Chance-Constrained Spectrum Allocation for Fair LTE-U/Wi-Fi Coexistence

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2019 ICOIN

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Date : 11 Jan, 2019

Outline

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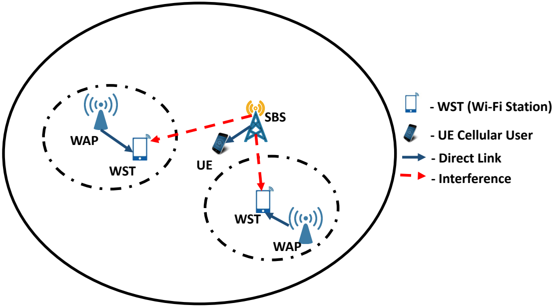
- Cellular networks are facing the challenges of spectrum scarcity while coping with the exponential growth in wireless traffic.
- To address such challenges of spectrum scarcity, enabling the LTE operation in unlicensed spectrum (LTE-U) is proposed.
- However, enabling LTE-U may cause severe performance degradation in the pertaining unlicensed spectrum technologies e.g. Wi-Fi.
- Therefore, a fair coexistence of Wi-Fi and LTE-U is required that can capture the uncertain performance of Wi-Fi system to dynamically allocate the redundant spectrum resources to LTE-U.

Contribution

- We propose a *chance-constrained* fair spectrum management scheme for the coexistence of Wi-Fi and LTE-U.
- The chance-constrained optimization helps to capture the volatile performance of Wi-Fi system
- Chance-constrained optimization problem formulation is suitable for such coexistence problem to guarantee sufficient performance of Wi-Fi.
- In order to efficiently utilize the available LTE-U duty-cycle, we formulated the knapsack problem for the user association of cellular users.
- The knapsack problem efficiently packs the cellular users such that LTE-U rate is maximized while meeting the available duty-cycle bounds.

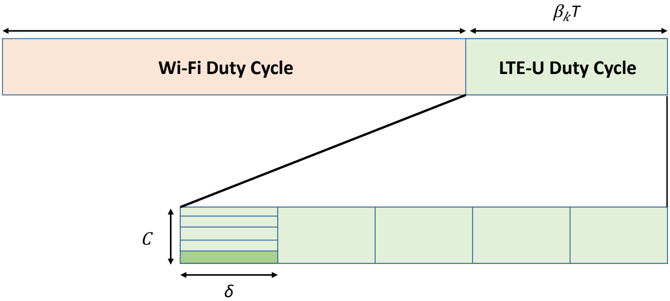
System Model

- We consider an SBS with a set $\mathcal{U}$ of U cellular users coexisting with a Wi-Fi system consisting of Wi-Fi Access Points (WAPs) and Wi-Fi users.
- We compositely represent WAPs and Wi-Fi users as a set $\mathcal{W}$ of W Wi-Fi stations.
- Both LTE-U and Wi-Fi system are operated on unlicensed spectrum having a set $\mathcal{K}$ of K channels



Duty-Cycle Frame Distribution

- The duty-cycle is divided into two sub-duty-cycles among Wi-Fi and LTE-U for sharing the unlicensed spectrum of bandwidth capacity C.
- The LTE-U duty-cycle is represented by $\beta_k T$, where T is the length of total duty-cycle and β_k is the proportion of the duty-cycle allocated to LTE-U.



Chance Constraint for WiFi Fairness

- In order to provide sufficient throughput to Wi-Fi, LTE-U duty-cycle i.e. $\beta_k T$ is adjusted dynamically based on the performance of Wi-Fi system.
- To maintain the Wi-Fi performance at the desired level ϑ, we use the following chance constraint.

$$P[(X_t + \beta_k T) \leq \zeta] \geq \vartheta, \tag{1}$$

where, X_t is the random time wasted in Wi-Fi collisions. ζ represents the tolerance threshold of Wi-Fi performance. The chance-constraint limits the collision time and LTE-U duty-cycle under a threshold ϑ.

LTE-U Resource Allocation

- LTE-U duty-cycle is further divided into sub-frames each of time duration δ.
- C is the total bandwidth of each Wi-Fi channel $k \in \mathcal{K}$.
- This bandwidth can be divided into $S = C/\omega$ number of LTE-U sub-channels, where ω is the bandwidth of one LTE sub-channel.
- Having $\beta_k T$ the length of LTE-U duty-cycle, the number of available LTE-U resource block units can be found as follows

$$Y_k = S \left\lfloor \frac{\beta_k T}{\delta} \right\rfloor, \tag{2}$$

where δ represents the duration of each LTE-U resource block.

- The SNR of each cellular user can be represented as:

$$\gamma_u = \log\left(1 + \frac{P_u g_u}{\sigma^2}\right), \quad \forall u \in \mathcal{U}, \tag{3}$$

Problem Formulation

To select the optimal cellular users, we introduce the following association variable:

$$x_u = \begin{cases} 1 & \text{if user } u \in \mathcal{U} \text{ is associated to the SBS,} \\ 0 & \text{Otherwise.} \end{cases}$$

Optimization Problem:

$$\max_{\boldsymbol{\beta},\boldsymbol{x}} \sum_{k \in \mathcal{K}} \beta_k C \sum_{u \in \mathcal{U}} x_u \log(1+\gamma_u), \tag{4}$$

$$\text{s.t.} \quad P[(X_t + \beta_k T) \leq \zeta] \geq \vartheta, \quad \forall k \in \mathcal{K}, \tag{4a}$$

$$\sum_{u \in \mathcal{U}} \eta_u x_u \leq Y_k, \quad \forall k \in \mathcal{K}, \tag{4b}$$

$$\beta_k \in [0,1], \quad \forall k \in \mathcal{K}, \tag{4c}$$

$$x_u \in \{0,1\}, \quad \forall u \in \mathcal{U}, \tag{4d}$$

Chance Constraint Solution

Rearranging (1), we get:

$$P[(X_t) \leq \zeta - \beta_k T] \geq \vartheta, \tag{5}$$

where, $P[(X_t) \leq \zeta - \beta_k T]$ can be considered as CDF of Poisson distribution and replaced as $F_{X_t}(\zeta - \beta_k T)$. By rearranging, we get:

$$\beta_k T \leq \zeta - \mathcal{F}_{X_t}^{-1}(\vartheta) \tag{6}$$

We get the following sub-problem:

$$\max_{\boldsymbol{\beta}} \sum_{k \in \mathcal{K}} \beta_k, \tag{7}$$

$$\text{s.t.} \quad \beta_k T \leq \zeta - \mathcal{F}_{X_t}^{-1}(\vartheta), \quad \forall k \in \mathcal{K}, \tag{7a}$$

$$\beta_k \in [0, 1], \quad \forall k \in \mathcal{K}. \tag{7b}$$

Optimal duty cycle is :

$$\beta_k^* = \frac{\zeta - \mathcal{F}_{X_t}^{-1}(\vartheta)}{T}, \quad \forall k \in \mathcal{K}. \tag{8}$$

Knapsack-based Solution

The second sub-problem

$$\max_{\boldsymbol{x}} \sum_{k\in\mathcal{K}} \beta_k^* C \sum_{u\in\mathcal{U}} x_u \log(1+\gamma_u), \tag{9}$$

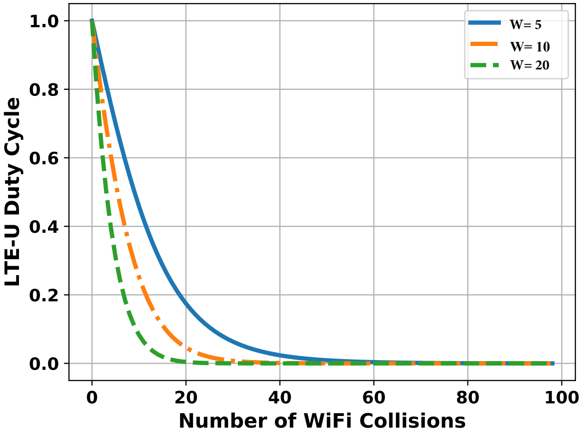
$$\text{s.t.} \quad \sum_{u\in\mathcal{U}} \eta_u x_u \leq Y_k, \quad \forall k \in \mathcal{K}, \tag{9a}$$

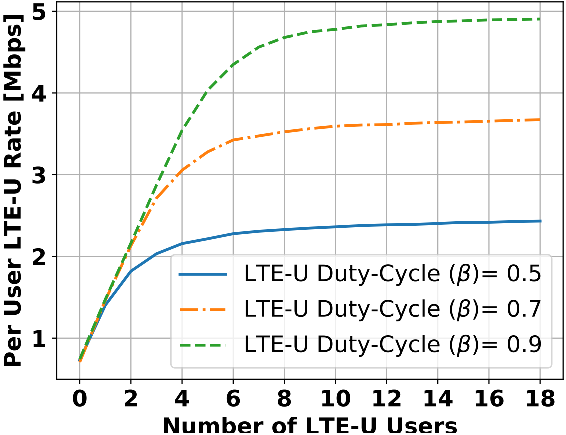
$$x_u \in \{0,1\}, \quad \forall u \in \mathcal{U}. \tag{9b}$$

We solved the given Knapsack problem by dynamic programming.

1. Compose a two dimensional array V_{U*Y}, where U is the the number of cellular users in the network and Y is the total unlicensed resource blocks computed from LTE-U duty-cycle.
2. Set $\mathbf{V}^{U*Y}$ to zero. Choose $V[u,y]$ according to the following rule.

$$V[u,y] = max(V[u-1,y], \gamma_u + V[u-1, y-\eta_u]) \tag{10}$$


W= 5
W= 10
W= 20
LTE-U Duty Cycle
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Number of WiFi Collisions


Per User LTE-U Rate [Mbps]
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
Number of LTE-U Users
LTE-U Duty-Cycle (β)= 0.5
LTE-U Duty-Cycle (β)= 0.7
LTE-U Duty-Cycle (β)= 0.9

Conclusion

- In this paper, we discussed the problem of unlicensed spectrum sharing between Wi-Fi and LTE-U networks.
- To provide fairness to Wi-Fi system while capturing the randomness of Wi-Fi network due to random collisions, we formulated the chance-constrained optimization problem.
- We decomposed the formulated problem and solved through stochastic optimization and knapsack problem for the LTE-U duty-cycle management and cellular users resource allocation.

Thanks