 4) is defined in Equation 5.

$$C_i^D = dD_i(Q_i) \quad (3)$$

The other QoS measure is the throughput given by:

$$T(Q_i) = \sum_{i=1}^N \frac{\beta Q_i}{\sqrt{n \log n}} \quad (4)$$

The cost due to this measure is expressed as:

$$C_i^T = dT_i(Q_i) \quad (5)$$

TABLE 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

3.3 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 [14] by Equation 6:

$$\psi(\mathbb{Q}) = \sum_{i=1}^M Q_i k_i^s - \frac{1}{2} \left(\sum_{i=1}^M Q_i^2 + 2\Delta \sum_{i=1}^M Q_i Q_j \right) + J \quad (6)$$

where $\mathbb{Q} = Q_1, \dots, Q_i, \dots, Q_M$ and J is given by Equation 7:

$$J = - \sum_{i=1}^M P_i Q_i \quad (7)$$

The spectrum substitutability is included in the utility function by way of parameter λ . 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 Equation 8 by differentiating the utility function w.r.t Q_i as follows:

$$\frac{d\psi(\mathbb{Q})}{dQ_i} = 0 \quad (8)$$

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 in Equation 9

$$Q_i = \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} \quad (9)$$

3.4 Bertrand Game Model

The Bertrand oligopoly is formulated as in Table 2.

The profit due to a delay QoS performance is defined in Equation 10

$$\phi(\mathbb{P})_i^{(D)} = Q_i P_i - C_i^{(D)} \quad (10)$$

While the throughput based profit is expressed by Equation 11

$$\phi(\mathbb{P})_i^{(T)} = Q_i P_i - C_i^{(T)} \quad (11)$$

The solution to this game is the Nash Equilibrium (NE) obtainable by way of the best response. For a best response of a Primary user i given the prices of other primary users P_i , where $j \neq i$ is defined by Eqn 12-Eqn 13

$$\mathbb{BR}_i(\mathbb{P}_{-i}) = \operatorname{argmax} \phi_i(\mathbb{P}_{-i} \cup P_i) \quad (12)$$

The set $\mathbb{P}^* = \{P_1^*, \dots, P_N^*\}$ represents the Nash equilibrium of this Bertrand game, if and only if

$$P_i^* = \mathbb{BR}(\mathbb{P}_{-i}^*), \forall i \quad (13)$$

TABLE 3: System Parameters

Parameter	Value
PrimaryuserSpectrum	5MHz
BER	10^{-4}
TrafficArrivalRate	1Mbps
d	1
ChannelQualitySpan	10-20dB
λ_i	4Mbps
y_1	15dB
y_2	18dB
Δ	0.4
P_2	1
Primaryusers	2

The NE value in the context of delay QoS measure is obtainable by differentiating —10 to obtain Equation 14

$$\frac{d\phi(\mathbb{Q})}{dP_i} = 0 \quad (14)$$

for all i where the profit function due to the delay is given by equation 15

$$\phi_i^D(\mathbb{P}) = P_i \frac{k_i^s - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} - \frac{d\lambda_i}{2(W_i - Q_i)^2 - 2\lambda_i(W_i - Q_i)} \quad (15)$$

The derivative of this profit function is equated to zero as in Equation 16

$$0 = \frac{k_i^{(s)} - 2P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} + \frac{d \frac{\lambda_i}{1 - \Delta^2 (4Q_i - \lambda_i)}}{(2Q_i^2 - 2Q_i \lambda_i)^2} \quad (16)$$

where Q_i is defined by Equation 17

$$Q_i = W_i - \frac{k_i^{(s)} - P_i - \Delta(k_j^{(s)} - P_j)}{1 - \Delta^2} \quad (17)$$

The same computational procedure is logical followed with regards to obtaining the NE for a model based on a throughput QoS parameter.

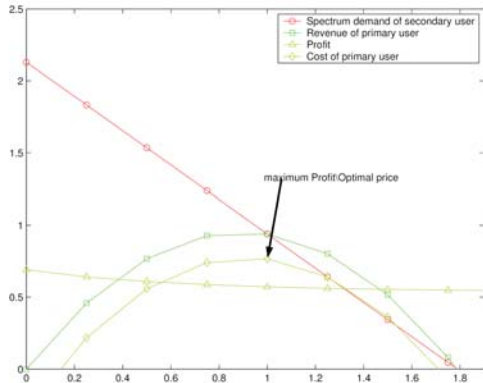
4. PERFORMANCE EVALUATION

We conducted a set of numerical simulations using the parameters defined in Table 3.

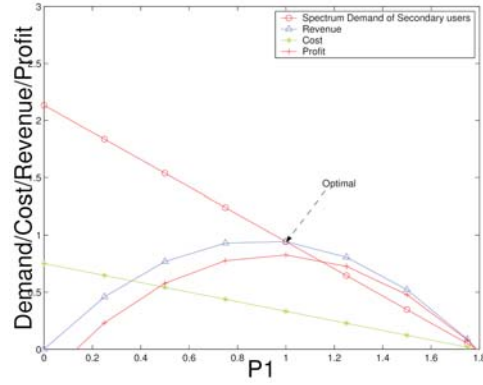
4.1 Numerical Analysis

In this section, we present numerical results to validate the efficacy of our low cost Smart Mesh network design using the two analytic models.

Fig 2 depicts the demand function of the secondary user, the revenue, cost and profit of the primary user under variable pricing options for the delay and throughput QoS performance metrics respectively. From a delay QoS performance perspective, when the first primary user strategizes by increasing the spectrum price, the secondary user correspondingly demands less spectrum owing to the decrease in the utility of the allocated spectrum. Moreover, the cost for the primary user decreases given a small demand from the secondary user. Needless to say, the size of the residual spectrum remains bigger giving rise to a small delay. However the revenue and profit of the primary user, traverses a parabolic path as



(a) Delay

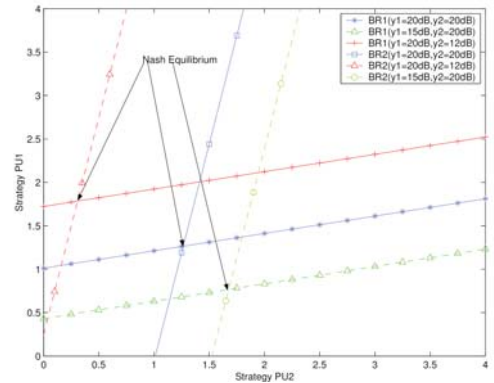


(b) Throughput

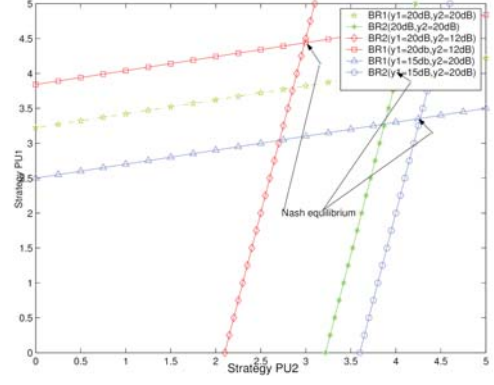
Figure 2: Demand,Revenue,Cost and Profit

it initially increases and then after the optimal point begins to decrease. Clearly for a small price, the first primary user can sell a bigger spectrum size to the secondary user, this translates to an increase in revenue and profit. Comparatively from a throughput QoS performance metric perspective, when the spectrum price increases, little spectrum is sold. Similarly when the primary user increases the price, the secondary user correspondingly demands less spectrum and vice-versa. However, the cost function shows a cost that is initially higher than that in the delay metric and then decreases sharply with an increase in price as depicted by the negative line gradient in the throughput version of the graph. The revenue and profit functions also follow a parabolic path. Notably for all the two QoS constraints, there exist points of maximized profit at which the price is considered optimal. The gap between the two parabolic curves, i.e profit curve and revenue curve is in a way reflective of the differences in the cost functions.

In Fig 3, we consider two primaries and their best responses under the delay and throughput QoS constraints. This in a way depicts attempts to catalyse spectrum price decrease and a subsequent increased access to internet services. The price catalysation is brought about by a change in strategy by both Primary 1 and Primary 2 as they both seek to attain the best price that will be attractive to the secondary user. The price strategy is itself a function of channel quality, thus when



(a) Delay



(b) Throughput

Figure 3: Best response

channel quality increases, the spectrum demand increases as it gives the secondary user a higher rate due to adaptive modulation. Consequently as in accordance with the law of demand and supply in economics, the primary user sets a higher price. The intersection of the best response lines from both primary 1 and primary 2 depicts the location of the optimal point which is also the Nash equilibrium point. The Nash equilibrium points for the delay metric are located at a lower position value points as compared to those of the throughput performance metric. This intuitively means it may be advisable to implement this performance metric to catalyze a decrease in service prices and subsequently enable entrepreneurs to achieve increased access in the rural and remote parts. Next we investigate and analyze, Nash equilibrium under variable channel quality depicted by Fig 4 for both performance metrics. A higher channel quality is deliverable via the delay QoS metric as compared to its throughput counterpart. This translates to a higher Nash equilibrium point for the delay QoS metric. This is a result of a higher demand emanating from the secondary users. For both graphs and metrics, the channel quality offered by one primary impacts the strategies adopted by the other primary. Consequently when the demand offered by one player is varied, the other player must responsively adopt the price to attain higher price. Ultimately, the throughput delivers the same channel quality at

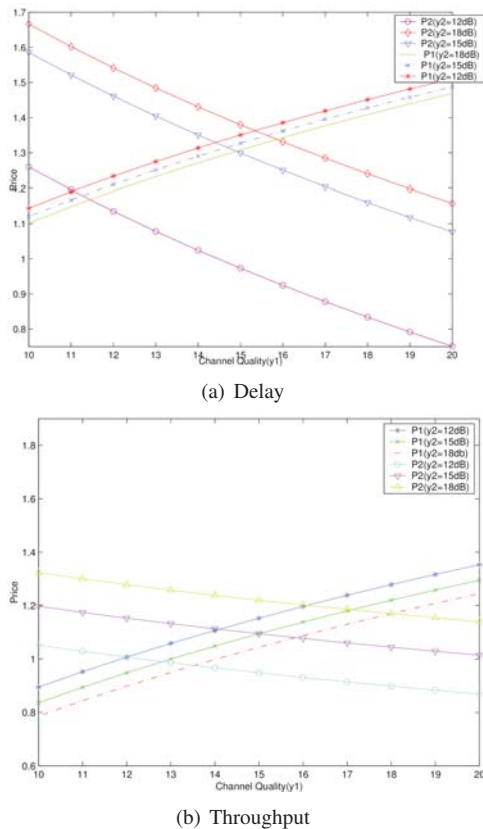


Figure 4: Channel Quality

a decreased price, a fact which gives the Throughput based model an edge over the delay based model.

5. CONCLUSION

This paper studied the non cooperative interaction of primary users(licensed users) and secondary users(mesh routers) with the context of a smart mesh network. Two non-cooperative analytic models were developed for a TV white space spectrum market applicable in rural and remote areas by entrepreneurs when provisioning internet access via smart wireless mesh network. The models are based on the delay and throughput QoS performance metric. Objectively the models strive to catalyse a decrease in costs (prices) and increase broadband internet access. The throughput based model is according to our performance evaluation capable of delivering high quality at a decreased cost price as compared to the delay based model. The use of different utility functions and applying these models to a cognitive routing scenario in which suitable routes are selected based on some strategy is an avenue for future work. Furthermore, when combined with real time spectrum sensing, the game theoretical model proposed in this paper can be used in the implementation of broadband markets in rural areas by mapping the game pricing into traffic demands and the spectrum sensing into bandwidth capacities which are both fed to the traffic engineering models proposed in [16]–[18] to enable time-of-

the-day traffic engineering based on white space availability. Finally, with the wide promotion of white space communication for machine-to-machine communication in Internet-of-Things (IoT) settings, the application of the white space market proposed in this paper to IoT schemes can boost long distance sensor networking [19] for water quality monitoring in rural and remote areas [20] in a more dynamic and efficient way than proposed in [21].

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