Computers and Electrical Engineering 000 (2017) 1–14

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

Radio access technology selection in SDN controlled reconfigurable base station☆

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ARTICLE INFO

Article history:
Received 15 June 2016
Revised 11 April 2017
Accepted 11 April 2017
Available online xxx

Keywords:
Software defined networking
Wireless
Multi-RAT
Mobility
Algorithm
Performance

ABSTRACT

Several Software Defined Networking (SDN) based architectures have been proposed for wireless networks. Among them, the proposal of Reconfigurable Base Station (RBS) programmable with different Radio Access Technologies (RATs) dynamically by an SDN controller has the potential to improve mobility. This improvement can be achieved by dynamically converting expensive inter-RAT mobility procedures into efficient intra-RAT ones by deploying RBSs along with traditional base stations. This conversion requires development of algorithms for optimal RAT selection in RBSs by the SDN controller, to increase the proportion of intra-RAT mobility procedures in the network. We propose three novel algorithms using parameters such as mobility procedure counts and execution time of each procedure. Simulation results compare these algorithms and suggest their applicability under various deployment scenarios and User Equipment (UE) mobility patterns. Also, the algorithm based on mobility procedure counts with preference only to incoming UEs in a cell, performs better in most scenarios.

1. Introduction

Software Defined Networking (SDN) is a key technology for future networks due to its advantages. SDN was initially experimented in wired networks for separating data and control planes to ease maintenance of network devices, e.g., switches. Standards, like OpenFlow [1], define the interface between SDN controller and network devices. SDN controller uses OpenFlow, to configure and maintain data flows in network devices.

Scope of SDN in wireless domain has been explored in various dimensions. They include virtualization of network nodes and functions [2], power saving approaches [3], and load balancing and coverage [4]. There have been several SDN based architectures suggested for overall network [5,6]. implements a programmable data plane, which can be configured with different Radio Access Technologies (RATs) dynamically [7]. suggests that in future, wireless networks (e.g., 5G) are likely to have multiple Radio Access Technologies (RATs) along with SDN, which need to be studied further. In [8], the authors propose a network architecture comprising of mobile cloud, cloud based radio access network and reconfigurable core network, to support virtualized 5G services. Comprehensive surveys of SDN and applications are available in [9]. Survey of SDN in wireless domain has been presented in [10]. It highlights the importance of research to explore and analyse scenarios/use cases of SDN usage in wireless domain. This reason motivates our study to explore a scenario where RBS along with

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Associate Editor Dr. M. Malek.

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http://dx.doi.org/10.1016/j.compeleceng.2017.04.008

Please cite this article as: D. Das, D. Das, Radio access technology selection in SDN controlled reconfigurable base station, Computers and Electrical Engineering (2017), http://dx.doi.org/10.1016/j.compeleceng.2017.04.008

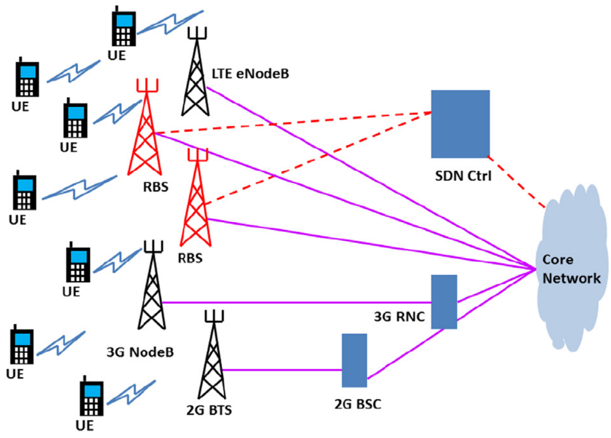

Fig. 1. SDN controlled multi-RAT network architecture [17].

traditional multi-RAT networks can be used to improve mobility of User Equipment(UE), and also propose algorithms for optimal RAT selection in RBS.

A few definitions in the context of this paper are as follows:

- ***Intra-RAT Mobility (IntraRM)***: IntraRM refers to procedure where a UE moves from a cell to another belonging to the same RAT, e.g., LTE to LTE.
- ***Inter-RAT Mobility (InterRM)***: InterRM refers to procedure where a UE moves from a cell to another but belong to a different RAT, e.g., LTE to UMTS.
- ***Reconfigurable Base Station (RBS)***: RBS is defined as a base station with generic hardware which can be configured to a RAT dynamically. In SDN approach, RBS only has the data plane, e.g., OpenRadio [6], and centralized control plane resides in the SDN controller. SDN controller programmes the RBS with the desired RAT.
- ***Traditional Base Station (TBS)***: TBS have integrated control and data planes running on RAT specific hardware, e.g., LTE eNodeB, and their configurations are static by nature.

InterRM procedures have overheads in terms of latency. Also, InterRM procedures are difficult to implement, both at network and UE [11]. IntraRM procedures are much more optimal with respect to above mentioned points [12]. If vertical mobility procedures (i.e., mobility at layer 3 and above) are used in multi-RAT scenarios, they have much higher latencies [13]. To explain our proposal, let us consider a multi-RAT network deployment with TBS and SDN controlled RBS (e.g., Fig. 1). If the network and SDN controller observe that UEs move predominantly from one RAT to another (e.g., LTE to HSPA) in an area, the SDN controller may decide to reconfigure some of the RBSs with the original RAT (i.e., LTE). This operation by the network needs control plane signaling procedures to be performed among network nodes and the SDN controller. Then, an IntraRM procedure has to be executed for the UE that triggers this RBS reconfiguration. Other UEs having similar mobility paths gain from this reconfiguration, since they can now execute efficient IntraRM procedures. Also, as a result, there is reduced impact of inter-RAT coexistence problems. On the other hand, intra-RAT issues, like interference, may increase. However, there have been extensive studies to respond to these problems, like advanced interference mitigation [14]. Also, necessary steps needs to be taken to avoid loss of coverage due to this reconfiguration with solutions, like change in cell size [15]. Having mentioned these couple of problems, several unprecedented and interesting issues in radio resource management, coverage etc., may arise as a result of dynamic reconfiguration of RBS, which will have scope of further research.

It should be noted that we are not proposing improvement in existing latencies of IntraRM or InterRM procedures, which have been studied at length. Neither are we enhancing UEs and/or network selecting an appropriate RAT to meet QoS, which is referred to as network selection [16]. We are suggesting dynamic conversion of some of the high latency InterRM to less latent IntraRM using RBS (programmable by SDN controller).

In this paper, we revisit the impact of deploying SDN controlled RBS in a traditional multi-RAT cellular network to improve mobility of UEs, by dynamically converting some of the InterRM procedures to IntraRM [17]. Simulation results show that with higher deployment of RBS, a maximum increase of 11% in probability of IntraRM procedures is observed. These results hint at the need for optimal RAT selection in RBS by SDN controller under different deployment scenarios and UE mobility patterns. However, to the best of our knowledge, no algorithms have been proposed in the literature (including [17]) to select appropriate RAT in RBS, to be programmed by the SDN controller for dynamically converting InterRM to IntraRM. Hence, we propose three novel algorithms for RAT selection in RBS. Simulations results compare these algorithms under various deployment scenarios of RBS along with TBS, and UE mobility patterns, and suggest their applicability. One key observation is that, the proposed algorithm based on mobility procedure counts, where preference is given only to incoming UEs in a cell, seems to perform better than the other two in most scenarios analyzed here.

Apart from designing the proposed algorithms, another key challenge faced in this contribution was the creation of a clustered multi-RAT deployment model with RBS, similar to the ones that exist in real deployments. Though, it would have been simpler to assume uniformly distributed cells from all RATs as well as for RBS, creating clusters is more realistic, albeit nontrivial. Having a realistic deployment model was an essential component to evaluate the proposed algorithms.

This paper is organized as follows. Section 2 discusses the latency problems in multi-RAT mobility. Proposals for base station reconfigurability is discussed in Section 3. An architecture of multi-RAT network with SDN support is described in Section 4. We propose three novel algorithms to select suitable RAT for RBS in Section 5. To evaluate the performance of proposed algorithms, simulation models are discussed in Section 6. Section 7 presents the results. Conclusion is drawn in Section 8.

2. Problems with multi-RAT mobility

2G systems primarily worked in silos. With the introduction of 3G systems, e.g., UMTS, the need for multi-RAT mobility arose to support seamless handoffs with 2G systems, e.g., GSM, and vice versa. The required latency during mobility has to be within the QoS requirements of applications. InterRM procedures between GSM and UMTS are horizontal in nature, i.e., RAT change happens at layers 1 and 2 of the protocol stack. InterRM procedures can also be designed at layer 3 and above, which is referred to as vertical mobility. One example of this kind is LTE and WLAN mobility, where mobility takes place at layer 3 with the help of Mobile IP. Vertical mobility seems to be typically advocated when the RATs involved are proposed by different standardization bodies. Different types of handoffs are studied in [13]. Various kinds of handoffs supported in LTE are discussed in [18]. Latency in InterRM (horizontal or vertical) is higher than IntraRM. In addition, InterRM have higher implementation complexities. Results from [11] indicate that Voice Call Continuity (VCC) from UMTS to LTE and vice versa requires 230ms to 500ms. On the contrary, LTE to LTE handoff requires around 100ms [12]. This discrepancy stimulates us to study ways to improve mobility through usage of RBS.

3. Reconfigurable networks proposals

One of the proposals for futuristic wireless networks is to support reconfigurability [19]. In the contexts of Software Defined Radio (SDR) and Cognitive Radio (CR), reconfigurability has been predominantly explored. Another proposal of managing radio resource from multiple RATs at a single network node has been advocated, which is designated as Single Radio Controller (SRC) [20]. A comprehensive survey of reconfigurability of wireless networks has been presented in [21]. Also, ETSI has forwarded functional requirements and use cases of Radio Reconfigurable Systems (RRS) [22]. An extended form of reconfigurability of base stations to support data plane programmability with required RAT using SDN has been proposed in [6].

4. Multi-RAT network architecture with SDN

In Fig. 1, an architecture of multi-RAT wireless network to handle the scenario of reconfiguration of base stations to a desired RAT with SDN controller, is shown. RBSs along with traditional 2G, 3G, 4G network nodes exchange messages to support mobility. In future, existing LTE eNodeBs, UMTS RNCs etc., may get virtualized, with network protocols and baseband processing being implemented in the cloud [23]. Network nodes send their InterRM reports, like handoff counts, to the SDN controller. The SDN controller, based on these reports, decides to reconfigure RBS with the desired RAT. This leads to some of the InterRM procedures being converted to IntraRM. Interaction between SDN controller and the network nodes is still an open research topic [24]. However, irrespective of how these interfaces are specified, our approach of configuring RBS to a different RAT for improving mobility holds good at an abstract level. There are a few choices the SDN controller can act upon. Firstly, the load on the RBS which needs to be reconfigured has to be considered. Ideally, it should have no UEs attached to it. This is because, those attached UEs have to be moved to the newly configured RAT. However, it is pertinent to make this sacrifice if large number of UEs in the overall network benefit from the reconfiguration of RBS.

5. Proposed algorithms for selecting appropriate RAT for RBS

In this section, three algorithms are proposed, each run by the SDN controller to select the appropriate RAT to configure the RBS. RAT selection algorithms have been studied in the context of network selection for heterogeneous networks. In network selection, UEs and/or network choose the best RAT to support the QoS of the application [16]. Typical scenarios where these algorithms apply are during admission control and offloading of some sessions of UEs to a different RAT. However, we have designed our algorithms for an entirely different paradigm (InterRM to IntraRM conversion) as already described.

We assume that there are cells from R RATs deployed in a region. Let u_is' be the number of UEs from its neighbours (with RAT_i) that move to a cell c_t (with RBS) configured with RAT_t undergoing InterRM, where both $i,t \in \{1,2 ..,R\}$ and $i \neq t$. Let u_t be the number of UEs that are already camped in the target cell c_t. All u_is' and u_t are cumulative values observed over a period of time, which we refer to as *history*. This history is used by the proposed algorithms in the SDN controller to select the optimal RAT with which an RBS will be programmed.

5.1. Algorithm 1

The first proposed algorithm finds the maximum of all the u_is'. If u_m is the maximum value (where $m \in \{1, 2.., R\}$), then the target RBS is configured with the RAT_m. This algorithm gives more importance to the incoming UEs. The maximum value of incoming UEs from different RATs to a cell with RBS, i.e., *MaxVal*, is calculated as,

$$MaxVal = max\{u_i\} \tag{1}$$

where $i \in \{1, 2.., R\}$. We explain this algorithm with an example.

Cell c_t has an RBS programmed with RAT_t, and it has u_1, u_2 and u_3 number of UEs coming into it from its neighbours with RAT_1, RAT_2 and RAT_3 respectively. This algorithm finds the maximum of u_1, u_2 and u_3 and configures the RBS with the corresponding RAT, e.g., if u_2 is the maximum value (i.e., $MaxVal = u_2$), then the RBS in c_t is configured from RAT_t to RAT_2.

The advantage of this algorithm is its simplicity, but it disregards the number of UEs already camped in the target cell, i.e., u_t. If u_t is high and the chosen RAT for reconfiguration is different from RAT_t, then u_t UEs have to undergo an unnecessary InterRM procedures. The pseudo code for the algorithm is given below, which is executed for each RBS, i.e., r times in all, where r is the number of RBS deployed in the region. Hence, the computational complexity of this algorithm is $O(rR)$. *HistoryUeMobility* contains the count of UE mobility over a period of time. Each row in *HistoryUeMobility* indexed by *CellIndex* represents a cell with RBS. The first column contains u_t. Thereafter, column $i + 1$ contains UEs moving to the RBS (row indexed by *CellIndex*) from RAT_i. This data structure interpretation holds good for all the three algorithms. Lines 15–24 calculate the maximum value of incoming UEs from different RATs and returns the RAT index, to be used by SDN controller to configure the RBS.

5.2. Algorithm 2

To circumvent the shortcoming of unnecessary InterRM procedures for UEs (already associated with the target cell) in the first algorithm, in the second proposal we give importance to incoming UEs as well as those camped in the cell. Firstly, the maximum value of all UEs u_is' and u_t is calculated which is designated as *MaxVal*, i.e.,

$$MaxVal = max(\{u_i\} \cup u_t) \tag{2}$$

where $i \in \{1, 2.., R\}$. Then, the sum is calculated for all u_is' and u_t except for the one which matches *MaxVal*, i.e., if

$$MaxVal = u_m, \ \ m \in \{1, 2, .., R\} \tag{3}$$

then

$$Sum = \sum_{l \in \{1,2..,R\} \cup \{t\}, l \neq m}^{R} u_l \tag{4}$$

If $Sum < MaxVal$, then the RBS is configured with RAT_m, else its RAT remains unchanged. We explain this algorithm with the following example.

Cell c_t has an RBS configured with RAT_t, and it has u_1, u_2 and u_3 UEs coming into it from its neighbours with RAT_1, RAT_2 and RAT_3 respectively. Then, $MaxVal = \max(\{u_1, u_2, u_3, u_t\}) = u_2$, assuming u_2 is the largest value. Next, the sum is calculated as, $Sum = u_1 + u_3 + u_t$. If $Sum < MaxVal$, then RBS is configured with RAT_2, else it remains unchanged.

The pseudo code of the algorithm is given below, which is executed for each RBS, i.e., r times in all. Computational complexity of this algorithm is same as Algorithm 1, i.e., $O(rR)$. The data structure interpretation is also same as Algorithm 1. Lines 7–15 calculate the maximum value of incoming UEs from different RATs as well as UEs from the camped RAT. Then, the partial sum, excluding this maximum value, is derived in lines 19–26. If the partial sum is less than the maximum value, then the RBS is reconfigured with the RAT that matches the maximum value, else there is no reconfiguration (lines 27–30).

5.3. Algorithm 3

In this algorithm, we calculate the difference of two parameters: 1) the total time of all the IntraRM procedures that would happen after reconfiguration, and 2) the total time for all the InterRM procedures that will happen after reconfiguration.

If RBS is configured with RAT_i, then the first parameter is,

$$d_{intra_i} = u_i t_{intra-RAT_i} \tag{5}$$

where $t_{intra-RAT_i}$ is the IntraRM procedure time in RAT_i. Second parameter is,

$$d_{inter_i} = [\sum_{j \in \{1,2..,R\}, j \neq i}^{R} u_j t_{inter-RAT_{ji}}] + u_t t_{inter-RAT_{ti}} \tag{6}$$

where $t_{inter-RAT_{kl}}$ is InterRM procedure time from RAT_k to RAT_l. $k, l \in \{1, 2, .., R\}$ and $k \neq l$. Now, the difference of (5) and (6) is,

$$\Delta d_i = d_{intra_i} - d_{inter_i} \tag{7}$$

```
procedure Algorithm 1(HistoryUeMobility, CellIndex)
/* This algorithm is executed for each cell with RBS in SDN controller.
Each row indexed by CellIndex in HistoryUeMobility
represents a cell information with RBS
HistoryUeMobility contains the history of UE mobility
from one RAT to another, i.e., u_i s' and u_t.
Column i + 1 in HistoryUeMobility
contains number of UEs moving from RAT_i to cell indexed by CellIndex
We start from column 2 in HistoryUeMobility because column 1
contains the number UEs camped in the cell, i.e., u_t.
*/
begin
/* Find the value of i for which incoming u_i from RAT_i is maximum */
MaxVal = HistoryUeMobility[CellIndex, 2]
i = 2
for  j = 2  to  R
begin
    if(HistoryUeMobility[CellIndex, j] > MaxVal)
    begin
        MaxVal = HistoryUeMobility[CellIndex, j]
        i = j
    endif
endfor
return(i) /* RBS configured with RAT_i */
end
```

If

$$MaxVal = max\{\Delta d_i\} = \Delta d_m \tag{8}$$

then RBS is configured with RAT_m. We take the following example to explain this algorithm.

Let c_t be a target cell configured with RAT_t, and it has u_1, u_2 and u_3 UEs coming into it from its neighbours with RAT_1, RAT_2 and RAT_3 respectively. If c_t is configured with RAT_1, then $d_{intra_1} = u_1 t_{intra-RAT_1}$, $d_{inter_1} = u_1 t_{inter-RAT_{21}} + u_3 t_{inter-RAT_{31}} + u_t t_{inter-RAT_{t1}}$ and $\Delta d_1 = d_{intra_1} - d_{inter_1}$. Assuming c_t is configured with RAT_2, then $d_{intra_2} = u_2 t_{intra-RAT_2}$, $d_{inter_2} = u_1 t_{inter-RAT_{12}} + u_3 t_{inter-RAT_{32}} + u_t t_{inter-RAT_{t2}}$ and $\Delta d_2 = d_{intra_2} - d_{inter_2}$. If c_t is configured with RAT_3, then $d_{intra_3} = u_3 t_{intra-RAT_3}$, $d_{inter_3} = u_1 t_{inter-RAT_{13}} + u_3 t_{inter-RAT_{23}} + u_t t_{inter-RAT_{t3}}$ and $\Delta d_3 = d_{intra_3} - d_{inter_3}$. Now, $MaxVal = \max\{\Delta d_1, \Delta d_2, \Delta d_3\} = \Delta d_2$, assuming Δd_2 is the largest. RBS in c_t is configured with RAT_2.

The pseudo code of the algorithm is given below, which is executed for each RBS, i.e., r times in all. Computational complexity of this algorithm is $O(rR^2)$. However, R is likely to be small, so the quadratic factor will not be a major hurdle. In addition to the data structures in the previous algorithms, in this case we have a two-dimensional data structure *HoTime*, which contains the time taken by IntraRM and InterRM procedures. Entry (i, j) contains InterRM time required from RAT_i to RAT_j whereas (i, i) is IntraRM time for RAT_i. Line 8 calculates d_{intra_i} whereas lines 10–16 derive d_{inter_i}, if RBS is configured with RAT_i. Corresponding Δd_i are calculated and stored in line 18. Lines 21–30 find out the maximum value of Δd_i, which is used by SDN controller to reconfigure RBS with RAT_i.

6. Simulation models for performance evaluation

To evaluate the performance of the three proposed algorithms, we take the system simulation approach. Our objective is to measure the change in number of IntraRM procedures, when SDN controller applies these algorithms to select the appropriate RAT for RBS. The first step in the simulation methodology is to create a multi-RAT deployment model (Section 6.1) consisting of clusters of cells (each cluster belongs to a RAT), and some of them have RBS configured with one of the RATs. Then, the UE mobility model (Subsection 6.2) is run on the deployment model. The number of InterRM and IntraRM procedures are recorded. Using this history of counts, the SDN controller uses one of the three algorithms and reconfigures the RBS with appropriate RAT. After reconfiguration, the UE mobility model is run again and the IntraRM and InterRM procedures are counted. The probabilities of IntraRM and InterRM procedures are calculated from these counts. For example, if x_{intra} and x_{inter} are the counts of IntraRM and InterRM procedures over time, then probability of IntraRM is calculated as,

$$p_{intra} = \frac{x_{intra}}{(x_{intra} + x_{inter})} \tag{9}$$

Similarly, probability of InterRM is,

$$p_{inter} = \frac{x_{inter}}{(x_{intra} + x_{inter})} \tag{10}$$

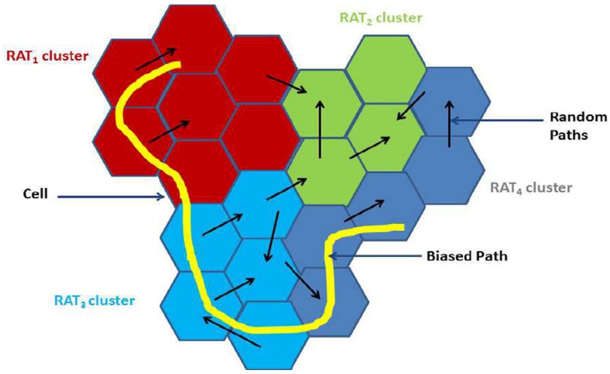

Fig. 2. Random and biased path mobility of UEs.

Table 1
Simulation parameter values and their descriptions [17].

Parameter	Values	Description
N	500	Max. number of cells
R	4	Max. number of RATs
K	54	Max. size of TBS cluster
L	24	Max. size of RBS cluster
k	0% - 100%	Percentage of RBS
M	$kN/(100 \times 24)$	Max. number of RBS clusters
p	100	Max. number of UEs in a cell
q	{10%, 40%, 70%} of p	Max. number of UEs moving out of a cell

These probabilities are calculated before and after the RBS reconfiguration. The total number of mobility procedures is kept same for both the cases. So, any increase in p_{intra} would mean higher IntraRM, which is always encouraged, and this in turn means decrease in expensive InterRM procedures. This process is repeated for each of the three algorithms with different UE mobility patterns (discussed latter in subsection 6.2) to evaluate their performances. We now discuss the two models [17]: 1) multi-RAT network deployment model which consists of TBS with different RATs as well as RBS, and 2) UE mobility model. These models were implemented in programming language R.

6.1. Multi-RAT network deployment model

This model provides a multi-RAT network deployment, where over a geographical area there are N cells. These cells are from R different RATs. Each RAT deployed form a cluster of uniformly distributed cells. The maximum number of cells in a cluster is K. Clusters themselves are distributed uniformly over the region. Among the clusters, M of them consist of RBSs. Each cluster of RBS can have a maximum of uniformly distributed L cells. A fraction k of N cells forms the cells of M clusters. Since, we are only interested to count the mobility procedures, the physical layer parameters are abstracted. We assume that each cell has the capacity to handle all the incoming UEs from its neighbours as well as those camped in it.

6.2. UE mobility model

For the UE mobility model, number of UEs that move out of camped cells to their neighbours is assumed to follow a poisson distribution. A fraction q of the p UEs that are camped in a cell can move to neighbour cells. UEs experience InterRM if the source cell has different RAT from that of the target cell, else they undergo IntraRM. In random mobility, UE can move to any of the neighbour cells. In addition to this random mobility, we define a model with biased paths, where UEs move out of camped cell only to one of its neighbours. This mobility pattern is used to simulate a city-like condition, where UEs seem to move in designated paths at given time of the day, e.g., during morning hours the mobility of people is from home to workplace. The concept of random and biased path is depicted in Fig. 2.

7. Results and discussion

Simulation results presented here use the models described in Sections 6.1 and 6.2. Table 1 lists the parameter values used in simulations. Value of N as 500 is chosen to make the simulated deployment model reasonably large. Value of R is taken as 4 because today's deployment already consists of GSM, UMTS and LTE, and we have added a futuristic RAT for 5G. Values of K and L are based on [25] which presented deployment scenarios with cluster of cells. We assumed that the RBS clusters will be small as they are likely to be deployed in selected areas. The parameter k represents the percentage of

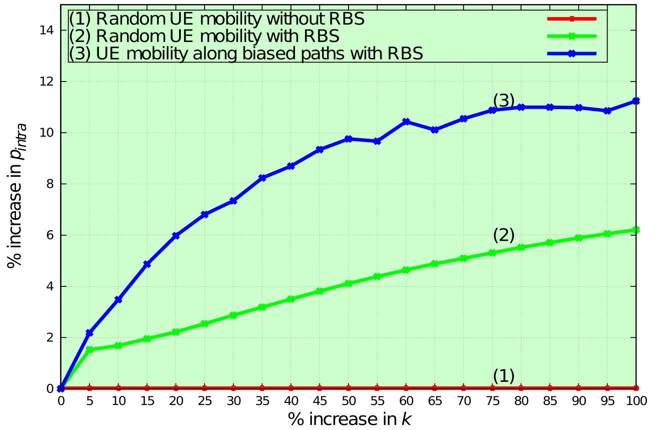

Fig. 3. Variation in p_{intra} with increase in k [17].

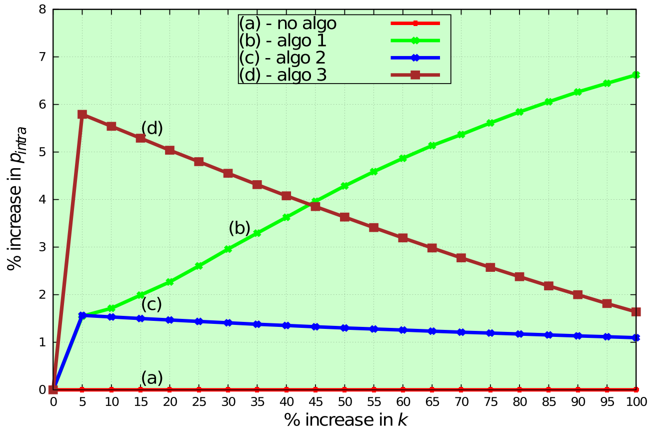

Fig. 4. Variation in p_{intra} with increase in k using the three proposed algorithms (UE mobility random).

RBS being deployed in the overall network. Parameter p is the number of UEs camped in a cell and q is varied (as shown in Table 1) to simulate different proportion of UE mobility from a cell to its neighbours. In the following paragraphs, we investigate the performance of the three algorithms, with two UE mobility patterns, random and biased, running on the deployment model. Also, we investigate the impact of increased history on the performance of the algorithms.

For Figs. 3–11, x-axis represents increase in deployment of RBS, i.e., k, whereas y-axis shows the variation in probability of IntraRM procedure, i.e., p_{intra}.

In Fig. 3, we observe the impact of RBS deployment in improving mobility of UEs in a multi-RAT network [17]. Label (1) which merges with x-axis is the scenario without our proposal of converting InterRM to IntraRM. The case where UEs move along random paths with presence of RBSs is labelled as (2). Label (3) represents the scenario when UEs have biased paths with RBSs being present. Plot reveals couple of interesting observations. A gain of 4%-6% in p_{intra} can be seen from (1) to (2) with increase in k. Also, a further increase of maximum of 5% from (2) to (3) is observed. So, a maximum increase of 11% in p_{intra} is possible. Another notable point is that the increase in p_{intra} saturates for $k > 70\%$. This happens because more UEs undergo InterRM with rise in RAT reconfigurations in RBSs, as k is increased.

7.1. Performances of proposed algorithms with UE mobility along random and biased paths

In this subsection, we study the performance of the three proposed algorithms with increase in RBS deployment and fixed proportion of UEs undergoing mobility in cells, i.e., $q = 40\%$. UEs can take either random or biased paths.

In Fig. 4, we see that Algorithm 1 performs well when k is above 45%. However, Algorithm 3 performs better than Algorithm 1 when k is below 45%, but both always outperforms Algorithm 2. Algorithm 2 shows minor variations for all values of k. The reason behind the above observations is Algorithm 3 being conservative. As RBS deployment increases, it triggers a suboptimal RAT selection based on the product of number of UEs and the InterRM period. For example, a suboptimal RAT selection happens in the case when the number of UEs is small and the InterRM period to the target RAT is high, versus the case when number of UEs is large and the InterRM time is low, leading to product of two quantities being similar. In case of Algorithm 2, we consider the importance to both incoming and outgoing UEs, hence they even out and

```
procedure Algorithm 2(HistoryUeMobility, CellIndex)
/* the variable descriptions used are same as algo1 */
begin
/* Find the value of i for which incoming UEs u_i from RAT_i
as well as u_t is maximum */
MaxVal = HistoryUeMobility[CellIndex, 1]
i = 1
for  j = 1  to  R
begin
    if(HistoryUeMobility[CellIndex, j] > MaxVal)
    begin
        MaxVal = HistoryUeMobility[CellIndex, j]
        i = j
    endif
endfor
/*find the partial sum of UEs coming into the cell
other than the maximum value calculated in the previous
loop*/
Sum = 0
for  j = 1  to  R
begin
    if(j! = i) /* exclude the maximum value */
    begin
        Sum = Sum + HistoryUeMobility[CellIndex, j]
    endif
endfor
if(Sum < MaxVal)
    return(i) /* RBS configured with RAT_i */
else
    return(NO_RAT_CHANGE) /* Don't reconfigure RBS */
end
```

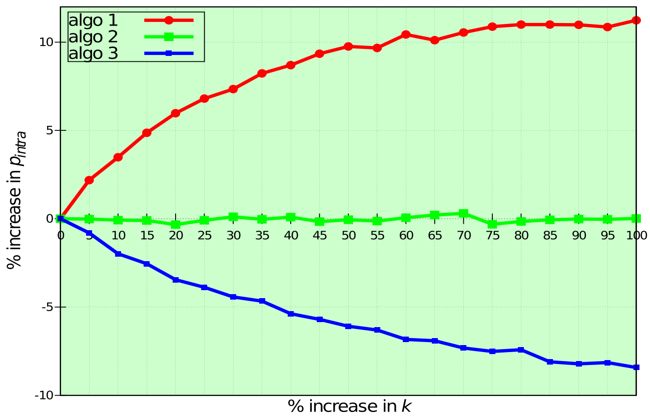

Fig. 5. Variation in p_{intra} with increase in k using the three proposed algorithms (UE mobility biased).

the performance is consistent with increase in k. On the other hand, Algorithm 1 is more aggressive in RAT reconfiguration since the incoming UEs are given higher priority leading to more UEs getting benefitted from the reconfiguration of RBS. These observations of the three algorithms seem to hold good for rest of the results also. Fig. 5 shows the performance of the three algorithms when the UE mobility is biased towards certain paths. Rest of the parameter values remain same as in Fig. 4. We observe that Algorithm 1 performs better compared to the other two. Algorithm 2 does not show any improvement. However, Algorithm 3 shows a decline in p_{intra}. This is because, when the mobility of the UEs follow biased paths, presence of any TBS brings down p_{intra} as InterRM procedures increase. Another reason is suboptimal selection of RAT in RBS, which leads to more InterRM procedures.

Please cite this article as: D. Das, D. Das, Radio access technology selection in SDN controlled reconfigurable base station, Computers and Electrical Engineering (2017), http://dx.doi.org/10.1016/j.compeleceng.2017.04.008

```
procedure Algorithm 3(HistoryUeMobility, CellIndex)
/* HoTime is a square matrix of size R × R
Any entry (i, j) gives InterRM time required from
RAT_i to RAT_j and (i, i) is IntraRM time for RAT_i */
/* rest of the variable descriptions used are same as algo1 and algo2 */
for i = 1 to R
begin
    d_intra_i = HistoryUeMobility[CellIndex, i + 1]
    *HoTime[i, i]
    d_inter_i = 0 /* calculate d_inter_i */
    for j = 2 to R + 1
    begin
        if(j! = i + 1) /* exclude IntraRM */
        d_inter_i = d_inter_i
        +HistoryUeMobility[CellIndex, j] * HoTime[j − 1, i]
    endfor
    /* store Δd_i for each RAT_i */
    Δd[i] = d_intra_i − d_inter_i
endfor
/* calculate max. Δd_i */
MaxVal = Δd[1]
i = 1
for j = 2 to R
begin
    if(Δd[j] > MaxVal)
    begin
        MaxVal = Δd[j]
        i = j
    endif
endfor
return(i) /* RBS is reconfigured with RAT_i */
end
```

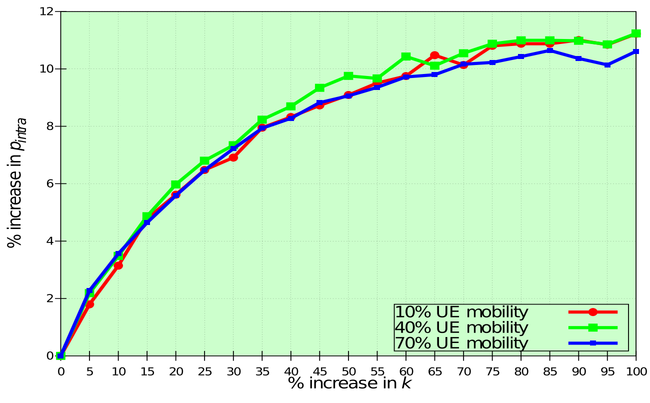

Fig. 6. Variation in p_{intra} with increase in k using Algorithm 1 (UE mobility biased).

7.2. Performances of proposed algorithms with increased UE mobility along biased paths

In this subsection, we study the performance of the three proposed algorithms with increased UE mobility along biased paths, as well as scaling up RBS deployment. For evaluation of the three algorithms in this condition, the proportion of UEs undergoing mobility in cells (i.e., q) varies as 10%, 40% and 70% respectively.

In Fig. 6, we investigate the performance of Algorithm 1 with varying q. We find that there is no major variation in p_{intra}. This observation essentially means that higher mobility does not have any impact on p_{intra}, since on average same number of UEs move in and out of the biased paths. Fig. 7 shows the impact on p_{intra} when Algorithm 2 is applied for reconfiguration of RBS. We observe that there is no major variation in p_{intra}. Also, the overall performance of Algorithm 2 is worse than Algorithm 1. Fig. 8 applies Algorithm 3. We see that there is a decrease in p_{intra} with increase in k due to similar reasons

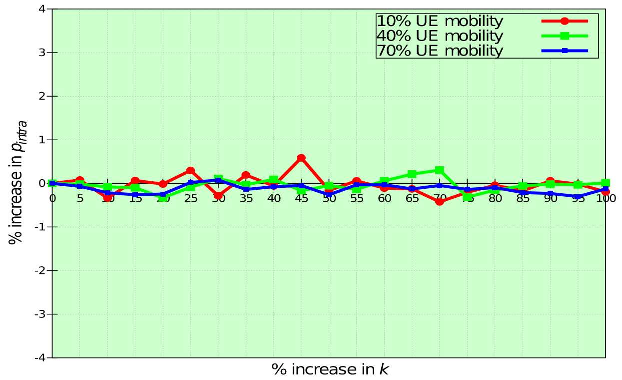

Fig. 7. Variation in p_{intra} with increase in k using Algorithm 2 (UE mobility biased).

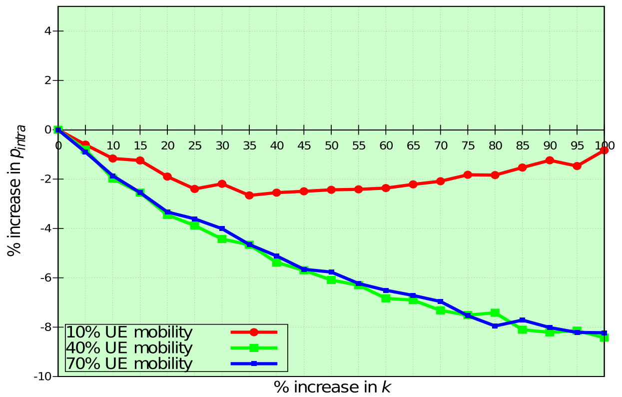

Fig. 8. Variation in p_{intra} with increase in k using Algorithm 3 (UE mobility biased).

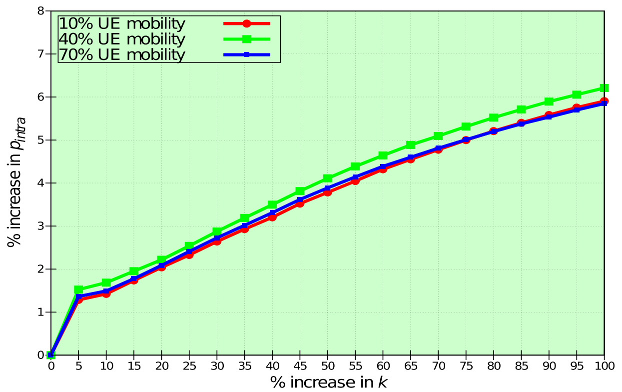

Fig. 9. Variation in p_{intra} with increase in k using Algorithm 1 (UE mobility random).

of suboptimal selection of RAT during reconfiguration. This decrease is also because of the presence of TBS along biased paths. For q = 10%, we do not see much decrease in p_{intra} because the impact of reconfiguration is less, since relatively small number of UEs undergo mobility. However, this decrease gets magnified with higher UE mobility.

7.3. Performances of proposed algorithms with increased UE mobility along random paths

In this subsection, we study the performance of the three proposed algorithms with increased UE mobility but along random paths in this occasion, as well as scaling up RBS deployment. As in previous subsection, the proportion of UEs undergoing mobility in cells (i.e., q) varies as 10%, 40% and 70% respectively.

In Fig. 9, we examine the performance of Algorithm 1. We observe that there is very little variation in p_{intra}, because almost same number of UEs move in and out of a cell as they move randomly. In Fig. 10, we study the performance of

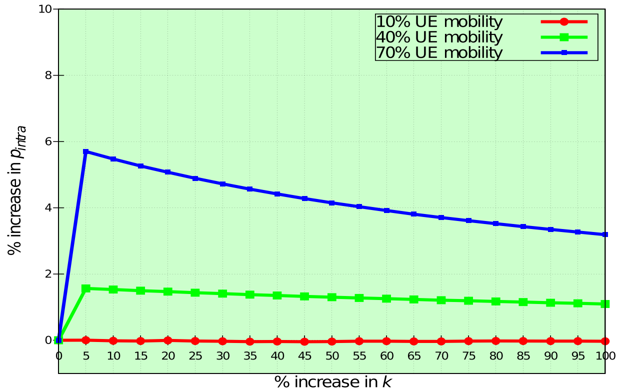

Fig. 10. Variation in p_{intra} with increase in k using Algorithm 2 (UE mobility random).

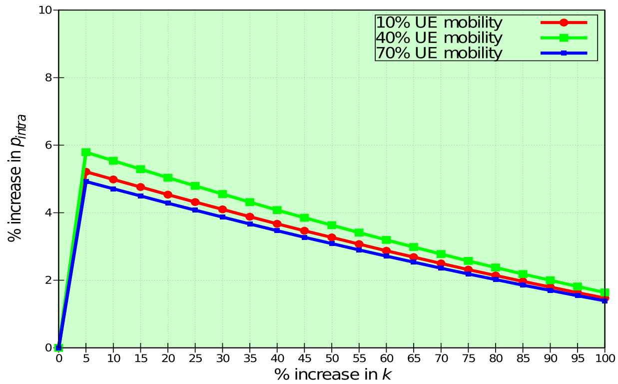

Fig. 11. Variation in p_{intra} with increase in k using Algorithm 3 (UE mobility random).

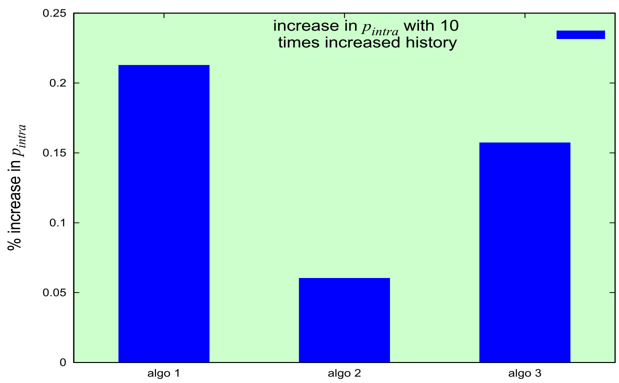

Fig. 12. Increase in p_{intra} with 10 times increase in history.

Algorithm 2. We observe that there is some amount of variation in p_{intra}. As q increases, there is marginal increase in p_{intra}. This is because Algorithm 2 does not always reconfigure the RBS, since with higher mobility more UEs come into cells having the same RAT as their previous camped cells. Fig. 11 evaluates the performance of Algorithm 3. We observe minor variation in p_{intra}.

7.4. Performances of proposed algorithms with increased mobility history

All three algorithms mentioned above depend on the history of mobility procedures undergone by the UEs in each cell. In Fig. 12, we increase the history, i.e., the observation window of mobility procedures (intra-RAT/inter-RAT) occuring in each cell, by 10 times. We see a marginal increase in p_{intra} in the overall network, with Algorithm 1 performing better than other two.

7.5. Summary of results

From the above plots, we summarize a few observations. Increase in deployment of RBS leads to higher IntraRM. For UE mobility along biased paths the increase in IntraRM is higher. However, after a certain density of RBS deployment (around 70%) no substantial increase in IntraRM is observed. Algorithm 1 performs better than the other two for most of the scenarios investigated here. When the UE mobility is random and deployment of RBS is low, then Algorithm 3 seems to perform better. We see no major gain with Algorithm 2 in majority of the scenarios. Also, if the mobility pattern is observed over a longer duration, i.e., larger history, it leads to marginal improvement in mobility.

8. Conclusion

To circumvent the problem of latency during mobility which hinders application QoS, we investigated the scenario of converting InterRM to IntraRM by deploying SDN controlled dynamically programmable RBS (with appropriate RAT) along with traditional multi-RAT base stations. Firstly, we revisited our observation where a maximum of 11% improvement in IntraRM procedure can be achieved with increased RBS deployment. Also, we concluded that beyond 70% of RBS deployment there is no substantial improvement in mobility.

Subsequently, we proposed three novel algorithms for choosing the most suitable RAT for reconfiguration of RBS, to achieve the objective of increasing IntraRM. These algorithms were based on parameters, like mobility procedure counts and time taken by each of them. Algorithm 1 gave importance to incoming UEs only. Incoming and camped UEs were both considered in Algorithm 2. Time taken by mobility procedures and number of UEs (both incoming and camped in a cell) were used in Algorithm 3. For evaluation of the algorithms, simulation models were described for multi-RAT deployment along with RBS, and also for UE mobility. Two types of UE mobility patterns were considered, random and biased. The proportion of UEs undergoing mobility was varied during simulation. Simulation results show that for most of the scenarios considered here, Algorithm 1 performs better than the other two with increased deployment of RBS.

We think further investigation is required for scenarios with UE mobility being biased towards certain paths, where there is scope of further improvements. Also, the dynamics of the overall system, e.g., uncertainty, estimation etc., need to be modelled and analyzed. We will pursue these aspects in our future work.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.compeleceng.2017.04.008

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