Design and Analysis of Elastic Handoff in Cognitive Cellular Networks

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***Abstract*—Cognitive cellular networks can enable opportunistic network access but their effectiveness relies on adaptive handoff algorithms. However, in cognitive radio networks the usufructuary rights of a secondary user are rescinded due to the unanticipated appearance of a primary user causing potential service disruption. In order to provide uninterrupted service to a cognitive cellular user, we propose elastic handoff as a composite framework of conventional cellular and voluntary spectrum handoffs. As with spectrum handoff, elastic handoff grants secondary users spectrum access while insulating them against the arrival of primary users. On the other hand, it is similar to cellular handoff in providing secondary users service assurance. The setup also offers users multiple network access choices, and affords carriers the means to generate additional revenue by capitalizing on excess capacity. We use a blockchain-based spectrum exchange and smart contracts to implement elastic handoff. Our tests show that user-initiated elastic handoff may reduce call drops by up to half compared to observations from a conventional cellular market, and network-initiated elastic handoff can improve a carrier's revenue maximization prospects.**

***Index Terms*—elastic handoff, blockchain protocol, options exchange, network access.**

I. Introduction

Currently, more than 4.7 billion out of the total 7.4 billion humans have a cellular subscription. By 2020, the number of subscribers is forecast to be 5.6 billion, and around this same time, it is estimated that one in ten cellular subscriptions will be used for machine-to-machine communications [1]. Although much progress has been made in increasing teledensity, processes governing access contracts have predominantly stayed the same, limiting network access [2] and inhibiting service quality [3]. The addition of new cellular users also accentuates demand for more radio spectrum [4]. Cognitive radio networks hold potential in improving access options using dynamic spectrum access methodologies. However, this technique is devoid of service guarantee as access to secondary spectrum is ephemeral, ending as soon as a primary user manifests in the same spectrum band.

In [5], we proposed a cloud-centric cognitive cellular network (CCN) topology to achieve opportunistic network access. We adopted a Network Access Exchange (NAE) approach to support a cognitive cellular user (CCU) make a judicious decision as to which carrier best meets its access requirements. However, this setup did not provide provisions to address user handoff, nor delve into the access exchange design. We address those inadequacies in the current paper with the introduction of elastic handoff.

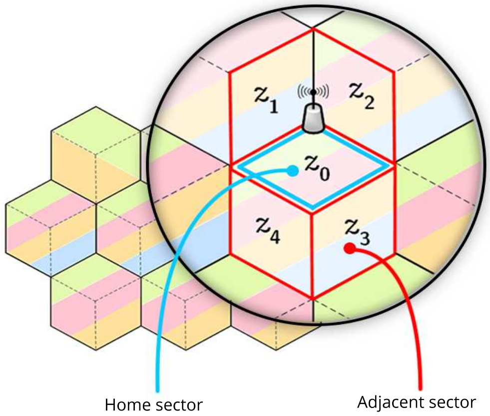
We start with the study of spectrum handoff techniques [6] and design elastic handoff as a framework that draws from both traditional cellular [7] and voluntary spectrum handoffs [8]. As markets help realize the true value of a commodity, we model the access exchange after an options exchange. The exchange is built using blockchain technology and smart contracts are used to administer network access [9]. A contract-based network access approach for a single carrier was evaluated in [10], whereas we test for multiple CCNs. For completeness [11], in our case we study both user- and network-initiated handoffs.

Irrespective of the spectrum handoff technique, the success of an options exchange relies on robust spectrum sensing data. We utilize the consensus mechanism in blockchain [9] to arrive at the true spectrum utilization level in a given location at all times. Our approach reduces spectrum sensing cost and minimizes access signaling traffic, as unlike most sensing setups that depend on census mechanism, the consensus method allows for the sensing pool to be a sample of random users. The proposal provides constructs to improve network access choices and enforce access contracts.

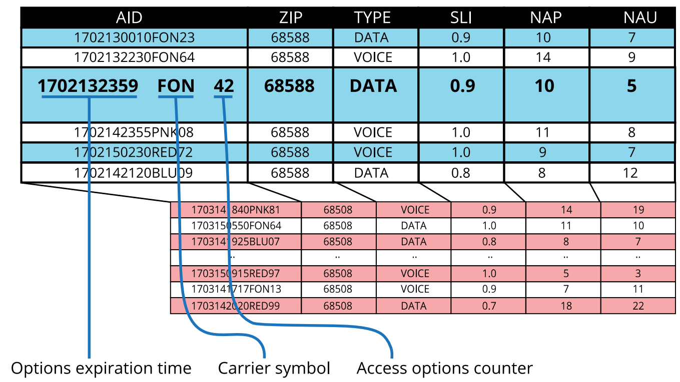
The performance of a cellular network is measured in no small part by its ability to handle handoffs and guarantee service assurance. However, there is some uncertainty with respect to service assurance that is inherent in cognitive radio networks which may prevent their wide adoption. Hence, it is important to study new handoff schemes that can ensure service continuity. We posit elastic handoff is a means to minimize the impacts of spectrum handoff, and more importantly, a vehicle to improve network access choices. We submit, to the best of our knowledge, we are unaware of any research in existing literature that uses blockchain technology and consensus mechanism to host a spectrum options exchange. Our proposal presents these benefits:

1) affords customers agency in selecting carrier as they are no longer constrained by long-term "analog" contracts,
2) enhances a carrier's revenue maximization opportunities by capitalizing on excess spectrum and network capacity,
3) enables user- and network-initiated handoff, enforces user and network accountability via smart contracts, and
4) reduces call drop ratio by up to half when compared to observations from real-world cellular networks.

The remainder of the paper is organized as follows: Section III discusses the spectrum exchange, Section IV elastic handoff, and Section V presents final remarks.



(a) CCU a in sector z_0 prefetches network access options from z_0 and adjacent sectors $z_{1..4}$.



(b) CCNs list in NAE the number of voice and data units that can serve based on spectrum and network availability

Fig. 1. Network Access Exchange – A market based options exchange built using blockchain technology.

II. Spectrum Exchange

Our topology is designed as a cloud-centric cognitive cellular network presented in [5], [12]. We leverage Network Function Virtualization and Cloud Radio Access Network technologies to pool resources and host network elements. This structure not only reduces capital and operational expenditure, but also makes spectrum and network management flexible and agile. The remote radio units and the softwarized base station controllers provide much needed flexibility to conjointly manage spectrum and network resources.

The CCNs serve as both primary networks (PN) and secondary networks (SN) in this architecture. These have a trust relationship with two vital network entities: (NAE) and *Identity and Credibility Service* (ICS). The CCUs operate as two classes of users: *primary users* (PUs) and *secondary users* (SUs). The CCUs collects spectrum utilization in its vicinity and the corresponding PN takes this information and based on available network capacity converts it into network access units before it is listed in the NAE, as shown in Fig. 1 (b). We assume all subscribers have devices that is equipped with cognitive radios. The conversion of spare spectrum and reserve network capacity is out of

Our proposal considers the NAE is designed as an options contracts exchange [13] using blockchain technology [9]. We use blockchain to arrive at a consensus on the actual spectrum utilization level in a geographic location based on a survey carried out by random CCUs.

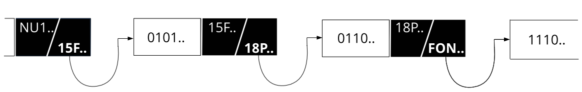


Fig. 2. A *blockchain* is a *chained* list of blocks added as a list based on *consensus* from participating CCUs.

A blockchain is a distributed ledger where records are stored in a list, as shown in Fig. 2.

A blockchain network is secured using public-key cryptography, and it has three access permission configurations, *public*, *private*, and *consortium*. The public blockchain network is open to all, and users can join the network without any prior approval. Unlike a public network, a private chain requires that a user have permission to join the network. A consortium blockchain, on the other hand, is partially decentralized and works based on consensus between its participating users. Each user in a blockchain network is assigned a unique pseudonymous address with which all transactions are performed.

The NAE is a consortium blockchain, where CCUs, CCNs, and NAE have different roles and varying read and write privileges. The interactions between the users - CCUs, CCNs, and NAE - in a blockchain network is governed by smart contracts. A smart contract is self-executing code with embedded conditions established between multiple parties. Once a contract is executed it is housed in the NAE until its time of execution. For instance, a contract between a set of CCUs and a CCN would require the former to poll spectrum utilization level in its vicinity periodically.

The NAE spectrum corpus has multiple uses. Apart from providing users with the best possible network access options, it can help a user execute futures contracts for network access. As network traffic is self-similar, it is possible to back-test data and determine time slots to obtain best service at the lowest possible cost. It will provide network carriers and policy makers a granular view of spectrum utilization at different geographic locations.

From a security standpoint, the NAE would be able to utilize the consensus mechanism to securely update the state of the blockchain. For instance, if a greedy user who is part of the network were to relay incorrect spectrum usage information and its peers were to not concur with the information, it could be rejected and user access privileges rescinded.

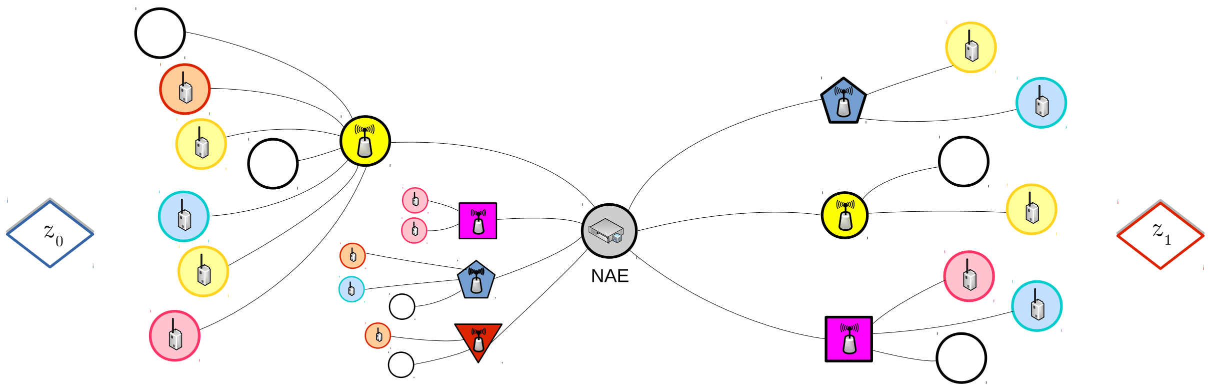


Fig. 3. Elastic handoff – Multiple cellular carriers in a given sector serve both primary and secondary users. Both network operators and cognitive cellular users may query the options exchange for open network access options in the home or adjacent sectors.

III. Elastic Handoff

We draw inspiration from both conventional cellular [7] and voluntary spectrum [8] handoff techniques to model *elastic handoff*. Similar to handoffs in cellular network, elastic handoff supports service assurance when moving between cells. Elastic handoff allows service continuity for secondary users and is immune to the arrival of primary users, as in voluntary spectrum handoff. Unlike typical spectrum handoff which is reactive in nature, elastic handoff is responsive and can be initiated either by the *user* or *network*.

In user-initiated elastic handoff, a CCU attempts to find a new CCN for itself, and in the case of network-intiated, a CCN tries to identify other CCNs to offload its CCUs. The goal in both instances is uninterrupted service for the CCUs at the same or better service level that provides the best payoff.

The CCUs and their Base Station Controller (BSC) relay spectrum and network utilization periodically to the CCN. The CCN translates this information into network access price (NAP), service level indicator (SLI), and number of network access units (NAU) allotted for voice or data (TYPE) in a given location (ZIP), and relays it for publishing in the NAE. The NAE assigns a unique access identity ticker (AID) to each record received from the various CCNs. The AID is metadata, which is a concatenation of when an access contract expires, the carrier and a counter as shown in Fig. 1 (b). SLI is a unit of measure indicating service tier and ranges from 0 .. 1. It is the metric used by a carrier to convey to a user both *when* and *how* its network access request will be serviced. A detailed analysis of these terminologies and their implementation will be presented in a future work.

Our setup considers a cell partitioned into three sectors, z_0, z_1, and z_2, as shown in Fig. 1 (a). Each sector is serviced by multiple CCNs and each sector has n network access options. When a CCU/CCN seeks secondary access for itself or its constituents, it retrieves access options from the NAE periodically. This information is prefetched for the home sector z_0 and four adjacent sectors z_1, z_2, z_3, and z_4. The latter lookups are required as a mobile CCU may travel from z_0 to any one of the four adjacent sectors. Thus, if the intent is to move away from the parent BSC, an upper limit of $4n+(n-1)$ prefetches are required: $4n$ for sectors z_1, z_2, z_3, z_4 and $(n-1)$ for sector z_0. We achieve user- and network-initiated elastic handoff using three functions, $Trigger$, $Candidates$, and $Target$, for *period*- and *event-based* triggers.

$Trigger$ is invoked to perform a NAE lookup. It is impacted by these variables: access contract duration (KDU), signal-to-noise ratio (SNR), network access price (NAP), and service level indicator (SLI). Based on the whether a hand-off is periodic- or event-based, a subset of these variables invoke $Trigger$. For instance, period-based scenarios are predictable, such as KDU expiration, whereas event-based are invoked, say, when SNR deteriorates.

For both and user- and network-initiated handoff, $Candidates$ takes as input a set of AID's and outputs a list of p potential candidates. This in turn is input to $Target$, which eventually selects a final target AID(s) for the CCU(s)

Notation	Description
AID	Access Identity Ticker
BSC	Base Station Controller
CCN	Cognitive Cellular Network
CCU	Cognitive Cellular User
KDU	Access Contract Duration
NAE	Network Access Exchange
NAP	Network Access Price
NAU	Network Access Units
SLI	Service Level Indicator
SNR	Signal-to-noise Ratio
a	Current CCU wanting to migrate
A	Set of all CCUs to be migrated
m	Current access options contract
i	Access options under review
p	Potential target options
n	Number of access options per sector
t	Time
T	Time interval between periodic checks

Our intent is to transfer one or more CCUs from one or more BSCs that provides the best possible service at the lowest possible cost.

IV. User-Initiated Elastic Handoff

User-initiated elastic handoff is invoked either periodically or in event-based scenarios as presented in Algorithm 1 and elaborated in Section IV-A and IV-B. It is impacted by multiple variables, which include KDU, NAP, and SNR. Let us consider CCU a is served by an options contract m that corresponds to an options listing AID. The contract contains $NAP_{a,m}$, $SLI_{a,m}$ and the duration $KDU_{a,m}$.

Algorithm 1 User-initiated

1: $a \leftarrow$ Current CCU
2: $m \leftarrow$ AID serving a
3: initialize t_{now} = 0, $Trigger$ = 0
4: initialize $\forall i$, $i \in (AID's - m)$, $Candidates$ = NULL, p = 0
5: initialize $Target$ = NULL
6: **while** 1 **do**
7:   **if** ($Trigger_{Periodic}$ == 1) from eq (1) **then** ▷ Period-based
8:     a performs a NAE lookup
9:     call Algorithm 2 ▷ Call Candidates
10:     **if** p == 0 from eq (4) **then** ▷ 0 candidates found
11:       do nothing, continue with m
12:     **else**
13:       call Algorithm 3 ▷ Call $Target$
14:       **if** $|Target|$ == 0 **then**
15:         **if** $t_2 - t_{now}$ == 0 **then**
16:           a falls back to $Primary\ Network$
17:         **else**
18:           a continues with m
19:       **else**
20:         handoff a from m to $Target$
21:   **else if** ($Trigger_{Event}$ == 1) from eq (6) **then** ▷ Event-Based
22:     Execute steps 8-20 to find new $Target$

A. Period-based Approach

Period-based user-initiated handoff is influenced by KDU and NAP values. In this case, a requests a list of potential network access options from the NAE at regular intervals of T or when $KDU_{a,m}$ is close to expiration. Assume t_{now} is current time, t_1 start-time of current contract, and t_2 end-time of current contract, i.e., $KDU_{a,m} = t_2 - t_1$. The function for periodic user-initiated handoff, $Trigger_{Periodic}$, is defined as:

$$Trigger_{Periodic} = \begin{cases} 1, & \text{for } t_{now} \bmod T == 0 \\ 1, & \text{for } t_2 - t_{now} \leq T \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Given there are n potential access choices in each sector, a has $4n$ possible options from sectors z_1 through z_4, and $(n-1)$ options in the home sector z_0, excluding m. The CCU a identifies the options that meet its needs.

An access option under review, AID_i, can serve a at a given $NAP_{a,i}$ and $SLI_{a,i}$ for duration $KDU_{a,i} = t_3 - t_{now}$, where t_3 is the end-time of option i. The CCU a considers only those $SLI_{a,i}$s that match or better its minimum requirements:

$$SLI_{a,i} \geq SLI_a \tag{2}$$

Assuming t_3 is always greater than t_2 and (2) is satisfied, the following condition is to be met in order for i to be considered a candidate:

$$NAP_{a,i} * (t_3 - t_{now}) \leq NAP_{a,m} * (t_3 - t_2) \tag{3}$$

$$|Candidates| = p \tag{4}$$

AIDs satisfying (2) and (3) form the set of all $Candidates$, as outlined in Algorithm 4.

Algorithm 2 User-initiated - Candidates

23: **for** $i \in (AID's - m)$ **do**
24:   **if** eq (2) **then**
25:     **if** eq (3) **then** $Candidates \leftarrow i$
26: $Candidates$ ▷ List of potential candidates

Before a user-initiated elastic handoff is realized, a must find a target AID from $Candidates$. While an AID may include the SLI offered by a CCN, it is possible a CCU's service experience may be impaired by factors such as signal interference and topography. This interference may cause a degradation in the quality of experience for the CCU. Hence, a CCU eliminates AIDs whose corresponding BSCs do not satisfy its quality requirements, one of which we use, SNR. This procedure is presented in Algorithm 3.

Of the remaining $Candidates$, $Target$ is determined by a based on Service per unit Cost (SpC) defined in (5). Once SpC is calculated for all $Candidates$, determining the maximum value amongst them helps a identify an options contract AID that offers the optimal combination of SLI and NAP.

$$SpC_{a,i} = \frac{SLI_{a,i}}{NAP_{a,i}} \tag{5}$$

After an AID is selected using Algorithm 3, a is handed off to the $Target$ CCN. If conditions outlined in Algorithms 1, 2 or 3 are not satisfied, no AID is identified as $Target$.

Algorithm 3 User-initiated - Target

27: **for** p > 1 **do**
28:   eliminate $Candidates$ with unacceptable SNR
29:   Compute eq (5) for each of $Candidates$
30:   $Target$ = AID with MAX($SpC_{a,i}$) $\forall i$, $i \in Candidates$
31: $Target$ ▷ Target candidate identified

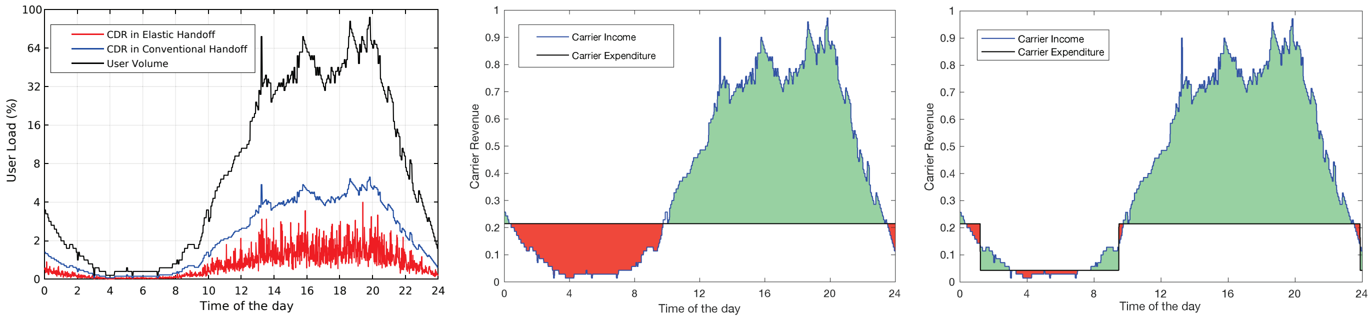
This leaves the CCU with two choices based on the time left in the current contract m. If m is still valid, it continues in the current contract; if the current contract has ended, it falls back to its primary network.

B. Event-based Approach

Event-based elastic handoff is triggered based on previously identified criteria, which in our case is the SNR experienced by the CCU. If the SNR experienced by a CCU while in the current contract m falls below a threshold, $Trigger_{Event}$ is set to 1, as described in (6). CCU a then polls the NAE for possible network access options. The steps involved in the selection of $Candidates$ and $Target$ are similar to period-based user-initiated handoff, from Algorithm 1.

$$Trigger_{Event} = \begin{cases} 1, & \text{for } SNR_{a,m} \leq SNR_{Threshold} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

It is possible that both period-based and event-based handoff mechanisms may lead to the CCU not finding a $Target$. In such a scenario, the CCU a has two options: fall back to its primary network to ensure service continuity, or continue with m which may lead to a call drop.



(a) Call drops - Conventional vs. Elastic handoff

(b) Profit maximization in conventional cellular networks

(c) Revenue maximization in cognitive cellular networks

Fig. 4. Elastic handoff – Call drop and revenue generation

Real-world metrics of call-drop probabilities in conventional cellular networks were published in [3]. We contrast the call-drop performance of elastic handoff against those results by adopting the cellular call pattern presented in [14]. Our simulation setup consists of a CCU with randomized trigger events for a period of 24 hours, and an NAE, implemented using Python FMS, which contains network information of 4 CCNs for the same period. Fig. 4a illustrates the comparative results – elastic handoff reduces call drops with a confidence range of 0.6% to 3.2%. We hypothesize that the lower percentages can be attributed to shorter contract duration.

V. Network-Initiated Elastic Handoff

We assume A is the set of CCUs that needs to be migrated. A network-initiated handoff is influenced by $|A|$ and the NAP values of the $n-1$ AIDs in the same sector. The handoff procedure is presented in Algorithm 4 and elaborated in V-A and V-B.

Algorithm 4 Network-initiated

$A \leftarrow$ Set of CCUs to be migrated
$m \leftarrow$ AID of A
initialize t_{now} = 0, $Trigger$ = 0
AT_i $\forall i \in (AIDs - m)$ = NULL
initialize $Candidates$ = NULL, p = 0
while 1 **do**
  if ($Trigger_{Periodic}$ == 1) from eq (7) **then** ▷ Periodic-based
    m's BSC gets NAE values
    call Algorithm 5 ▷ Call Candidates
    received $Candidates$ are arranged in increasing NAP_i
    all CCUs in A are arranged in decreasing $NAP_{a,m}$
    call Algorithm 6 to transfer CCUs to maximize profit for m
  else if ($Trigger_{Event}$ == 1) from eq (11) **then** ▷ Event-based
    m's BSC gets NAE values
    call algorithm 5 ▷ Call Candidates
    if (p == 0) **then**
      do nothing, m continues servicing AT
    else call algorithm 6 ▷ Profit-maximization

A. Period-based Approach

The CCNs poll the NAE periodically at every T to obtain a list of network access options. As profit maximization is the motive of periodic network-initiated handoff, we consider NAP as the determining factor to trigger the handoff. This trigger function is defined in (7).

$$Trigger_{Periodic} = \begin{cases} 1, & \text{for } t_{now} \bmod T == 0 \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

AT_i is a subset of A that can be serviced by access option i. We treat $Cost_i$, the cost incurred by a BSC i to service a CCU, to be constant for any given access option i. Also we assume that $Cost_m \geq NAP_{a,m}$, where $Cost_m$ is the cost incurred by m to service a CCU and $NAP_{a,m}$ is amount the CCU is charged for this service.

$$NAP_{a,i} < Cost_m \quad (8)$$

All AID's satisfying (8) are listed in $Candidates$. Any AID considered as a Candidate charges a lesser NAP value than what it would cost the CCN ($Cost_m$) to service the CCU itself. As it may not be possible for a single AID to cater to all CCUs in A due to its own user load, subsets of A have to be transferred to various $Candidates$ to maximize profit. Individual CCU and prospective AID pairs are verified to eliminate any AID whose BSC does not satisfy the CCU's signal quality requirements. The CCU and AID pairs are then validated for condition (9).

$$SLI_{a,i} \geq SLI_{a,m} \quad (9)$$

Algorithm 5 Network Initiated - Candidates

for i in (n-1) other AID's **do**
  if eq (8) **then**
    $Candiates \leftarrow i$
$Candidates$ ▷ Potential candidates

Algorithm 6 Network Initiated - Profit Maximization

for i in $Candidates$ **do**
  for (a in A && $qty(i)$ > 0) **do**
    if ($SNR_{a,i}$ is acceptable value) **then**
      if ($SLI_{a,i} \geq SLI_{a,m}$) **then**
        $AT_i \leftarrow a$
        $A = A - a$
        a is transferred to i
    else a will continue with m

$qty(i)$ is the maximum number of CCUs i can accommodate. After selecting p potential AID's, m tries to maximize its profit in the following way. $Candidates$ are arranged in increasing order of quoted $NAP_{a,i}$ and CCU in A are arranged in decreasing order of $NAP_{a,m}$. m transfers $qty(i)$ CCUs from A to i based on conditions in Algorithm 6.

$$\Delta Profit = \sum_{i}^{Candidates} \sum_{a}^{AT_i} (Cost_{a,m} - NAP_{a,i}) \quad (10)$$

The increase in profit of m due to migration of $qty(i)$ CCUs to i is represented in (10). The CCN keeps transferring CCUs to i's as long as either $|A| = 0$ or $Candidates$, cannot accommodate any more CCUs. The CCN uses a greedy approach to maximize profit by allocating $qty(i)$ highest-paying CCUs to AID i charging least NAP according to Algorithm 6.

B. Event-based Approach

In our model, an event-based network-initiated trigger is invoked for two reasons: *First*, when the number of users served by a given BSC falls below a minimum threshold resulting in the operating expenses of that BSC exceeding the net income generated from serving users. *Second*, when the number of users served by a given BSC has risen above the estimated maximum value, at which point it can no longer provide the level of service promised. Migrating a set of users to other CCNs is important at this juncture so that all users, including the ones moved, may receive uninterrupted service.

For a given $|A|$, the lower threshold on the number of CCUs is represented by $LowThreshold_m$ and upper threshold by $HighThreshold_m$. We define $Trigger$ as (11):

$$Trigger_{Event} = \begin{cases} 1, & \text{for } |A| \leq LowThreshold_m \\ 1, & \text{for } |A| \geq HighThreshold_m \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

If $Trigger_{Event}$ is set to 1, a CCN selects p potential $AIDs$ i.e., $Candidates$ to transfer the CCUs that needs to be migrated.

If $Trigger_{Event}$ is set to 1 due to

$$|A| \leq LowThreshold_m,$$

then the CCUs transferred are A.

On the other hand, if $Trigger_{Event}$ is set to 1 because of

$$|A| \geq HighThreshold_m,$$

then $|A| - HighThreshold_m$ CCUs are transferred.

Since the objective of the CCN is to maximize profit, it arranges A, in decreasing order of NAP. m transfers AT from A in the first case of equation 11, and $AT = |A| - HighThreshold_m$ CCUs in the second case. The search for candidate AIDs and distribution of CCUs to each is done as described in Algorithms (5) and (6). The area in green in Fig. 4b represents the time of day when there is greater demand on the network resources of a CCN; this is also the time when a carrier makes the most profit. The area in red depicts the time of day when the CCN has to expend more resources to cater to the least number of users. Unlike the situation in conventional cellular networks, where it may not be possible to shutdown a BSC, the CCN with its virtualized network elements may do so once it makes provisions to offload its users. After the users are moved as secondary users to other carriers, the CCN may terminate the cloud instance of a BSC thereby minimizing losses as shown in Fig. 4c. Together Figs. 4b and 4c depict how a CCN can minimize its expenditure and maximize profit during times of low demand by offloading a subset of its users.

VI. Results and Remarks

We present a novel user- and network-initiated elastic handoff as a composite framework of conventional cellular and voluntary spectrum handoffs. Elastic handoff improves a subscriber's network access choices and indicates it can reduce call drop ratio by up to half. It can also aid in improving carrier profit maximization. We consider our work as a first step to better our understanding of elastic handoff methodologies. In the future, we plan to evaluate how elastic handoff fares against various options methodologies.

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