Relevance Based Power Saving Mechanism in a Multi-RAT User Equipment

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Abstract

In a mobile device or user equipment (UE) with multiple radio access technologies (RATs) an essential procedure to enable mobility across all RATs is to search for suitable cells in each supported RAT. The search procedure includes measurement of signal strength of the cells and receiving of network parameters, e.g., system information in LTE cell. To perform the search procedure it involves power consumptions by each of the RAT access stratum (RAT-AS) in a UE. In this paper, the authors propose a novel mechanism to selectively switch OFF less relevant access stratums of the dormant RATs. This paper defines a set of parameters for this purpose. These parameters are (1) user preference, (2) ratio of number of cells with Received Signal Strength Identifier (RSSI) above a defined threshold to the number of cells searched, (3) ratio of the number of cells searched to maximum number of cells that can be searched within a given power usage limit, (4) ratio of the number of cells suitable for mobility procedures to number of cells searched. Based on these parameters criteria are defined which are used to switch OFF irrelevant RATs in a UE. Simulation results show that for lesser number of cells searched (around 30% of maximum possible), the ratio of the number of cells searched to maximum number of cells that can be searched within a given power limit is the preferred parameter for switching OFF an irrelevant RAT-AS. Whereas for higher number of cells searched, user preference is the preferred option to switch OFF an irrelevant RAT-AS.

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1 Introduction

In the near future, a mobile device or User Equipment (UE) will support multiple radio access technologies (Multi-RATs). To support an application the UE has to use the network resources of a cell from supported multiple RATs which satisfies the Quality of Service (QoS) requirements of the application. The UE tries to select the most suitable cell (either user initiated or network initiated) from all the supported RATs as it moves. This searching of all the RATs to find a suitable cell for an application use leads to major power consumption in a UE. Moreover, all the RATs may not support the application due to various Quality of Service (QoS) issues. Such RATs are irrelevant. RATs which do not have cells in the vicinity of the UE are also irrelevant. If these irrelevant RAT access stratums (RAT-ASs) are switched off, then this can lead to power saving in the UE. This paper proposes a mechanism to achieve this power saving.

Conventionally, in a UE which supports any RAT, e.g., LTE, the 3GPP standard defines a power saving mechanism. This mechanism is essentially designed in the 3GPP standard to consume only the required power to run an application, e.g., voice. Once the application is over, the UE switches to power save mode which is a low power consumption state (idle state). Standards for other RATs like UMTS, WLAN and WiMAX also define similar mechanisms to conserve power by moving to low power consumption state when the applications using the corresponding interface is dormant. Thus, specification and implementation of power-save mechanisms are proprietary to the respective RAT. Hence, for a UE supporting multiple RATs to enable seamless mobility an integrated approach is required. When an application with a certain QoS is running in a multi-RAT UE, to support mobility the UE has to search for a suitable cell from all the RATs. So, the RAT access stratum (RAT-AS) on which the application is running currently is in active state whereas the rest of the access stratums of the supported RATs are dormant. The access stratums of dormant RATs periodically wake up and searched for cells. From the list of searched cells of all the supported RATs the next candidate cell to move to can be found out. The search process in any RAT involves measuring signal strength and calculation of RAT specific suitability criteria. The mobility procedure in the UE can either be initiated by itself or by the network. In case of network initiated mobility the overhead on the UE is a little less since the network provides the radio resource information of the candidate cell. However, in this case also the UE has to measure the signal strength of the cell list provided by the network and report it back to the network. In case of UE initiated handover the UE has to search for cells and select a candidate cell to move to. So, in either case this cell search procedure performed in the UE by each of the access stratum of the RATs can consume a lot of power.

The types of solutions so far investigated in the literature on UE power save mechanisms are discussed here. Bontu and Illidge [1] describe the discontinuous receptions (DRX) parameters in LTE and a way to optimize them for better power saving. This optimization is done without any impact on the connection re-establishment time of UE to the network, while moving from idle state to active state, and minimizes packet delay for the applications running in the UE. Kolding et al. [2] look into how LTE DRX parameters can be optimized taking into account user experience. It models the UE battery and explains how network should set LTE DRX parameters. Although Yang et al. [3] propose a multi-RAT UE power saving mechanism for UMTS and WLAN, it does not consider the signalling overhead in the UE. The scenario describes sending data from the network on the active RAT always even though the other RAT may be the preferred RAT leading to saving of UE power. An adaptive mechanism in the case of IEEE 802.16e, to schedule the wake up time of a UE from sleep mode and its trade-off with response time of the application has been described in [4]. In [5], an implementation of multiple levels of progressively deeper sleep states has been dealt with to achieve better application response time while the UE wakes up. Tse-Hua and Tewfik [6] propose multimedia application specific low power consumption method by using efficient protocol and low complexity multivariate transmission. A mechanism has been put forward in [7] to reduce UE power consumption during broadcast and multicast operations for multimedia traffic using IEEE 802.11 power save methods. Again, for WLAN a power save mechanism using parameters like packet delay, intensity of load, number of queued packets, channel state, packet delay has been proposed [8]. In-depth analysis of entire scope of power saving mechanism, taking multi-RAT UE into consideration, has been surveyed in [9]. The author proposes that host centric networks leads to inefficient power saving and subsequently introduces the concept of information centric. In [10] a framework Multi-Radio Power Management (MRPM) is specified which defines its own set of paging, location update and idle mode procedures triggering the active RAT to wake up other dormant RATs used by newly initiated applications. MRPM silently or in most cases implicitly, mentions the scenario to switch OFF unused RATs to save power without going into detailed analysis. However, MRPM leaves a lot of open points, for example, on the question of signalling overhead and its interworking with RAT specific procedures defined in their respective standards. Haitao et al. [11] talk about registration and non-registration based multi-RAT paging for effective UE power save mechanisms. Hollos et al. [12] deal with paging in ambient networks and Multi-access Radio Resource Management (MRRM) for RAT selection.

As discussed above, most research literature primarily deals with single RAT case of minimizing the power consumption by calculating maximum sleep time of the UE without affecting the QoS of the application, e.g., packet delay. Whenever there are dealings of multi-RAT power save scenarios in the literature, they are related to problems of multi-RAT paging issues and joint radio resource management issues. To the best of the authors' knowledge, none of the previous work analyses this use case of selectively switching OFF less relevant RAT-ASs in detail, apart from a silent mention of the use case. The authors propose a novel mechanism to selectively switch OFF less relevant access stratums of the dormant RATs. This paper defines a set of parameters for this purpose applicable to a dormant RAT-AS. The parameters are (1) user preference, (2) ratio of number of cells with Received Signal Strength Identifier (RSSI) above a apriori defined threshold to the number of cells searched, (3) ratio of the number of cells searched to maximum number of cells that can be searched within a given power usage limit, (4) ratio of the number of cells suitable for mobility procedures from the list of searched cells to number of cells searched. Based on these four parameters, criteria are defined which are used to switch off irrelevant RATs. Simulation results reveal that for lesser number of cells searched (around 30% of maximum possible), the ratio of the number of cells searched to maximum number of cells that can be searched within power usage limit is the preferred parameter for switching OFF RAT-AS. For higher number of cells searched, user preference is the preferred option to switch OFF RAT-AS.

This paper is organized as follows. Section 2 presents the multi-RAT UE architecture. Section 3 depicts an algorithm to switch OFF a dormant RAT-AS. Sections 4 and 5 briefly explain Analytic Hierarchical Process (AHP) and (Quasi) Monte Carlo Simulations respectively. The analytical model is described in section . Simulation and results are shown in Section 7. Section 8 concludes this work and outlines future work.

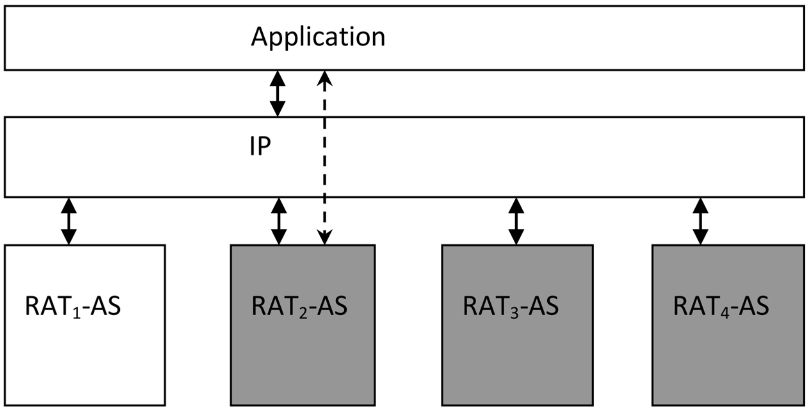

Figure 1 Multi-RAT UE architecture.

2 Multi-RAT UE Architecture

The multi-RAT UE architecture and functionality is described with an example in Figure 1. The UE supports four RATs and access stratum of RAT_1 is used by the application. Hence, RAT-AS_1 is the active RAT. The remaining access stratums namely, RAT_2-AS, RAT_3-AS and RAT_4-AS are dormant, and periodically search for cells. While the UE moves it may use a different RAT based on inter-RAT mobility procedures defined in standards. For example, the RAT_4-AS may become active in case of target cell being from this RAT during a mobility procedure and RAT_1-AS, RAT_2-AS and RAT_3-AS are dormant.

As shown in Figure 2 (Case 1), in a Multi-RAT UE each RAT-AS does a periodic search of cells as required, guided by its respective standards. If RAT_1-AS, RAT_3-AS and RAT_4-AS do this operation (Case 1), it could lead to significant power consumption in the UE. Based on the location of the UE, all the three RAT-AS may not be relevant, e.g., WLAN may not be relevant outside the four walls of the office. Those RAT-ASs can be switched OFF when they are irrelevant as shown in Figure 2 (Case 2). This relevance is defined in terms of four parameters in this paper as mentioned already. In later sections, criteria are defined based on these four parameters and they are evaluated to decide on the most effective criterion to switch OFF the access stratum of the dormant RATs. For evaluation of the criteria with respect to practical scenarios one of the most acceptable techniques namely, Analytic Hierarchical Process (AHP) along with Monte Carlo simulations based on

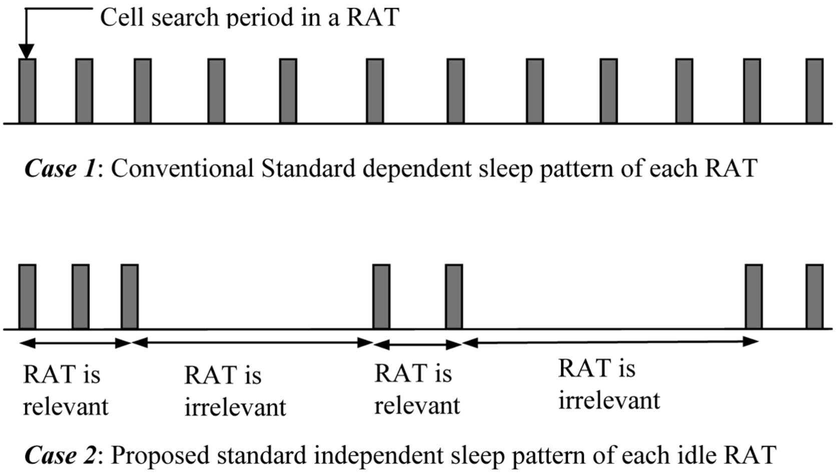

Figure 2 Scheduling of cell search procedure in a RAT.

pseudo-randomness and quasi-randomness are used. These techniques are discussed below.

3 Algorithm

In Figure 3, the flow chart of an algorithm with the proposed ideas to switch OFF the access stratum of a RAT supported by the UE and subsequently switching ON the RAT to search for suitable cells for the UE's mobility is shown. The algorithm holds good for all the RATs supported by the UE. A multi-RAT network deployment is assumed as shown in Figure 4 where no single RAT region is completely within another RAT region. In case of completely overlapping RATs both of RAT-ASs can be relevant simultaneously leading to higher level of power consumption. Initially, each AS of all the supported idle RATs are in active state and searches for cells. After a periodic interval the criteria to switch OFF the RAT-AS are evaluated. The criteria to evaluate will be discussed in the subsequent section. If the criterion to switch OFF the RAT-AS are satisfied, then the RAT-AS is switched OFF, else it remains in active state. A switched OFF RAT-AS can be switch ON again later based on a time-out.

For the evaluation of the criteria to switch OFF a RAT-AS, a few techniques have been used in this paper, which are described briefly in the following sections.

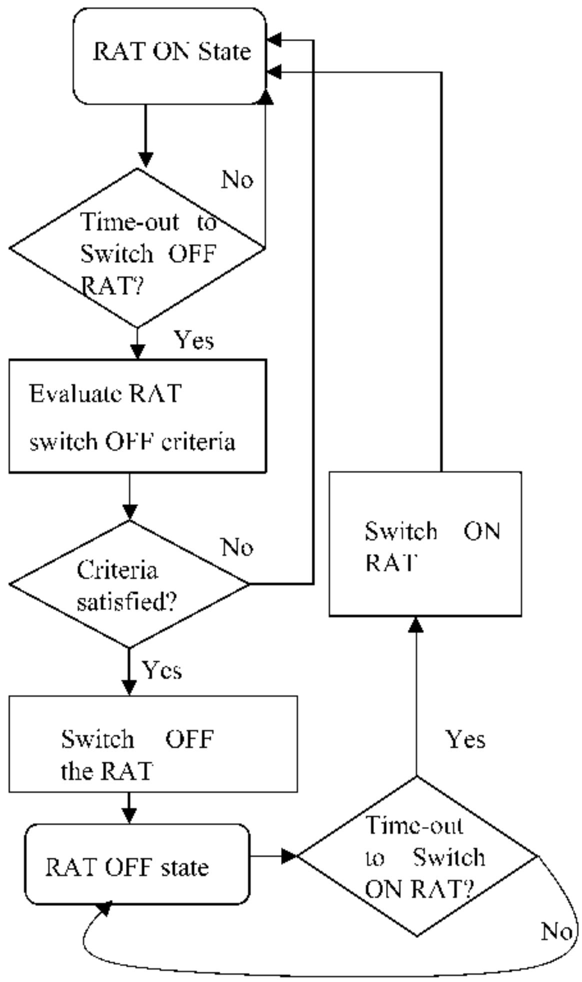

Figure 3 Algorithm to Switch ON and Switch OFF a RAT access stratum.

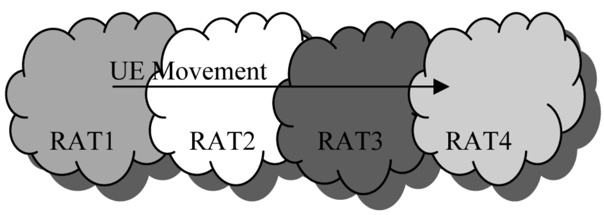

Figure 4 UE movement trajectory.

4 Analytic Hierarchical Process

Analytic Hierarchical Process (AHP) is a method [13, 14] for multi-criteria decision making, to arrive at a best-fit solution from a set of alternative solutions to a given problem. It involves pair-wise comparison of relative importance of each criterion with others from the set of criteria supported by the alternative solutions. Relative importance is assigned by human judgment. Based on this comparison the weights for each of the criteria are calculated using techniques like Eigen values. These weights, along with the alternative solutions available are used to select the best-fit solution. It should be noted that the solution chosen from the set of alternatives will be different if the relative importance of criteria is changed. AHP is used in this paper for deciding on what criteria should be used to switch OFF the RAT-AS.

5 Quasi-Monte Carlo Simulations

In this paper, Monte Carlo simulation [17] has been used to arrive at the results. Normally, Monte Carlo simulations are performed with different types of input distribution to the mathematical model of the addressed problem. To obtain the final result, the output generated by large number of samples from the input distribution is analysed. This paper uses uniformly distributed pseudo-random numbers and quasi-random numbers as its input distributions.

Quasi-random numbers are numbers with predefined statistical properties. In a simulation quasi-random numbers converges much faster than pseudo-random numbers. Quasi-random numbers are also called low-discrepancy sequences. Monte-Carlo simulation performed with quasi-random numbers is called Quasi-Monte Carlo simulation. One example of quasi-random numbers is the van der Corput [15] sequence which is used in this simulation.

The two types of distribution (pseudo-random and quasi-random) are used to compare the results when the geographical deployment of the RAT cells follows those. More specifically, quasi-random numbers are used with the intention that since the RAT cells are deployed in a deterministic way during the radio network planning stage, it would provide a more realistic behaviour of the parameters (user preference, ratio of number of cells above a certain threshold (T_{RSSI}) to the number of cells searched, ratio of the number of cells searched to maximum number of cells that can be searched within power usage limit, ratio of the number of cells suitable for mobility procedure to the number of cells searched) considered in this paper.

6 Analytical Modelling

Let us assume that the UE supports n RATs. Each RAT has its own RAT-AS containing its access technology protocols. These RAT-ASs can be switched OFF and ON independently. Each RAT-AS has its own power requirements. For example, if the UE is in ideal mode, AS of each RAT_i has its power usage limit p_{i-idle}. Similarly, when one of the RAT-AS is fully operational with a running application, the other RAT-ASs are idle most of the time and they wake up to active state to find out if there are any suitable cells available for multi-RAT mobility procedures. Let $p_{i-active}$ be the power usage limit of the RAT_i-AS when active. Also let $p_{threshold}$ is the total power usage limit of all the RAT-ASs in the UE. There total power consumed by AS of RAT_i-AS is $p_{i-RAT} = p_{i-idle} + p_{i-active}$. For the RAT-AS on which the application is running is the active RAT-AS for which we can assume $p_{i-idle} = 0$ since it will not be idle. In active state, the idle RAT-AS which is not supporting any application, wakes up periodically to search for cells in its neighbourhood. To simplify, p_{i-idle} for the idle RAT-AS is ignored since the power consumption will be very less. Let m_i be the maximum number of cells that can be searched by an idle RAT_i-AS within power limit p_{i-idle}. c_i be the number of cells actually searched by RAT_i-AS. Let pc_i be the power consumed by idle RAT_i-AS to search a single cell. Let $p_{x-active}$ is the power consumed by the RAT_x-AS which is active.

Therefore, for an idle RAT-AS

$$c_i \le m_i \quad \text{and} \quad pc_i \cdot c_i \le p_{i-active} \tag{1}$$

For n RATs,

$$\begin{aligned} w_1 \cdot (pc_1 \cdot c_1) \;+\; & w_2 \cdot (pc_2 \cdot c_2) + w_3 \cdot (pc_3 \cdot c_3) + \cdots \\ & + \; w_{x-1} \cdot (pc_{x-1} \cdot c_{x-1}) + w_{x+1} \cdot (pc_{x+1} \cdot c_{x+1}) + \cdots \\ & + \; w_{n-1} \cdot (pc_{n-1} \cdot c_{n-1}) \le p_{threshold} - p_{x-active}, \end{aligned} \tag{2}$$

where $w_1, w_2, \ldots, w_i$, are the weights associated to each RAT_i-AS and RAT_x is used by the application. Also, $i = 1, 2, \ldots, n$, $w_i = 0$ or 1. In this paper, the aim is to derive conditions under which w_i can be set to 0. This means that the power consumption is lowered by quantity of $w_i \cdot (pc_i \cdot c_i)$ for the RAT_i-AS, implying power saving from the UE.

To switch OFF a particular RAT-AS, four criteria are taken into account:

1. *User preference of the RAT (k_1)*: User preference is defined by a user supplied value, u_i. This is a parameter which is assigned a value at the

Table 1 Parameters used in analysis.

Notations	Definitions
n	Number of RAT-AS supported by the UE
i	Denotes ith RAT
p_{i-idle}	Idle state power consumed by RAT$_i$-AS
$p_{i-active}$	Active state power consumed by AS of RAT$_i$-AS
$p_{threshold}$	Total power usage limit of all the RAT-ASs
m_i	Maximum number of cells that can be searched by an idle RAT$_i$-AS
c_i	Number of cells searched by RAT$_i$-AS
pc_i	Power consumed by idle RAT$_i$-AS to search a single cell
$p_{x-active}$	Power consumed by the active RAT$_x$-AS which the application is using
w_i	Weights associated to RAT$_i$-AS
k_1	Identifier for user preference criterion
k_2	Identifier for criterion of number of searched cells having RSSI above a threshold (T_{RSSI})
k_3	Identifier for criterion of number of cells searched within power budget $p_{i-active}$
k_4	Identifier for criterion for number of cells suitable among searched cells
u_i	Value of user preference
s_i	Number of cells searched
r_i	Number of searched cells having RSSI above certain threshold
e_i	Number of suitable searched cells
f_{pq}	Human judgment based relative importance of any two criteria among k_1, k_2, k_3, k_4
$[v_1, v_2, v_3, v_4]^T$	Eigen vector which provides the relative weights of each of the criteria k_1, k_2, k_3, k_4
$algo_{ij}$	Arbitrary algorithmic solutions: $algo_{i1}$ is biased towards e_{ij}/s_{ij}, $algo_{i2}$ is biased towards s_{ij}/m_i, $algo_{i3}$ is biased towards r_{ij}/s_{ij}, $algo_{i4}$ and is biased towards u_{ij}
$[z_1, z_2, z_3, z_4]^T$	Final solutions vector. The highest value in it provides the best criteria to switch of RAT-AS

UE design stage. If, for example, this value is low, then the RAT-AS can be switched OFF.

2. *Number of cells of the RAT from the list of cells searched which has RSSI above a threshold (k_2)*: This criterion is defined by the ratio r_i/s_i where r_i is the number of cells from the list of cells searched which are above a threshold (T_{RSSI}) and s_i is the number of cells searched within a certain period of time. If, for example, this fraction is very low, then the RAT-AS can be switched OFF.
3. *Number of cells searched within the power usage limit (k_3)*: This criterion is defined by the ratio s_i/m_i where s_i is the number of cells actually searched within a certain period of time and m_i is the max-

Table 2 Relative importance matrix.

	k_1	k_2	k_3	k_4
k_1	1	f_{12}	f_{13}	f_{14}
k_2	$1/f_{12}$	1	f_{23}	f_{24}
k_3	$1/f_{13}$	$1/f_{23}$	1	f_{34}
k_4	$1/f_{14}$	$1/f_{24}$	$1/f_{34}$	1

imum number of cells that can be searched within power usage limit $p_{i-active}$. If, for example, this fraction is very low, then the RAT-AS can be switched OFF.

4. *Number of cells suitable from the list of cells searched within the power usage limit (k_4)*: This criterion is defined by the ratio e_i/s_i where s_i is the number of cells searched within a certain period and e_i is the number of cells suitable for mobility procedure. If, for example, this fraction is very low, then the RAT-AS can be switched OFF.

The thresholds used in the above criteria can be determined based on learning mechanisms. It should be noted that the inter-RAT mobility procedures takes care of which RAT will be used by the application. The algorithm proposed in this paper will be applied in the UE after a cell from a different RAT is selected (network initiated or UE initiated) to be used by the currently running applications. To compare the above four criteria k_1, k_2, k_3, k_4 AHP is applied. The relative importance matrix (K) is given in Table 2.

The values f_{pq} which are relative importance of any two criteria (k_p and k_q where $p = 1, 2, 3, 4$ and $q = 1, 2, 3, 4$ and $f_{pp} = 1$) are assigned based on human judgment as defined in AHP. From this matrix (Table 2) the eigen vector (V) is derived which provides the respective weights of each of k_1, k_2, k_3, k_4.

$$V = [v_1, v_2, v_3, v_4]^T \tag{3}$$

Also,

$$v_1 + v_2 + v_3 + v_4 = 1 \tag{4}$$

However, the above eigen vector V only provides the weights for each of the four criteria and does not provide the exact criteria to be applied to switch OFF a RAT-AS. Since, to the best of the knowledge of the authors, there is no algorithm available in literature, for the problem dealt in this paper, four arbitrary algorithmic solutions, $algo_{i1}$, $algo_{i2}$, $algo_{i3}$ and $algo_{i4}$ for RAT$_i$ have been chosen for this analysis. Each of the algorithms take as input the maximum number of cells that can be searched (m_i) within the given

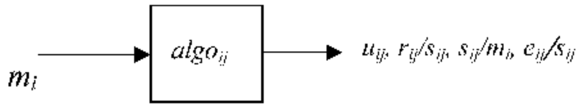

Figure 5 Solution model.

Table 3 Solutions matrix.

	k_1	k_2	k_3	k_4
$algo_{i1}$	u_{i1} (4)	r_{i1}/s_{i1} (3)	s_{i1}/m_i (2)	e_{i1}/s_{i1} (1)
$algo_{i2}$	u_{i2} (3)	r_{i2}/s_{i2} (2)	s_{i2}/m_i (1)	e_{i2}/s_{i2} (4)
$algo_{i3}$	u_{i3} (2)	r_{i3}/s_{i3} (1)	s_{i3}/m_i (4)	e_{i3}/s_{i3} (3)
$algo_{i4}$	u_{i4} (1)	r_{i4}/s_{i4} (4)	s_{i4}/m_i (3)	e_{i4}/s_{i4} (2)

power usage limit ($p_{i-active}$) and provides u_i, r_i/s_i, s_i/m_i and e_i/s_i as output (Figure 5).

Each of these algorithms is assumed to be biased towards one of the four output parameters. $algo_{i1}$ is biased towards e_{ij}/s_{ij}, $algo_{i2}$ is biased towards s_{ij}/m_i, $algo_{i3}$ is biased towards r_{ij}/s_{ij}, and $algo_{i4}$ is biased towards u_{ij}. The bias introduced is a uniform pseudo-random value. Output of each of the algorithms $algo_{ij}$ is different and values of each output parameter have ranking 1, 2, 3, 4, with 1 (highest rank) being assigned to the largest value and 4 (lowest rank) being the smallest value. The algorithmic solution matrix is given in Table 3. The value in parenthesis is the rank.

This above solutions matrix is normalized column wise and then multiplied by the eigen vector in Equation (3), the final solution vector (Z) is obtained.

$$Z = [z_1, z_2, z_3, z_4]^T \tag{5}$$

This highest value in the final solution vector (Z) provides the best criterion to be given preference over other three to switch OFF the RAT-AS. For example, if z_1 is the highest value under certain condition (which means $algo_{i1}$ is the best), then criterion k_4 can be given preference over others. Similarly, if z_2 has the highest (which means $algo_{i2}$ is the best) then k_3 can be given preference, if z_3 has the highest value (which means $algo_{i3}$ is the best) k_2 can be given preference and if z_4 has the highest value (which means $algo_{i4}$ is the best) k_1 can be given preference. This final solution vector (Z) is derived through Monte Carlo simulation under various conditions in the next section (Section 7). A quick reference to all the parameters is listed in Table 1.

Table 4 Relative Importance Matrix for simulation.

	k_1	k_2	k_3	k_4
k_1	1	10.0/8.55	10.0/8.3	10.0/8.8
k_2	8.55/10.0	1	10.0/8.75	9/10
k_3	8.3/10.0	8.75/10.0	1	8.5/10.0
k_4	8.8/10.0	10.0/9.0	10.0/8.5	1

7 Simulation Results and Discussion

In this paper, the criteria to be preferred for switching OFF a RAT-AS are evaluated through well accepted Monte Carlo simulation techniques. We assign different types of distribution for each of parameter for the four criteria defined in Section and compare the results. These assignments are required to make the simulation more practical and take care of UE design (for k_1) and network planning approaches (for k_2, k_3, k_4) taken in an actual multi-RAT network deployment.

For simulation, the relative importance matrix K (as explained in Section 4) is assumed to have the values as given in Table 4. These values are concluded based on human judgment as envisaged in AHP (Section) to select the best criterion for switching OFF idle RAT-AS. All the four criteria are assumed to be equally important with a slight bias towards user preference. Hence, the values for relative importance of each of the criteria are close together.

From these values (Table 4) the eigen vector is calculated which provides the relative weights [vector V in Equation (3)] of the four criteria k_1, k_2, k_3, k_4. The relationship among calculated weights is $v_1 > v_4 > v_2 > v_3$. This means that k_1 has the highest weight, followed by k_4, k_2, k_3 respectively. For the solutions matrix the values of u_{ij}, r_{ij}/s_{ij}, e_{ij}/s_{ij} is assigned values based on distributions, e.g., uniform distribution, quasi-random and also for fixed pattern values, etc., and mi is assumed to have fixed value (except for Figure 14). Large numbers of random samples (10,000) are taken for each of the parameters and then the average value over the number of samples is used to calculate the final solutions vector. In all the plots below, the value of Z vector (Equation (5); along Y-axis) is plotted against s_{ij} (along X-axis).

As explained above, the highest value among z_1, z_2, z_3, z_4 for a particular of s_{ij} (number of searched cells) arrived at through simulations is the best criterion to switch OFF the RAT-AS leaving the rest. For better readability, the relationship between criteria (k_1, k_2, k_3, k_4), arbitrary algorithms ($algo_{i1}$,

Table 5 Relationship between solution vector, algorithms, criteria and weights.

Solution value	Corresponding algorithm	Implied Criterion	Criterion Weights
z_1	$algo_{i1}$	k_4	v_4
z_2	$algo_{i2}$	k_3	v_3
z_3	$algo_{i3}$	k_2	v_2
z_4	$algo_{i4}$	k_1	v_1

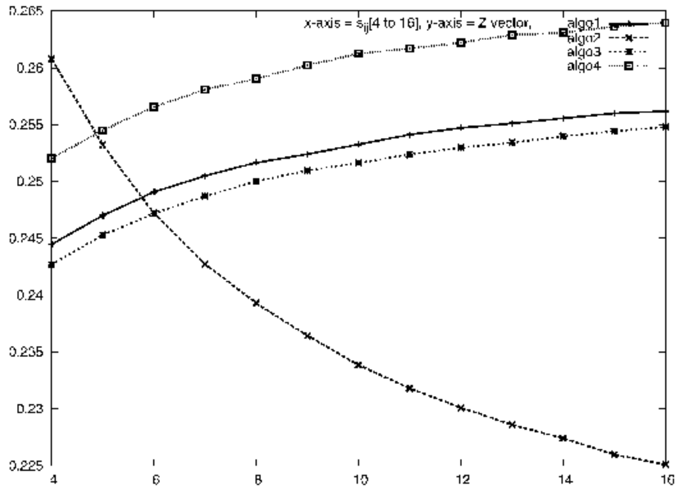

Figure 6 X-axis = s_{ij}, Y-axis = Z vector, u_{ij} = uniform random, r_{ij}/s_{ij} = uniform random, e_{ij}/s_{ij} = uniform random, m_i = 16.

$algo_{i2}$, $algo_{i3}$, $algo_{i4}$), solution values (z_1, z_2, z_3, z_4) and criterion weights (v_1, v_2, v_3, v_4) is shown in Table 5.

In Figure 6, the values of the Z vector in Y-axis is plotted against number of cells searched s_{ij} in X-axis. Here, the three parameters u_{ij}, r_{ij}/s_{ij} and e_{ij}/s_{ij} assume uniform random values for the simulation. The plot shows, for number of cells searched s_{ij} being less than or equal to 5 the highest value is z_2, i.e., $algo_{i2}$ (implying k_3; Table 5). This means when number of cells searched is less than or equal to 5 the RAT-AS can be switched OFF if k_3 is satisfied (Table 5 and Section 6). Rest of the criteria like k_1, k_2, k_4 can be ignored. For s_{ij} from 5 to 16, z_4 i.e., $algo_{i4}$ (implying k_1) performs best. In this case, criterion k_1 decides to switch OFF RAT-AS. However, k_2 and k_4 perform better than k_3, but not as good as k_1 for number of cells searched beyond 6.

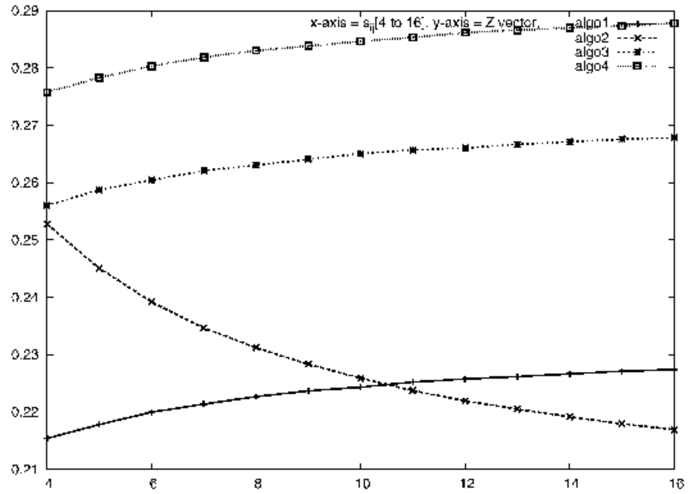

Figure 7 X-axis $= s_{ij}$, Y-axis $= Z$ vector, u_{ij} = fixed, r_{ij}/s_{ij} = uniform random, e_{ij}/s_{ij} = uniform random, $m_i = 16$.

In Figure 7 the Z values are evaluated where u_{ij} are assumed to be fixed (whereas in Figure 6, u_{ij} value are random), e.g., $u_{i1} = 0.25$, $u_{i2} = 0.50$, $u_{i3} = 0.75$ and $u_{i4} = 0.99$, whereas r_{ij}/s_{ij}, e_{ij}/s_{ij} are assumed to have uniform random values. In the above consideration, the plot shows, irrespective of the number of cells searched, solution is z_4 i.e., $algo_{i4}$ (implying k_1). So, based on criterion k_1 RAT-AS can be switched OFF ignoring rest of the criteria.

In Figure 8, the values of u_{ij} (Series 4) are assumed to be quasi-random whereas r_{ij}/s_{ij} and e_{ij}/s_{ij} are assumed to have uniform random values. The plot shows that, for a number of cells searched less than 5, the best solution is z_2, i.e., $algo_{i2}$ (implying k_3). This means that when the number of cell searched is less than 5, the RAT-AS can be switched OFF if k_3 is satisfied. Rest of the criteria can be ignored. For s_{ij} from 6 to 16, z_4 i.e., $algo_{i4}$ (implying k_1) performs best. In this case, criterion k_1 decides on RAT-AS switch OFF, rest of the criteria can be ignored. It is interesting to note that u_{ij} being quasi-random (Figure 8) or uniform random (Figure 6) does not make any significant difference. However, if u_{ij} is fixed then preference should be given to it over other criteria (as shown in Figure 7).

In the next few plots, the behaviour of the r_{ij}/s_{ij} is analysed under various conditions.

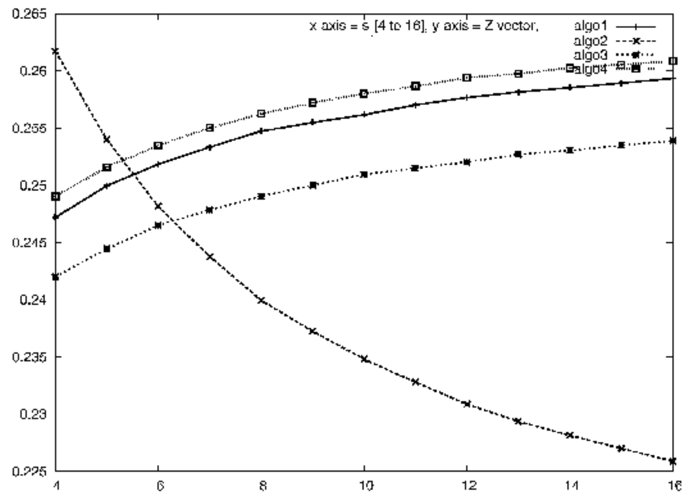

Figure 8 X-axis = s_{ij}, Y-axis = Z vector, u_{ij} = quasi-random, r_{ij}/s_{ij} = uniform random, e_{ij}/s_{ij} = uniform random, $m_i = 16$.

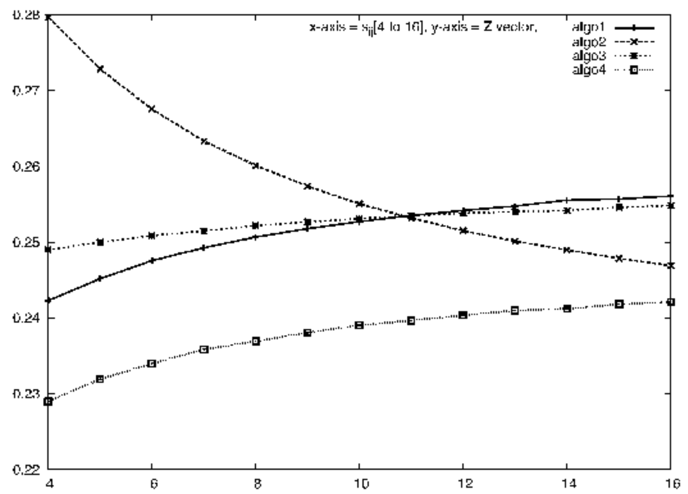

Figure 9 X-axis = s_{ij}, Y-axis = Z vector, u_{ij} = uniform random, $r_{ij}/s_{ij} = \{r_{i4}/s_{i4} = 20\%$, $r_{i2}/s_{i2} = 40\%$, $r_{i1}/s_{i1} = 60\%$, $r_{i3}/s_{i3} = 80\%\}$, e_{ij}/s_{ij} = uniform random, $m_i = 16$.

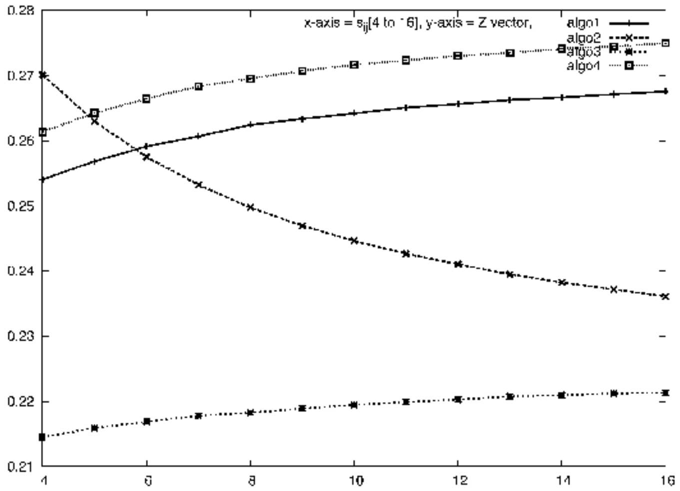

Figure 10 X-axis = s_{ij}, Y-axis = Z vector, u_{ij} = uniform random, r_{ij}/s_{ij} = very close fixed values, e_{ij}/s_{ij} = uniform random, $m_i = 16$.

Figure 9 shows that, if r_{ij}/s_{ij} varies in a fixed pattern $\{r_{i4}/s_{i4} = 20\%$, $r_{i2}/s_{i2} = 40\%$, $r_{i1}/s_{i1} = 60\%$, $r_{i3}/s_{i3} = 80\%\}$, and u_{ij} and e_{ij}/s_{ij} are uniformly random, for s_{ij} below 10, the best solution is z_2, i.e., $algo_{i2}$ (implying k_3). For s_{ij} above 10, z_1, i.e., $algo_{i1}$ (implying k_4) and z_3, i.e., $algo_{i3}$ (implying k_2) performs almost the same. However, z_4, i.e., $algo_{i4}$ (implying k_1) performs less than k_2 and k_4.

In Figure 10, the parameters are same as except for r_{ij}/s_{ij}. Here, r_{ij}/s_{ij} values are very close (72, 75, 77, and 80%) to each other rather than a difference of 20% as above. The plot shows z_2, i.e., $algo_{i2}$ (implying k_3) performs better for s_{ij} below 5. For s_{ij} above 5, z_4 i.e., $algo_{i4}$ (implying k_1) and z_1, i.e., $algo_{i1}$ (implying k_4) performs almost equally better than the rest.

In Figure 11, the r_{ij}/s_{ij} values are quasi-random, and u_{ij} and e_{ij}/s_{ij} are uniformly random. z_4, i.e., $algo_{i4}$ (implying k_1) performs better in most cases except for $s_{ij} = 4$. The rest of the criteria does not perform well.

From the previous three plots, the following conclusions can be drawn. If the difference in the values of r_{ij}/s_{ij} is significant (e.g., 20%) then z_2, i.e., $algo_{i2}$ (implying k_3) can be applied to switch OFF RAT-AS. Rest of the criteria can be ignored. However, if difference in values of r_{ij}/s_{ij} is less, then either of z_4, i.e., $algo_{i4}$ (implying k_1) or z_1, i.e., $algo_{i1}$ (implying k_4) can be applied to switch OFF RAT-AS. Comparing Figures 6 and 11, r_{ij}/s_{ij} being uniform or quasi-random does not make any significant difference.

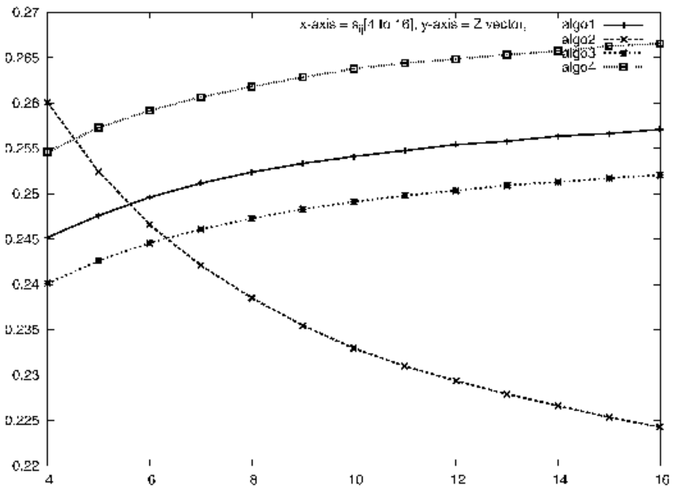

Figure 11 X-axis = s_{ij}, Y-axis = Z vector, u_{ij} = uniform random, r_{ij}/s_{ij} = quasi-random, e_{ij}/s_{ij} = uniform random, $m_i = 16$.

In the next few plots, the behaviour of e_{ij}/s_{ij} is analysed under various conditions.

Figure 12 shows that if e_{ij}/s_{ij} varies in a fixed pattern $\{e_{i4}/s_{i4} = 45\%$, $e_{i2}/s_{i2} = 15\%$, $e_{i1}/s_{i1} = 60\%$, $e_{i3}/s_{i3} = 30\%\}$, and u_{ij} and r_{ij}/s_{ij} are uniformly random. For all values of s_{ij}, z_1, i.e., $algo_{i1}$ (implying k_4) performs best.

In Figure 13, the e_{ij}/s_{ij} values are quasi-random, and u_{ij} and r_{ij}/s_{ij} are uniformly random. The plot shows that z_4, i.e., $algo_{i4}$ (implying k_1) performs better in most cases except for $s_{ij} = 4$. Rest of the criteria does not perform well.

From the above two plots, if e_{ij}/s_{ij} has a fixed pattern then z_4, i.e., $algo_{i4}$ (implying k_1) can be used to switch OFF RAT-AS. Comparing Figures 6 and 13, e_{ij}/s_{ij} being uniform or quasi-random does not make any significant difference.

In all the previous plots (Figures 6 to 12) m_i has been constant, i.e., 16. However, in Figure 14, we varied m_i from 16 to 32 and the rest of the parameters e_{ij}/s_{ij}, u_{ij} and r_{ij}/s_{ij} are assumed to be uniformly distributed to see its impact on Z. Simulation results show that for lesser number of cells searched (30% of maximum possible), the ratio of the number of cells searched to maximum number of cells that can be searched within power

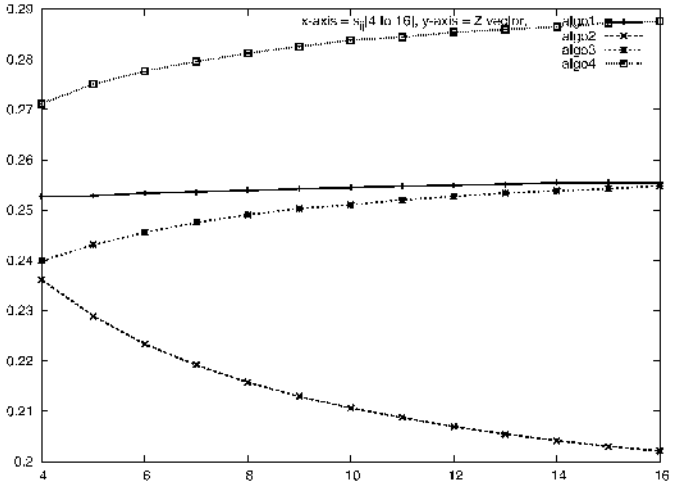

Figure 12 X-axis $= s_{ij}$, Y-axis $= Z$ vector, u_{ij} = uniform random, r_{ij}/s_{ij} = uniform random, $e_{ij}/s_{ij} = \{e_{i2}/s_{i2} = 15\%, e_{i3}/s_{i3} = 30\%, e_{i4}/s_{i4} = 45\%, e_{i1}/s_{i1} = 60\%\}$, $m_i = 16$.

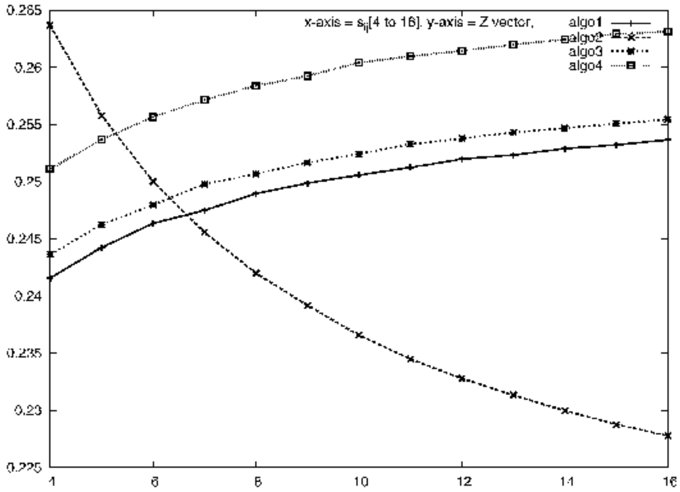

Figure 13 X-axis $= s_{ij}$, Y-axis $= Z$ vector, u_{ij} = uniform random, r_{ij}/s_{ij} = uniform random, e_{ij}/s_{ij} = quasi-random, $m_i = 16$.

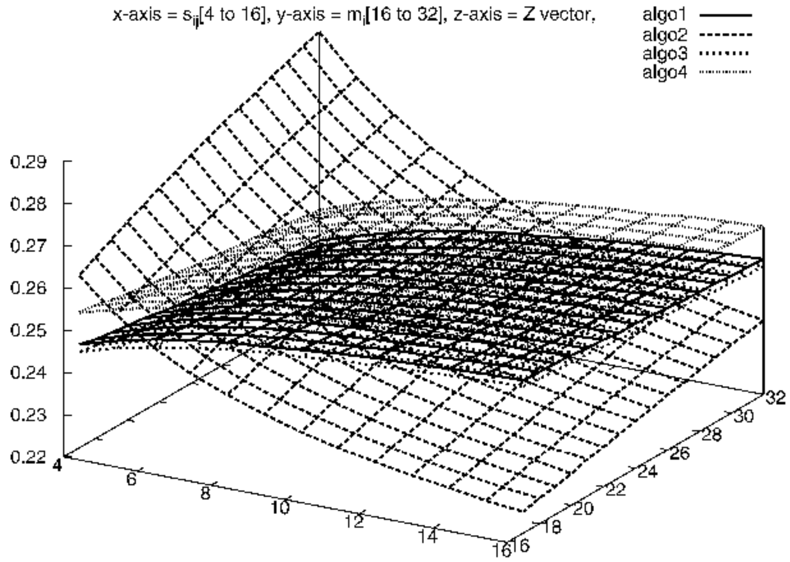

Figure 14 X-axis $= s_{ij}\{4, \ldots, 16\}$, Y-axis $= m_i\{16, \ldots, 32\}$, Z-axis $= Z$ vector, $u_{ij} =$ uniform random, $r_{ij}/s_{ij} =$ uniform random, $e_{ij}/s_{ij} =$ uniform random, $m_i = 16$ to 32.

usage limit (i.e., k_3) is the preferred criteria for switching OFF RAT-AS. For higher number of cells searched, user preference (k_1) is the preferred option.

From the above results derived from Monte Carlo simulation, the following points can be concluded:

1. User preference seems to outperform rest of the criteria to switch OFF RAT-AS for most of the cases if the number of cells searched are more (greater than 30% of maximum possible).
2. For lower number of cells searched (less than 30% of maximum possible), ratio cells searched to maximum cells that can be searched can be used to switch OFF RAT-AS. Rest of the criteria can be ignored.
3. The input parameters of user preference, ratio of suitable cells to cells searched, ratio of cells with RSSI better than threshold to cells searched, being uniformly random and quasi-random does not make a significant difference.

8 Conclusion and Future Work

In this paper, the authors proposed a relevance based RAT-AS switch OFF mechanism to conserve power in a multi-RAT UE. This work defines a set of parameters to be used in this mechanism. They are user preference, ratio of number of cells above a certain threshold (T_{RSSI}) to the number of cells searched, ratio of the number of cells searched to maximum number of cells that can be searched within power usage limit, ratio of the number of cells searched to the number of cells suitable for mobility procedure. Based on these parameters criteria are defined which are used to switch OFF irrelevant RATs. These criteria are prioritized and the best solution under different scenarios is derived using a combination of AHP and Monte Carlo simulations. Simulation results show that for lesser number of cells searched (30% of maximum possible), the ratio of the number of cells searched to maximum number of cells that can be searched within power usage limit is the preferred parameter for switching OFF RAT-AS. For higher number of cells searched, user preference is the preferred option. Future work will concentrate on ways to switch ON RAT-AS effectively so that the UE consume minimum power.

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Biographies

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Debabrata Das received his Ph.D. degree from the Indian Institute of Technology Kharagpur (IIT Kharagpur). At present he is serving as Hewlett Packard Chair and Associate Professor at IIIT-Bangalore (IIIT-B). Before joining IIIT-B, he had served at G S Sanyal School of Telecommunication at IIT Kharagpur and later at Kirana Networks in New Jersey, USA. At present he is Principal Investigator (PI) of Department of Information Technology, Government of India Sponsored project on Green Broadband Wireless Network, and Intel sponsored project on Cross Layer Optimization of Broadband Wireless Network. His areas of teaching interest are, Wireless Access Network, Mobile Computing with IMS and Internetworking. His main areas of research interest are Wireless Access Network's MAC, QoS, Power saving and IP Multimedia Subsystems. Dr. Das has more than 60 peer reviewed papers in different journals and International conferences. He and his wireless network team had contributed three ideas to IEEE 802.16m Broadband Wireless Standard. He is also board member of IT-Service Management Forum India (itSMF), OCAC of Orissa Govt.; and a member of e-Governance committee under Govt. of Karnataka. He was General Chair of IEEE International Conference IMSAA-09. He has been TPC member of number of international conferences and reviewers of IEEE Journals.