Stochastic Optimal SIM Selection for Multi-SIM Cell-phone Architecture using semi-Markov Decision Processes

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***Abstract*—Cell-phones equipped with multiple subscriber-identity-modules (SIMs), have already started capturing the cellular market. It is expected that these cell-phones will capture more than 7% of global cell-phone sales by 2014. The key advantage of these phones over their conventional counterpart is the simultaneous access to different cellular networks. The selection process among available cellular service providers becomes a complicated task when multiple factors have to be accounted for by the user. We propose an optimal SIM selection mechanism for multi-SIM cell-phones by employing semi-Markov decision process framework. Performance evaluation results reveal the effectiveness of the proposed model, which is flexible and can easily be adapted for different cell-phone architectures.**

I. Introduction

The cellular wireless networks have experienced an unprecedented growth mainly due to technological revolution as well as information explosion. At the same time, the cellular networks have gone through multiple generations, where the ultimate objective is to tailor variety of applications from the user perspective [1] [2]. A superior voice quality, higher data rate, improved multimedia capabilities on one hand and reduced infrastructure as well as operating costs on the other hand, are the key objectives of a cellular network service provider. In the context of user experience as well as their satisfaction level, the cell-phone architectures have also gone through many updates. With the advancement in semiconductor technology, cell-phones, which few years back were a means of mere communication, has emerged as pervasive computers.

The growth in the cellular wireless networks have also lead to a highly competitive market, where multiple cellular service providers are always vying for a fair share of the market. On the other hand, this healthy competition among cellular service providers along with availability of cellular services in a particular area has forced the users to keep more than one subscriber identity module (SIM) for their daily usage. Recently cell-phones with two subscriber-identity-modules (SIMs) have been introduced in Asia and part of Europe. These cell-phones are designed to utilize one of the two SIMs by means of an electrical multiplexer, eradicating the process of manually replacing one with other. Its only recently that some cell-phones are designed to work with both SIMs simultaneously. Such cell-phones are called active dual SIM. Due to the feasibility and low cost, dual-SIM cell-phones have shown a growth rate of 74% in 2009. In fact its expected that they would be contributing to approximately 7% of the global cell-phone sales by 2014 [3]. It can be easily anticipated that the number of SIMs will not be limited to two in future, rather it would depend on average count of cellular service providers in a metropolitan area as well as user demands, justifying the need for having multi-SIM cell-phone architectures.

The availability of multi-SIM (currently dual and three SIM phones) allows users to avail any benefits as well as limited time offers from different service providers by keeping more than one SIM for their daily usage. However, to avail benefits from different service providers in the form of reduced cost, improved quality of service etc., users have to manually switch among the SIM modules. As the number of parameters involved in SIM selection process are increased, it becomes very difficult for the user to keep track of all the parameters. In addition, performing the final SIM selection task manually, which provides an optimal compromise among the performance parameters is not a trivial task.

To address the above mentioned SIM selection problem for a multi-SIM cell-phone architecture, we have proposed a systematic approach based on semi-Markov decision process. The proposed solution will not only achieve an optimal SIM selection, but will also automate the process. The relevant work in literature includes some studies related to multi-radio node architectures. In particular, a node lifetime maximization solution employing semi-Markov decision process have been proposed in [4], [5] for dual CPUs and radios node architecture. The issue of designing resource allocation and pricing, discussed in [6], exploits the heterogeneity of wireless networks and is not applicable in our case. To the best of our knowledge, this is the first paper to employ stochastic resource control mechanism based on semi-Markov decision process for multi-SIM cell-phone architecture to solve the SIM selection problem. Rest of the paper is organized as follows.

In Section II, we discuss the general architecture of Multi-SIM phone architecture and also outline the system model.

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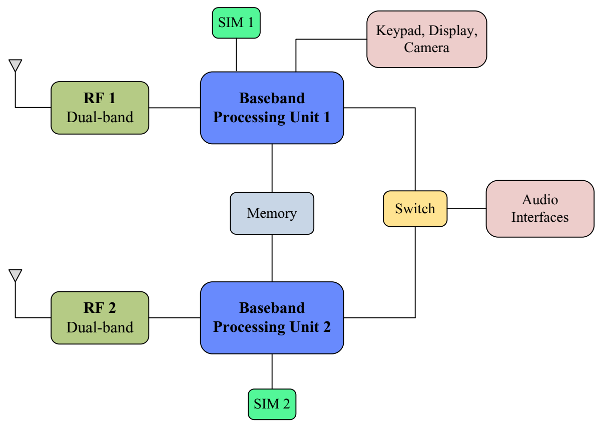

Fig. 1. Block diagram for Dual-SIM (Samsung GT-C5212) cell-phone.

Framework to achieve the optimal policy is discussed in Section III and performance evaluation of proposed solution is discussed in Section IV. Finally we conclude our findings in Section V.

II. System Architecture and Model

Cell-phone comprises of three key functional blocks, namely, baseband subsystem, radio-frequency (RF) subsystem and multiple user interfaces. Baseband subsystem primarily consists of a general purpose microprocessor (P_1) and a digital signal processor (P_2). General purpose processor is responsible for radio resource management, short messaging service, human machine interface and operating system softwares. It also interfaces with user display, keyboard and subscriber identity module (SIM). Digital signal processor (DSP) is responsible for speech coding and decoding, error correction, channel coding/decoding etc. RF subsystem consists of frequency up/down converters, power amplifiers and analog baseband interface. Active dual-SIM cell-phones contain separate RF as well as baseband subsystems to achieve satisfactory performance in realtime. When a SIM is selected for use its corresponding RF and baseband subsystem become active. Extending this architecture for multi-SIM cell-phones, we expect either multiple RF and baseband subsystems will be used in parallel or a time multiplexing approach can be employed to share lesser number of baseband subsystems for larger number of RF subsystems. Based on the above discussion, we assume that for an n SIM cell-phone, there will be a corresponding call cost and quality of service (QoS) associated with each SIM. The number of SIMs, their associated charges and the corresponding QoS depends on the specific cellular service providers. The functional block diagram for dual-SIM cell-phone, GT-C5212, from Samsung is shown in Fig. 1.

Based on the type of activity initiated by the subscriber (either voice call or data), the baseband subsystem can utilize either processor P_1 alone or both P_1 and P_2 simultaneously. After preprocessing, the voice call or data link will be established using one of the SIMs or it is discarded in case the optimal SIM reports that network is busy. This sequence of operations and the associated choices made can be represented using a state transition diagram. The set of states that can be used to model the sequence of operations is denoted by $\mathbf{s}$ with $\mathbf{s} = \{s_i, s_p, s_c, s_t\}$, where s_i represents the idle state, s_p is the processing state, s_c represents the communication state after SIM selection and s_t is the termination state as shown in Fig. 2. The termination state, s_t, can be considered as an auxiliary state and is effectively same as state s_i.

In the formulation of our model, we have made the following assumptions.

- Event arrival rate from user or operating system follows truncated exponential distribution with mean arrival rate λ.
- The time spent by the node in each state is independent and follows identical but arbitrary distribution.

These assumptions allow us to model the problem of optimal SIM selection for a multi-SIM cell-phones as semi-Markov decision process.

III. Optimal Resource Control Framework for Multi-SIM Architecture

A. Action Space

For each event arrival initiated either by the user or application, the system being in idle state s_i, takes an action to initiate either P_1 or P_1 and P_2 simultaneously depending on the type of the event, for further processing and possible communication of this event. When the event is a voice call both processors P_1 and P_2 are used simultaneously, but in case of sending short messages or web browsing only P_1 is sufficient. Once the event is processed and needs to be transmitted, a decision is taken by an action to select one of the SIMs. Let A denotes the set of all control actions, while $A(s_j)$ is the sub-set of control actions which are possible in state s_j, then control action $a_k \in A(s_j) \subseteq A$, at discrete time instant k, can take the following values:

$$a_k = \begin{cases} 0 & \text{select } s_t \\ 1 & \text{select } \mathrm{P}_1 \text{ or } \mathrm{SIM}_1 \\ 2 & \text{select } \mathrm{P}_1\&\ \mathrm{P}_2 \text{ or } \mathrm{SIM}_2 \\ 3 & \text{select } \mathrm{SIM}_3 \\ \vdots & \vdots \\ n & \text{select } \mathrm{SIM}_n \end{cases} . \qquad (1)$$

The notation is simplified by using a instead of a_k whenever it is appropriate. For $a = 1$ or $a = 2$ the selection between P_1 and SIM_1 or (P_1,&P_2 and SIM_2) depends on the current state where the action is being taken. For instance, in state s_i, action $a = 1$ will result in using processor P_1, while in state s_p, action $a = 1$ will result in using SIM_1. Since all actions are not possible in each state, so irrespective of current time instant, the state s_i has only two possible actions i.e. $A(s_i) = \{1, 2\}$, while for state s_p we have $A(s_p) = \{0, 1, 2, 3 \cdots, n\}$.

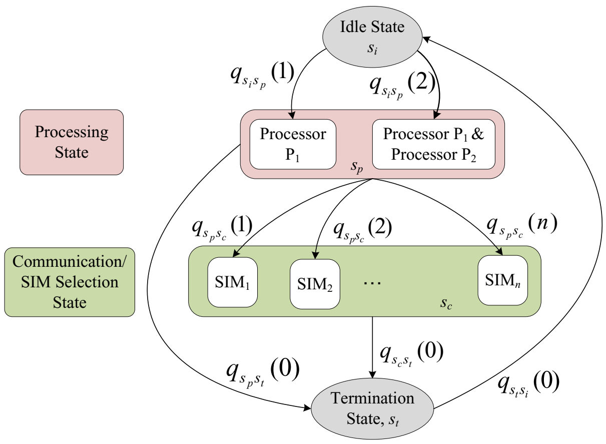

Fig. 2. The state transition diagram for muli-SIM cell-phone architecture with multiple processors.

B. State Dynamics, Policy and Cost Function

The state dynamics of the proposed model are characterized by considering the state transition probabilities, $q_{s_js_m}(a)$ and expected time $\tau_{s_j}(a)$ that is spent in state s_j associated with action a for different states. Whenever an action a is chosen it will have an associated cost and a transition from state s_j to state s_m is made. Different state transition probabilities are given by

$$q_{s_js_m}(a) = \begin{cases} 1 & j=i, m=p, a \in \{1,2\} \\ p_{s_js_m} & j=p, m=t, a=0 \\ 1-p_{s_js_m} & j=p, m=c, a \in \{1,2,\cdots,n\} \\ 1 & j=c, m=t, a=0 \\ 1 & j=t, m=i, a=0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

In (2), $p_{s_js_m}$ is the probability of not being able to use the selected SIM which might happen due to network congestion. For each state $s_j \in \mathbf{S}$ an action $a \in A(s_j)$ is chosen according to a policy $h_{s_j} \in \mathcal{H}$, where the set $\mathcal{H}$ is considered to be collection of all admissible policies, and is given by

$$\mathcal{H} = \{h : \mathbf{s} \rightarrow A | h_{s_j} \in A(s_j), \forall s_j \in \mathbf{S}\} \tag{3}$$

The proposed semi Markov decision framework selects a processing unit based on the power consumption whereas it selects an appropriate SIM based on an immediate as well as running cost and the quality of service provided. Each state transition from s_j to s_m when action a is taken, incurs an immediate fixed cost $C_{s_js_m}(a)$ to account for startup in case of processor selection and link establishment in case of SIM selection. In addition, a cost rate of $c_{s_js_m}(a)$ is accumulated for power consumption in case of processor or call cost rate and QoS in case of SIM, in state s_j, till the next action is taken. These cost components are used to obtain the mean expected cost for action a in state s_j as

$$\bar{C}_{s_j}(a) + \bar{c}_{s_j}(a)\tau_{s_j}(a) = \sum_{s_m} p_{s_js_m}\left(C_{s_js_m}(a) + c_{s_js_m}(a)\tau_{s_j}(a)\right). \tag{4}$$

Selecting optimal action based only on cost always yields selection of processor P_1 ignoring the benefit of utilizing DSP processor, P_1, along with P_1. To account for performance benefit of DSP processor at high data rates as well as during voice call, we introduce reward rate earned for each state. For processing state, the reward rate is product of MIPS (processing capability) and the event arrival rate. Similarly, selection of SIM based on immediate cost only does not take into account quality of services or distance from base station, which controls the power consumption. Therefore, we also introduce a cost components based on distance to account for the channel conditions. Now our aim is to devise an optimal policy $h^* \in \mathcal{H}$, which minimizes the associated costs and maximizes the reward for an arbitrary state.

C. Problem Formulation

The policy to obtain an optimal tradeoff between cost incurred and the resulting quality of services (QoS) for SIM, is obtained by solving the following linear programming problem formulation of semi-Markov decision problem:

$$\textbf{minimize} \sum_{s_j \in S} \sum_{a \in A(s_j)} \{\bar{C}_{s_j}(a)\pi_{s_ja} + \bar{c}_{s_j}(a)\tau_{s_j}(a)\pi_{s_ja} - \beta_k(\bar{r}_{s_j}(a)\tau_{s_j}(a)\pi_{s_ja})\}$$

$$\textbf{subject to}$$
$$\sum_{a \in A(s_m)} \pi_{s_ma} - \sum_{s_j \in S} \sum_{a \in A(s_j)} q_{s_js_m}(a)\pi_{s_ja} = 0, s_m \in S$$
$$\sum_{s_j \in S} \sum_{a \in A(s_j)} \tau_{s_j}(a)\pi_{s_ja} = 1, \ 0 \leq \pi_{s_ja}. \tag{5}$$

In (5), π_{s_ja} are the decision variables and the term $\tau_{s_j}(a)\pi_{s_ja}$ is defined as the long term average time, the system is in state s_j when an action a is taken. The parameter β is user defined scaling coefficient, which provides the tradeoff between call cost and the relative emphasis on power efficiency due to cost $\bar{C}_{ss_j}$ in state s_j. The first constraint in (5) ensures that long term average number of transitions out of state s_j are equal to long term average number of transitions into state s_m, whereas the second constraint makes sure that all decision variable are equal or greater than zero and their sum is equal to unity ensuring the Markov property.

IV. Performance Evaluation Results

To study the performance of proposed optimal SIM selection mechanism, we have selected four SIMs for multi-SIM cell phone architecture. All the SIMs are assigned appropriate costs as well as rewards for their operating states. The fixed cost with each SIM is measured in terms of its initial call setup cost $C_{s_js_m}(a)$ and the cost rate $c_{s_js_m}(a)$, which is a measure of QoS, is quantified in terms of distance from the base station. The call cost and associated transmitted power for each SIM is provided in Table I. Higher prices and corresponding lower transmit power levels in Table I can be attributed to better coverage from the service provider. In our evaluation, processors P_1 and P_2 represent, respectively, ARM11 (general purpose processor) and Texas Instrument TMS320x55x (DSP). The

TABLE I
COST FOR COMMUNICATION.

SIM	SIM_1	SIM_2	SIM_3	SIM_4
Call Cost	0.50$	0.75$	1$	2$
Transmitted Power	1000 mW	750 mW	500 mW	100 mW

rewards for these processing states P_1 and P_2 are described in Table II and obtained by multiplying processing speed (MIPS) and mean event arrival rate, λ. State transition probabilities along with expected mean time spent in each corresponding state are tabulated in Table III.

TABLE II
COST AND REWARDS FOR PROCESSORS

Processor	Processing cost	Reward (MIPS*λ)
General Purpose	0.35 mW/MHz	100*λ
DSP	0.22 mW/MHz	500*λ

TABLE III
MEAN SOJOURN TIMES AND STATE TRANSITION PROBABILITIES

Symbol	Value	Symbol	Value
$\tau_{s_c}(1)$	300 ms	$\tau_{s_c}(3)$	330 ms
$\tau_{s_c}(2)$	450 ms	$\tau_{s_c}(4)$	100 ms
$\tau_{s_i}(0)$	$1/\lambda$	$\tau_{s_p}(1)$	200 ms
$\tau_{s_p}(2)$	120 ms		
$p_{s_p s_c}$	0.99	$p_{s_p s_t}$	$1 - p_{s_p s_c}$

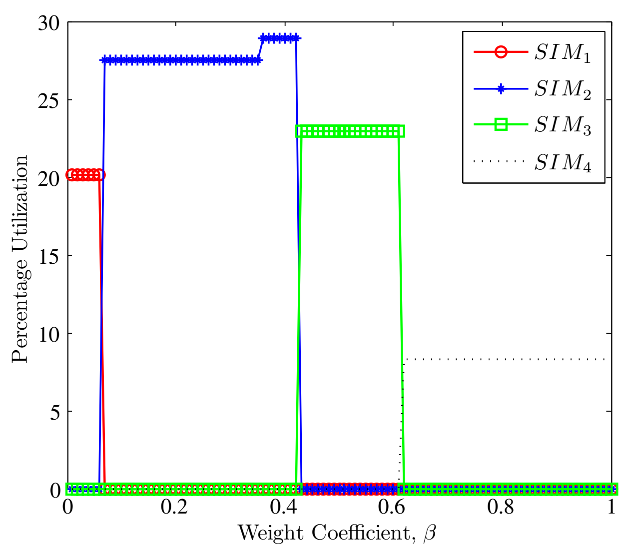

Fig. 3. Utilization of different SIMs as a function of weight coefficient β.

To evaluate the performance of proposed SIM selection mechanism, we have studied the percentage utilization of each SIM. The result in Fig. 3 shows the utilization of different SIMs as a function of weighting coefficient β for fixed event arrival rate λ. The result in Fig. 3 shows that SIM_1 is selected when initial cost is dominant. However, optimal selection switches from SIM_1 to SIM_2 or SIM_3, when relatively higher

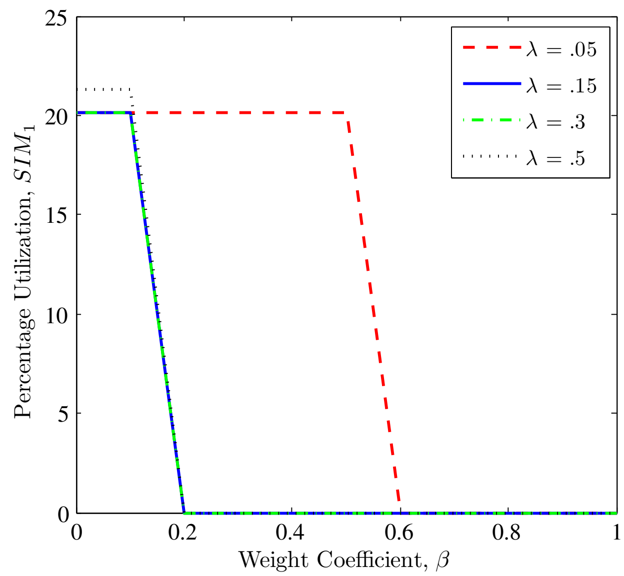

Fig. 4. SIM_1 utilization for different values of λ.

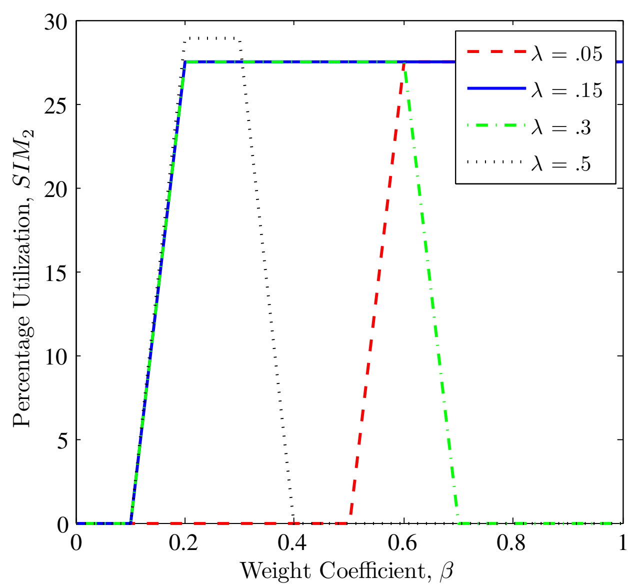

Fig. 5. SIM_2 utilization for different λ.

weight is assigned to quality of service or when we need to conserve transmit power. SIM_4 becomes dominant only at high data rates when selection is mainly based on quality of service and little weight is assigned to call initiation.

Similarly analyzing the result in Fig. 4 shows that utilization of SIM_1 remains dominant for smaller values of event arrival rate λ for lower values of weight coefficient β. Subscriber identity module SIM_2 utilization depicted in Fig. 5 shows that it is selected and utilized at all event arrival rates, however with an increase in β, priority to quality of service can be observed from the result in Fig. 5. The results in Fig. 6 and Fig. 7 show that the corresponding SIM selection and utilization is

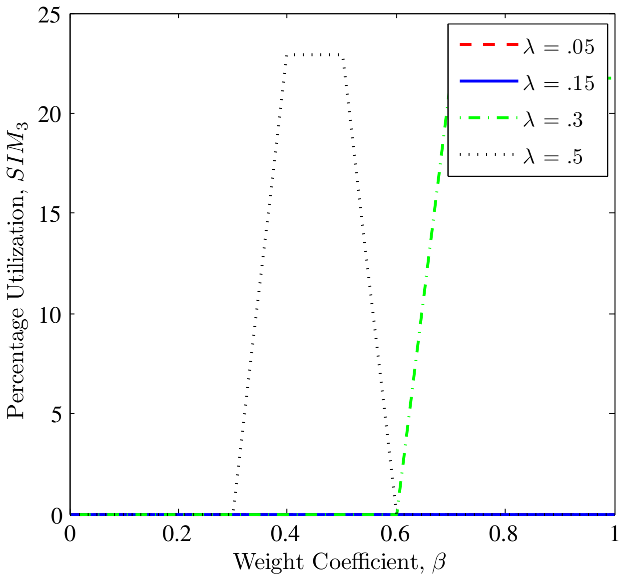

Fig. 6. SIM_3 utilization for different λ.

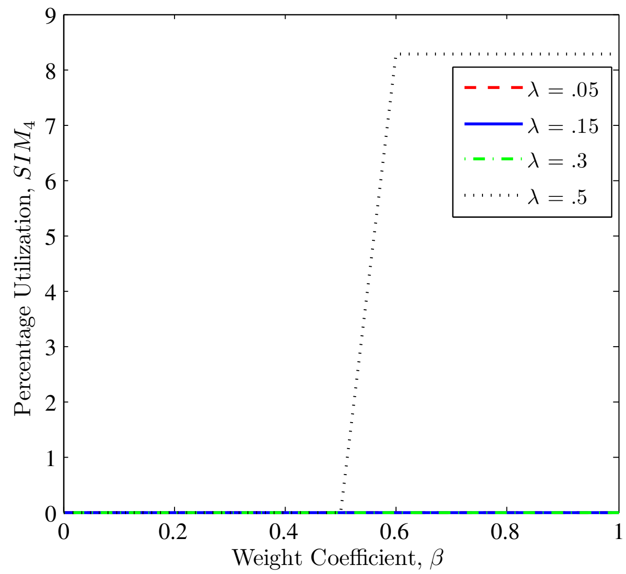

Fig. 7. SIM_4 utilization for different λ.

only limited for high data rates, due to high initial cost and a relatively lower transmission power cost.

V. Conclusions

An optimal SIM selection strategy for multi-SIM cell-phones, utilizing a semi-Markov decision process based approach, is proposed. From the performance evaluation results it is observed that an application requiring high data rates, selects a SIM with better quality of service even if it has higher initial cost. However, for low data rate applications, SIM with lower initial cost among the available SIMs is selected. The proposed solution can be modified to other future applications related to optimal and economical usage of multi-SIM cell phones. In future, it will be worthwhile to analyze the fairness issues at the network level, which may arise when employing the proposed SIM selection approach.

Acknowledgments

This research is partly funded by Higher Education Commission (under Pakistan-US Science and Technology Cooperation Program) and Directorate of Research University of Engineering and Technology Lahore.

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