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A Price Based Spectrum Sharing Scheme in Wireless Cellular Networks

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Abstract

Radio frequency spectrum scarcity has become a high priority research area over the past few years. The huge increase of network subscribers with multimedia applications coupled with underutilization of radio frequency spectrum motivates the search for other measures to address the scarcity of radio frequency spectrum. This work investigates on a price based spectrum sharing scheme for connection-oriented traffic in wireless cellular networks as a solution to address the scarcity of radio frequency spectrum. Dynamic pricing approach is applied with traffic overflows into neighbor networks. Performance evaluations of the scheme at steady state using MATLAB simulations reveal significant gains to the quality of service. Application of the scheme to highly loaded network traffic improves both network revenue and traffic channel utilizations.

Keywords: Pricing, spectrum sharing, traffic overflows, Quality of service, channel utilizations, Wireless cellular networks.

1. Introduction

The wireless cellular industry is growing fast coupled with an increase in bit rates and multimedia applications. The global mobile cellular subscriptions stand at 6.8 billion users in 2013 with a global penetration rate of 96%, 128% in developed countries, and 89% in the developing countries(ITU 2013). In Tanzania, the mobile cellular subscription was about 27.4 million in December 2012 with a penetration rate of 61%(TCRA 2012). This growth demands for extra radio frequency spectrum capacities especially during busy hour periods.

Various approaches are used to optimize radio frequency utilization in wireless cellular networks including cell split and frequency reuse, overlapping of cell layers, and dynamic channel allocation techniques (Rappaport 2009), (Garg 2007) &(Katzela and Naghshineh 1996). However, even with the high level of frequency reuse, as with the introduction of micro, pico and femto cells, during busy hour periods the networks are overwhelmed with high volumes of traffic resulting into congestions. Furthermore, repeated use of most of these methods ends up with network complexity and an increase in radio frequency interference.

Wireless cellular network traffic is heterogeneous with spatial and temporal fluctuations. The demand for wireless radio resources differs significantly between peak and off-peak hours. Radio frequency spectrum utilization varies in the range of 15% to 85% in the band below 3 GHz (Akyildiz, Lee et al. 2006). Currently, most wireless cellular networks offer cheaper or even free off-peak calls as a marketing incentive, in an attempt to effectively utilize the available network capacity. However, this approach lacks flexibility to take into account the actual network load by increasing the price when higher demands are anticipated (Bouroche 2003). Variation of prices according to utilization assists to lighten network congestion and potentially yields more revenue to network operator (Fitkov-Norris and Khanifar 2000)&(Viterbo and Chiasserini 2001).

Radio frequency (RF) spectrum sharing exploits the differences in traffic loadings between networks (Heinonen, Pirinen et al. 2008). Sharing are feasible in three different cases depending on the objective; Sharing as a last option, always connected to the base station that has the greatest of unused resources, and as a secondary user. For networks with primary and secondary traffic routes, extra capacities are obtained by allowing incoming traffic to overflow from primary channel groups to secondary channel groups (Iversen 2005). Alternative path routing of overflow traffic widely improves the performance of hierarchical networks and IP networks (Huang, Ko et al. 2008).

In Tanzania, wireless cellular networks' traffic is disrupted by frequent power cut-off due to power shortage and rationing. The growth of the industry, use of multimedia applications and frequent power rationing motivates the search for other RF management strategies to address the problem of RF scarcity and quality of service. This work investigates a price based spectrum sharing scheme for connection- oriented traffic in wireless cellular network that applies dynamic pricing strategies with traffic overflows into neighbor networks at busy hour periods. The rest of the paper is organized as follows; section II presents the state of art of RF spectrum optimization and utilizations. Section III presents the system and traffic model of the network. Section IV presents the network simulations and the results. Section V concludes our work paving directions for further research.

2. State of Art

RF spectrums are assigned to wireless cellular networks exclusively on long term basis. In Tanzania seven companies are licensed to offer wireless cellular network services(TCRA 2011), four of which operates GSM technology while the remaining operate CDMA technology services. Absolute RF Channel Numbers (ARFCNs) are assigned to GSM operators both in the 900 MHz and 1800 MHz bands. Furthermore, all GSM operators are also licensed with UMTS/WCDMA services in 2100 MHz band. Wireless cellular network operators implement a combination of traffic channels from the above frequency bands to support multi band terminals. Mobile networks evolve from macro cell systems to micro, pico and femto cell systems in the search for more capacity to accommodate more network users. Two categories of channel allocations are noted to be in use currently; the baseband hoping (fixed channel assignment) and frequency hopping (dynamic channel assignment). Baseband hoping are mainly used in rural areas sites are far from each other and each radio transceiver is assigned a fixed frequency while frequency hopping schemes are commonly used in towns and cities. Cells in rural areas are grouped into bigger clusters with a 4×3 cell cluster being in common use. In cities and towns a tight frequency reuse pattern is used due to high traffic loads in these areas with a 1×1 cell cluster being in common use. To avoid frequency collision, RF hopping techniques are used with appropriate parameter settings including; the mobile allocation (MA), hopping sequence numbers (HSN), and mobile allocation index offset (MAIO). However, some of the cells are poorly utilized while others are over utilized. Table 1 presents some of traffic channel utilizations per cell extracted randomly from a wireless cellular operator as observed in our study.

Table 1: Traffic channel utilizations per cell

S/N	**Sample Traffic Channel (TCH) Utilization per cell**				
	Site No.	***Average TCH utilization (%)***		***Site No.***	***Average TCH utilization (%)***
1	Site 1	122.4	17	Site 17	58.6
2	Site 2	6.6	18	Site 18	206.2
3	Site 3	19.3	19	Site 19	197.3
4	Site 4	115.2	20	Site 20	152.2
5	Site 5	118.7	21	Site 21	64.1
6	Site 6	91.3	22	Site 22	4.3
7	Site 7	131.4	23	Site 23	78.0
8	Site 8	106.4	24	Site 24	145.5
9	Site 9	114.1	25	Site 25	60.0
10	Site 10	154.4	26	Site 26	43.1
11	Site 11	138.6	27	Site 27	45.5
12	Site 12	73.6	28	Site 28	67.8
13	Site 13	142.2	29	Site 29	3.6
14	Site 14	103.7	30	Site 30	184.0
15	Site 15	74.8	31	Site 31	129.2
16	Site 16	160.4	32	Site 32	237.1

3. System Model

We consider two wireless cellular networks each operating the same radio access technology to allow RF spectrum sharing when such requirement arises. Each network operator is basically assigned with a certain amount of absolute RF channel numbers (ARFCNs). The home network and the neighbor network together constitute a $n_1 + n_2$ server/ traffic channels loss system ($M/M/n/n$ queue), where $n = n_1 + n_2$. Mobile stations are randomly distributed in the area of study and are randomly assigned to their home network from which they buy services regularly. Sequential (ordered) hunting is done when mobile stations arrive at the base transceiver stations such that home network traffic channels are always utilized first. When incoming traffic load exceeds the capacity of the base transceiver station, extra traffic load overflows into neighbor wireless cellular network. This depends on the availability of traffic channels at that operator.

We assume a pure chance traffic type I is offered into a system that works as a loss system (Blocked calls are cleared). The call arrivals follow the standard poison modulated process with mean arrival rates of λ_{i-1} and service times that are exponentially distributed with mean service rate of μ_i. Fig. 1 presents a two dimensional Markov Chain used to represent the system evolution. Fig. 2 presents a traffic model where blocked calls in the home network overflows into a neighbor network with available traffic channels n_2. Calls that overflow into the neighbor network do not return to their home network even when the traffic channels are released. Overflowing traffic is not pure chance traffic type I any more but burst. If all available traffic channels in the neighbor network are also occupied, arriving calls are blocked and cleared.

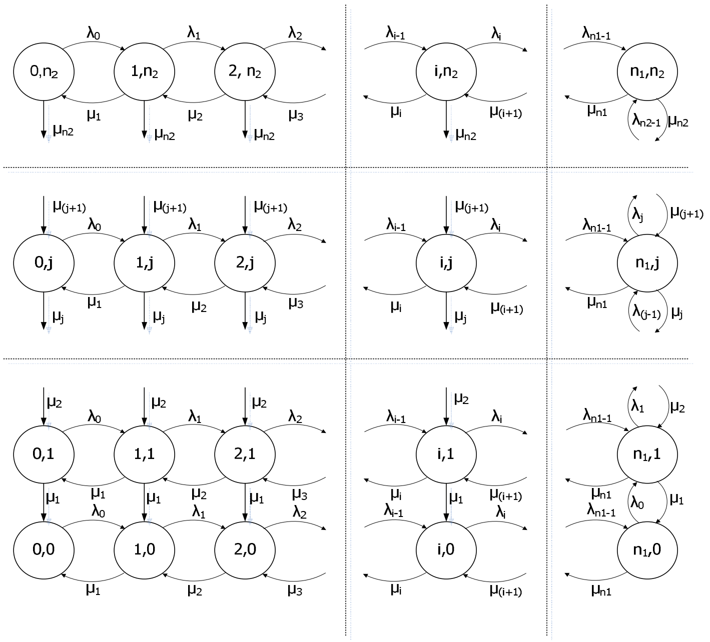

Figure 1: A two dimensional Markov Chain

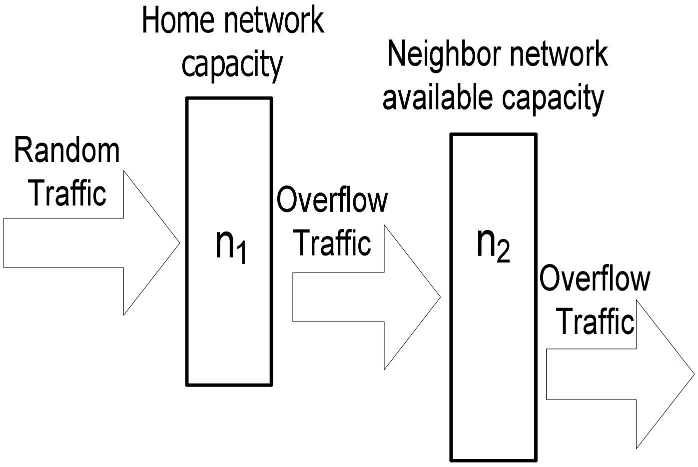

Figure 2: Traffic model

1.1 A price based spectrum sharing algorithm

We propose a scheduler that is decentralized and works at the base station controller/radio network controller. The scheduler iterates through the base transceiver stations assessing their traffic channel utilization status, thus providing base information for price adjustments based on the current traffic load. When traffic load is low, the price is lowered to motivate more network users to place their calls into the network. As traffic load increases arrangements are made such that when the home network capacity is used up, the extra traffic load overflows into traffic channels available at the neighbor network. The limitation of the traffic channels at the neighbor network operator will cause a steady increase in call pricing accordingly to deter additional traffic and suite the available capacity.

1.2 The demand function

We use the demand function appearing in (Viterbo and Chiasserini 2001), where in (1) p is the call price per time unit. Q is the quality of service index for call success probability ($Q = 1 - P_b$) and P_b is the call blocking probability. The parameters α and β are related to the user population characteristics.

$$D(p,Q) = e^{(-\alpha p+\beta Q)} \tag{1}$$

The demand in the time span Δt is assumed to equal the actual traffic generated in the time span of Δt, thus,

$$\Delta t. e^{(-\alpha p+\beta(1-P_b))} = \Delta t.\gamma.(1-P_b) \tag{2}$$

Where, $\gamma = \frac{\lambda_i}{\mu_i}$, for $0 \le i \le n_1 - 1$

$$\lambda_i = \frac{m_i}{1-P_b}.e^{(-\alpha p_i+\beta(1-P_b))} \tag{3}$$

for $0 \le i \le n_1 - 1$

Assuming that $p = (p_0, p_1, p_2, \ldots . p_{n1-1})$ is the price vector that represents the cost per time unit of a call started when the system is in a given state. Network users react to the changes in price per time unit by reducing their number and duration of calls. Significant reaction is expected when network users access the RF traffic channels from the neighbor network since these traffic channels are charged at slightly higher prices than the charges of home network. If t_{min} and t_{max} are the minimum and maximum call duration of a call per time unit, then the call duration in state $(i, 0)$ is given by (4).

$$\frac{1}{m_i} = t_{max} e^{-K_m(p_i - p_0)} \qquad (4)$$

$$\text{for } 0 \le i \le n_1 - 1)$$

Where,

$$K_m = \ln \frac{(t_{max}/t_{min})}{(p_{n1-1} - p_0)}$$

The average call termination rate when the system is in state $(i, 0)$ is obtained by (5).

$$\mu_i = m_0 + m_1 + \cdots + m_{i-1} \qquad (5)$$

$$\text{for } 1 \le i \le n_1$$

1.3 Call blocking

Analysis of the two dimensional Markov Chain is limited by state explosions as the number of traffic channels is increased. We therefore obtain the blocking probability for the home network is at steady state and approximate the overflow traffic using Fredericks and Hayward's approximation method. Considering a single dimension markov chain with $n_1 + 1$ states and using cut equations we obtain the call blocking for the home network as in (6).

$$p(n_1) = E(n_1, a) = P_{b1} = \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \prod_{i=1}^{n_1} \frac{\lambda_{i-1}}{\mu_i} \qquad (6)$$

The overflow traffic is given by (7).

$$w = a. E(n_1, a) = \frac{\lambda_{i-1}}{\mu_i} \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \prod_{i=1}^{n_1} \frac{\lambda_{i-1}}{\mu_i} \qquad (7)$$

The mean and peakedness of overflow traffic are obtained by (8) below (Iversen 2005).

$$\text{Mean, } w = \frac{\lambda_{i-1}}{\mu_i} \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \prod_{i=1}^{n_1} \frac{\lambda_{i-1}}{\mu_i}$$

$$\text{Peakedness, } z_2 = 1 - \left(\frac{\lambda_{i-1}}{\mu_i} \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \prod_{i=1}^{n_1} \frac{\lambda_{i-1}}{\mu_i}\right) + \frac{\frac{\lambda_{i-1}}{\mu_i}}{n_1 + 1 - \left(\frac{\lambda_{i-1}}{\mu_i}\right) + \left(\frac{\lambda_{i-1}}{\mu_i} \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \prod_{i=1}^{n_1} \frac{\lambda_{i-1}}{\mu_i}\right)} \qquad (8)$$

We apply Fredericks and Hayward's approximation method (Iversen 2005) to approximate the overflow traffic blocking as in (9).

$$E(n, a, z) \sim E\left(\frac{n}{z}, \frac{a}{z}, 1\right) \sim E\left(\frac{n}{z}, \frac{a}{z}\right) \qquad (9)$$

Thus, the overflow traffic blocking is given by (10).

$$w_l = \frac{\lambda_{i-1}}{\mu_i} \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \prod_{i=1}^{n_1} \frac{\lambda_{i-1}}{\mu_i} E\left(\frac{n_2}{z_2}, \frac{w}{z_2}\right) \qquad (10)$$

And system traffic congestion (STC) is obtained by (11).

$$STC = \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \prod_{i=1}^{n_1} \frac{\lambda_{i-1}}{\mu_i} E\left(\frac{n_2}{z_2}, \frac{w}{z_2}\right) \qquad (11)$$

1.4 Traffic channel utilizations

We assume a sequential assignment of traffic channels to incoming traffic. The traffic carried by the i^{th} channel is the difference between the traffic lost from $(i-1)^{th}$ channel and the traffic lost from i^{th} channel. Traffic carried by the i^{th} channel is independent of the number of channels after the i^{th} channel in the hunting order. In the home network traffic channel utilizations is obtained by (12).

$$y_i = \frac{\lambda_{i-1}}{\mu_i} \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} \left\{\prod_{i=1}^{k-1} \frac{\lambda_{i-1}}{\mu_i} - \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\} \qquad (12)$$

$$\text{for: } 0 \le k \le n_1$$

For the spectrum shared network the traffic channel utilizations when the system is in state (i, j) is given by (13).

$$y_i = \frac{\lambda_{i-1}}{\mu_i} \left\{\sum_{k=0}^{n_1} \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\}^{-1} E\left(\frac{n_2}{z_2}, \frac{w}{z_2}\right) \left\{\prod_{i=1}^{k-1} \frac{\lambda_{i-1}}{\mu_i} - \prod_{i=1}^{k} \frac{\lambda_{i-1}}{\mu_i}\right\} \qquad (13)$$

$$\text{For } 0 \le k \le n_1 \text{ and } 0 \le j \le n_2$$

1.5 Network revenue

We assume that $g_i = (g_1, g_2, \ldots, g_3, \ldots . g_{n_1})$ is the revenue vector representing the total revenue per time unit of the network when a system is in a given state. The revenue per time unit when the system is state $(i, 0)$ is given by (14).

$$g_i = \sum\nolimits_0^i p_i \qquad \text{for } 0 \le \mathrm{i} \le \mathrm{n}_1 \tag{14}$$

And the total network revenue is obtained by the following equation.

$$G_i = \sum\nolimits_{i=0}^i (1 - Pb_i) * g_i \qquad \text{for } 0 \le \mathrm{i} \le \mathrm{n}_1 \tag{15}$$

In a spectrum shared network when the system is in state (i,j), the total network revenue is obtained using (16).

$$G_i = \sum\nolimits_{i=0}^i (1 - STC) * g_i \qquad \text{for } 0 \le \mathrm{i} \le \mathrm{n}_1 \tag{16}$$

4. Simulations

We apply linear pricing vector (dynamic prices) to the demand function and allow extra incoming traffic load to overflow into a neighbor network. We further assume that eight traffic channels (TCHs) are available from the home network cell and traffic channels from the neighbor network are available in intervals of one traffic channels. We also assume the variation of call holding periods from a maximum of 180 seconds to a minimum of 60 seconds. The ratio of the constants β and α in the demand function is assumed to equal four ($^{\beta}/_{\alpha} = 4$) as used in (Viterbo and Chiasserini 2001). We allow the dynamic price to vary from 0.7 to 1.4 units per second and for the purpose of simplification, in all experiments we ignore the hand-off traffic. We use MATLAB simulations to calculate the probability of blocking iteratively until the steady state is reached. The parameters obtained at steady state are then used to compute various performance measures of the scheme.

4.1 Simulation Results

Dynamic pricing with spectrum sharing schemes produces lower call blocking probability of incoming calls when traffic overflows into a neighbor network. Fig. 3 presents the comparative results of call blocking probabilities (system traffic congestions) for a dynamic pricing with and without spectrum sharing.

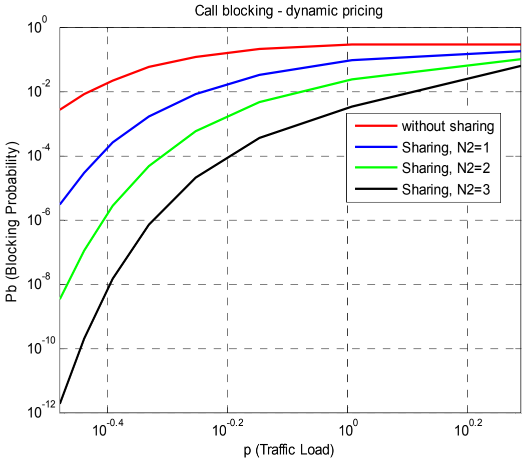

Figure 3: Call blocking for a dynamic priced network with and without spectrum sharing

Traffic overflow causes poor traffic channel utilization in the system. This is explained by the burstness of the traffic that overflows into the neighbor network (Peakedness = Variance /Mean being greater than one). However, when traffic load is high the traffic channel utilizations for dynamic prices with spectrum sharing exceed dynamic prices without spectrum sharing. This suggests the applications of the scheme to highly traffic loaded network scenarios. Fig. 4 presents the simulations results for traffic channel utilization.

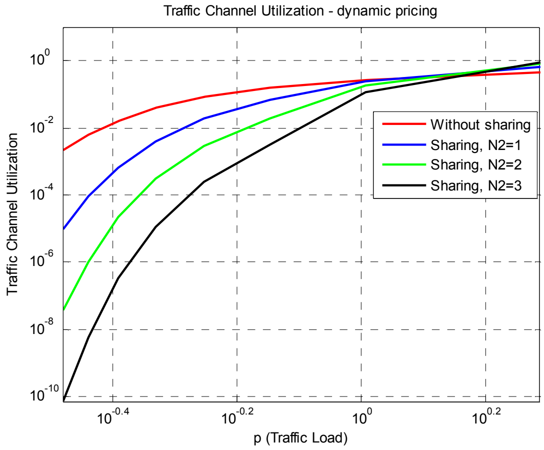

Figure 4: Traffic channel utilization for a dynamic priced network with and without spectrum sharing

A small increase to the total network revenue is observed when dynamic pricing with traffic overflows into the neighbor network is applied as compared to dynamic pricing without spectrum sharing. Fig. 5 presents simulation results for the total network revenue in the network. However, the change in the network revenue generated for successive increase of neighbor network traffic channels is minimal.

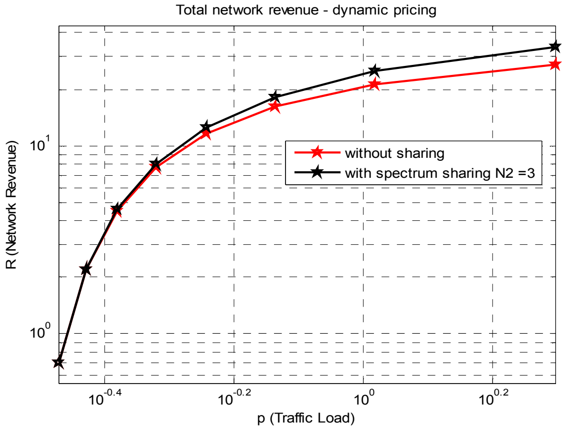

Figure 5: Total network revenue for a dynamic priced network with and without spectrum sharing

5. Conclusions

We have presented a price based spectrum sharing scheme for connection oriented traffic in wireless cellular networks. Dynamic prices are applied with traffic overflows into neighbor networks. Performance evaluation using MATLAB simulations reveals significant gains in the quality of services offered and an improvement of traffic utilizations when sharing are opted in a highly traffic loaded network. Gain in the network revenue is also observed when spectrum sharing is allowed. The application of the scheme to the connectionless oriented traffic is left as a direction for further research.

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