Hierarchical Ring Topology for E-UTRAN

Kishore Kshirsagar, Kesav Kaza, Krishnan Rajan
International Institute of Information Technology, Hyderabad, India
{kishore.kl, kesav.kaza}@research.iiit.ac.in, rajan@iiit.ac.in

Abstract— **The evolved UTRAN architecture is expected to sustain data rates of around 1Gbps to handle the multimedia traffic expected in 4G systems. The multifarious services promised in the new generation networks, coupled with high speed data transfers impose great strain on the few network elements that perform these services, due to the flat architecture. There is a need for a reliable topology interconnecting eNBs which distributes this heavy load as well as renders the network immune to S1, X2 link damages. In this work, we propose a new RAN topology for LTE-Advanced systems that is robust to link damages. We compare this with the current standards in LTE. This comparison is expressed as *Average Number of Towers Lost*, in the event of link damages in the EUTRAN. We then test the flexibility of the topology in terms of the *Average Change in Hop Count*. We proceed to show that this new RAN structure is compatible with LTE Advanced technologies like CoMP. We also show how it reduces load on the MME and the SGW and helps provide a platform for better synchronization between eNBs.**

I. INTRODUCTION

The Long Term Evolution (LTE) standardization by 3GPP has progressed well and taken up a final shape in the past few years and only a few more modifications are expected. At the end of 2009, the LTE-Advanced specifications were released (see [1]) and LTE-A has been seen as an evolution of LTE to meet the IMT-Advanced requirements. A good introduction to the major features of LTE and LTE-Advanced can be found in [10] and [2], respectively.

In the context of advances in mobile technology and communications, and the increasing user requirement for data exchange, LTE and LTE-Advanced envision requirements such as: peak data rates of 1Gbps in Downlink (DL) and 500Mbps in Uplink (UL), latency of the order of 10ms, Multimedia Broadcast/Multicast Services (MBMS), real time video, online gaming etc. To cope with these, new features were added that were not present in earlier 3GPP releases. Some of these are Coordinated Multiple Point Transmission and Reception (CoMP), Relaying Functionality, Flat Architecture, Spectrum Aggreation with up to 100MHz transmission bandwidth etc.

An important aspect of LTE and LTE-A has been the introduction of a new Radio Access Network (RAN) architecture, called as the Evolved Universal Terrestrial Radio Access Network or E-UTRAN (also E-UTRA). An important characteristic of E-UTRAN are the Base Stations, known as evolved NodeBs (eNBs), which perform the functions of the NodeB's as well as the RNCs of the UMTS. A new packet core, the Evolved Packet Core (EPC) has been introduced to support the E-UTRAN whereby the Mobility Management Entities (MMEs), the Serving Gateways (SGWs) and eNBs are connected in a many to many relationship. MMEs and SGWs are the pivotal nodes in the control and user plane respectively, in this new architecture. They are responsible for packet forwarding, routing, inter-Radio Access Technology (RAT) connections, ID verification, User Equipment (UE) tracking etc. The rationale for this approach is that it leads to a reduction in the number of network elements, simpler functionality and improved redundancy. This is apart from allowing connections and hand-overs to other fixed line and RATs [2].

It is imperative that the topology employed in the RAN should be conducive to the features mentioned earlier. For exmaple, CoMP would be unfeasible if we didn't have a system in place for clock synchronization mounted on a node from where simultaneous synchronization of all eNBs would become easier. The current 3GPP proposed topology for E-UTRAN has very few network elements performing a host of functions. This overloading of network elements will probably leave the system in poor health in the long run. Also, this would add latency to the system. Let us consider for example, UE tracking by an MME. MMEs have to know the Tracking Area of all LTE_IDLE UEs, which is typically of the granularity of a group of cells. If we employ a node from within the eNBs for this purpose, we might be able to reduce load on the MME and track the idle-mode UE to a single cell, so that latency is improved when DL data for that UE arrives. Hence we need a topology in which the load is effectively distributed in the system, while maintaining a flat architecture.

Also, the migration of network architecture is from macro to micro cells which implies more number of base stations are needed and effective communication between these base stations is a must. Hence what is also needed is a robust system that is impervious to physical damages and is adept in load handling and delay minimization.

Towards a solution for this, a new topology for an advanced RAN was proposed in [4], where the flatness of E-UTRAN was replaced by a hierarchical structure of Central Stations (CS) and ordinary BSs. While the CS took over the function of cooperation/coordination of BSs in the vicinity, no other control plane functionality was proposed for the CS. Apart from this, no other work in literature has focussed on improving robustness of the E-UTRAN or studied the consequences of establishing a node between the E-UTRAN and EPC layers to distribute load.

This is the endeavour we propose to undertake in this work. We consider the performance of a topology

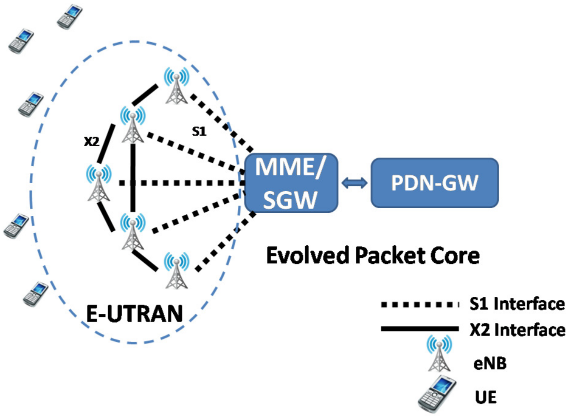

Figure 1. High-level E-UTRAN architecture

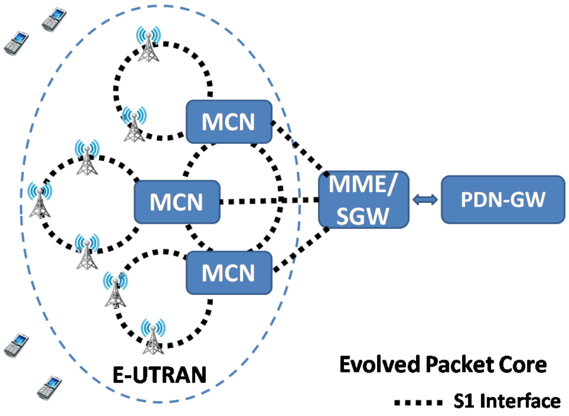

Figure 2. The Hierarchical Ring Topology

that not only reduces load on the MME/SGW, but also improves the robustness of the system by making the system immune to S1/X2 link damages.

The rest of the paper is organized as follows: in Section II we discuss the current E-UTRAN topology and the proposed Hierarchical Ring Topology (HRT). In Section III we perform a robustness comparison of the two, by deriving expressions for loss of eNBs. We then present requirements of LTE, LTE-A vis-a-vis the RAN topology in Section IV. In Section V a conclusion and the aim of the future work are given.

II. TOPOLOGIES FOR THE E-UTRA

In this section, we have a look at the 3GPP proposed E-UTRAN and also introduce a candidate topology.

A. *Current E-UTRAN Topology*

The current LTE RAN Topology is as shown in Fig. 1. Here we have a set of eNBs that are all connected to the MME and the SGW through the S1 interface in a many-to-many network. We also have inter-connections between the eNBs in the form of the X2 interface. It has been estimated in [6] that the bandwidths required for the S1 and X2 interfaces are around 17000 kbps and 131 kbps respectively.

It has to be noted here that in the event of a link damage, eNB communication is definitely lost. The X2 interface does not have the bandwidth and the functionality of carrying normal traffic. The traffic of that eNB is shared by the eNBs in its neighbourhood and hence load on these eNBs is greatly increased. So, taking into account the restrictions posed by the X2 bandwidth, this topology can be considered to be a “Radial Topology” (RT).

B. *Hierarchical Ring Topology*

The Hierarchical Ring Topology (HRT) is as shown in Fig. 2. In this topology, we have groups of eNBs that are connected to each other in a ring-like structure. This topology has been modelled variously in literature as 2-layer Hierarhical Ring Network, [9] and as a Tree Of Rings [8]. Each ring of eNBs is once again connected to each other in a ring. We proposed to call the eNBs in the central ring as the Main Control Nodes (MCN). These MCNs are the pivotal nodes in their local rings, as some of the tasks we conceive for these are routing and synchronization for CoMP, idle mode UE tracking, SGW selection, serving as the mobility anchor for user plane during handovers etc.

The S1 interface from the MME/SGW to all eNBs is removed and is limited to the MCNs. However, the X2 interface between eNBs is replaced by the S1 interface. There has been a discussion in the literature ([6], [7]), on how the X2 interface can be multiplexed with the S1. Hence we assume in this paper, that the functions of X2 are performed by the S1 itself, without loss of generality. This topology however, has two important drawbacks. First, there is no dynamism in the structure. For example, if due to unforeseen circumstances a new eNB has to be put up, then unlike a Radial Topology, we cannot easily assimilate this new eNB into a ring-like network. Second, having S1 interfaces between eNBs could prove to be a costly affair, because, as mentioned above, these links require high bandwidth.

However, this has many advantages over the radial topology. We show in Section III that the HRT provides a more robust structure than the RT. Furthermore, we argue in Section IV that it reduces load on the important network elements, the MME and the SGW, and reduces latency in the system.

III. ROBUSTNESS ESTIMATE

We now try to compare the robustness of the topologies in the event of link damages. An eNB that is connected to the system through just one link, will be lost if that link is damaged. However an eNB that is connected to multiple nodes will only have to re-route traffic bound outwards and inwards of it. Both these conditions are taken into perspective in the following metrics.

A. *Average Number of eNBs Lost*

We assume that the number of eNBs, n_{eNB}, in both the scenarios, i.e., one with the Radial Topology and another with the HRT is the same. If n_L is the number of links in a topology, then, $n_L = R * L + R$ for the HRT and $n_L = R * L$ for the RT, where R and L are the number of rings and the number of links per ring respectively in the HRT.

We estimate the average number of eNBs that are unable to communicate due to damages in the links making up the S1 interface. As mentioned in [5], we assume that the damages in the links follow a homogeneous Poisson process, with a certain rate λ_d per unit time. So, we have,

$$\lambda_d = n_L * p_d \tag{1}$$

where p_d is the probability of a single link getting damaged in unit time.

Now, the probability of losing l links in the whole network in unit time would be,

$$p_l = \frac{e^{-\lambda_d}\lambda_d^l}{l!} \tag{2}$$

The average number of eNBs lost in unit time can now be expressed as a function of R, L and p_d as follows:

$$A_{eNB}\left(R, L, p_d\right) = \sum_{l=1}^{\infty} A_{eNB}\left(R, L|l\right) p_l. \tag{3}$$

It is shown in [3] that p_l becomes very small for $l \geq 4$ and hence, accordingly,

$$\begin{aligned} A_{eNB}\left(R, L, p_d\right) = {} & A_{eNB}\left(R, L|l=1\right) e^{-\lambda_d}\lambda_d \\ & + A_{eNB}\left(R, L|l=2\right) e^{-\lambda_d}\lambda_d^2/2 \\ & + A_{eNB}\left(R, L|l=3\right) e^{-\lambda_d}\lambda_d^3/6 \end{aligned} \tag{4}$$

1) Radial Topology: In the Radial Topology, loss of a link leads to definite loss of an eNB. Hence we estimate $A_{eNB,R}$ as

$$\begin{aligned} A_{eNB,R}\left(R, L, p_d\right) = {} & e^{-\lambda_d}\lambda_d + 2e^{-\lambda_d}\lambda^2/2 \\ & + 3e^{-\lambda_d}\lambda_d^3/6. \end{aligned} \tag{5}$$

2) Hierarchical Ring Topology: Similarly, for the HRT, $A_{eNB}(R, L, p_d)$ is given as,

$$\begin{aligned} A_{eNB,H}\left(R, L, p_d\right) = {} & e^{-\lambda_d}\frac{\lambda_d^2}{2}\left(\frac{{}^{L}C_2 R}{{}^{RL+R}C_2}\right)\left(\frac{L+1}{3}\right) \\ & + e^{-\lambda_d}\frac{\lambda_d^3}{6}\left[\left(\frac{(L+1)\,{}^{L}C_3 R}{2^{RL+R}C_3}\right)\right. \\ & + \left.\left(\frac{2\left(L+1\right){}^{R}C_2{}^{L}C_2{}^{L}C_1}{3^{RL+R}C_3}\right)\right] \end{aligned} \tag{6}$$

It has to be noted that we do not lose any eNB in the HRT network if a single link is broken and we need to lose atleast two links for an eNB to lose communication.

Fig. 3 shows the variation of A_{eNB} and $log\left(A_{eNB}\right)$ with p_d. Here, other parameters were kept constant, with $R = 10$ and $L = 10$. The graph on the top compares the HRT and RT directly, whereas the graph on the bottom is a semi-log graph. The Poisson assumption can be verified from the graph. From the bottom, $log(A_{eNB})$ graph, we can verify that the distance between the HRT and the RT curves is approximately 2 units and almost constant. Hence the HRT performs 100 times better than the RT, consistenly. This is due to the redundancy introduced in the form of extra S1 interfaces.

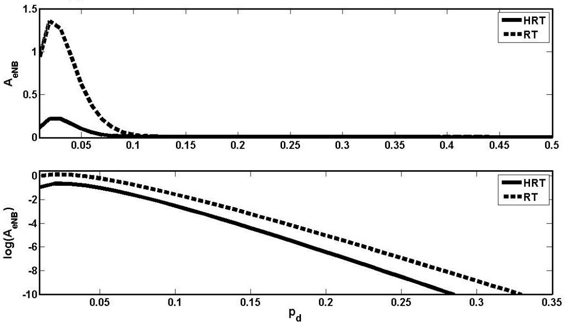

Figure 3. A_{eNB} as a function of p_d

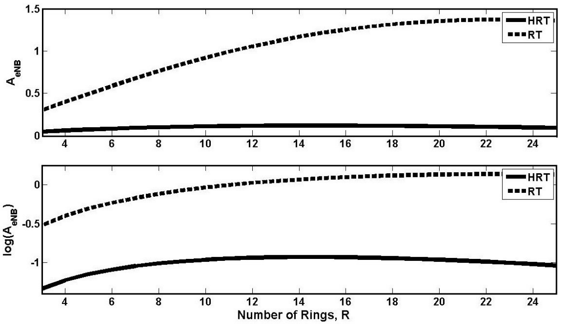

Figure 4. A_{eNB} as a function of R

In Fig. 4, the reliability performance is shown as a function of R. Here once again, the other two network parameters are kept constant: $L = 10$ and $p_d = 0.01$. Here, it is to be noted that as R increases, we have a relatively small L and hence the reliability performance increases.

The Fig. 5, shows the A_{eNB} as a function of L. Here the value of $R = 10$ and $p_d = 0.01$. This graph is almost linear with a positive slope. This is due to the fact that as the number of links per ring increases, more towers are lost on average when two links break in the same ring. Hence for best robustness performance, the value of L should be kept low. This would however mean increase in the link cost, as we would have more number of links in the central ring.

B. Average Change in Hop Count

In this section, we estimate the average number of hops that are increased when links are severed in the network. We only consider those link damages which do not lead to an eNB loss. Such a cost function will help us determine the flexibility of the network in the event of re-routing. As each hop count demands availability of a physical link, we desire to have a minimum change. We define α as this cost parameter.

We cannot estimate α for the Radial Topology as there is no option for re-routing. Once a link to an eNB breaks in the RT, traffic cannot be re-routed through other links.

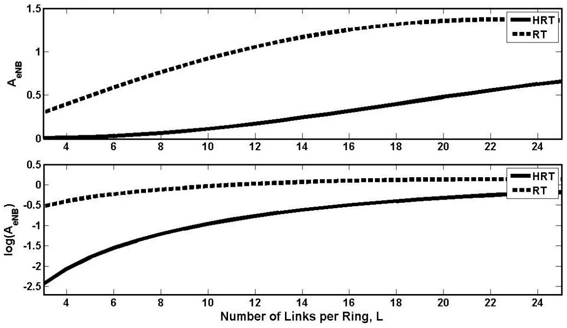

Figure 5. A_{eNB} as a function of L

Here we assume that call requests arrive at all eNBs with an equal rate. Let this rate be λ_r. α is expressed as a function of R, L and λ_r.

$$\begin{aligned}\alpha\left(R, L, \lambda_r\right) = {} & \alpha\left(R, L, \lambda_r | l = 1\right) p_1 \\ & + \alpha\left(R, L, \lambda_r | l = 2\right) p_2 \\ & + \alpha\left(R, L, \lambda_r | l = 3\right) p_3. \end{aligned} \tag{7}$$

If $\alpha_H\left(R, L, \lambda_r\right)$ is the average hop count change for the HRT,

$$\begin{aligned}\alpha_H\left(R, L, \lambda\right) = {} & \left[{}^R C_1 \left(\sum_{i=1}^{L} \alpha_i \right) + \left(\sum_{i=1}^{R} \beta_i \right) \right] \frac{p_1}{RL + {}^R C_1} \\ & + \left[\left(2L\,{}^R C_2 + R\,{}^R C_1 \right) \left(\sum_{i=1}^{L} \alpha_i \right) \right. \\ & \left. + \; L\,{}^R C_1 \left(\sum_{i=1}^{R} \beta_i \right) \right] \frac{p_2}{RL + {}^R C_2} \\ & + \left[\left(3L^2\,{}^R C_3 + 2RL\,{}^R C_2 \right) \left(\sum_{i=1}^{L} \alpha_i \right) \right. \\ & \left. + \; L^2\,{}^R C_2 \left(\sum_{i=1}^{R} \beta_i \right) \right] \frac{p_3}{RL + {}^R C_3} \end{aligned} \tag{8}$$

where p_1, p_2 and p_3 are as given before and

$$\sum_{i=1}^{L} \alpha_i = \frac{2\lambda}{R\left(L-1\right)+1} \left(L + 2\left(R-1\right)\left(L-1\right)\right) \chi\left(L\right) \tag{9}$$

$$\sum_{i=1}^{R} \beta_i = 2L\lambda\chi\left(R\right) \tag{10}$$

and

$$\chi\left(x\right) = \begin{cases} \left(\frac{x-1}{2}\right)^2 + \left(\frac{x-3}{2}\right)^2 + \cdots + 1, \\ \text{if } x \text{ is odd}, \\ \\ \left(\frac{x-2}{2}\right)\left(\frac{x}{2}\right) + \left(\frac{x-4}{2}\right)\left(\frac{x-2}{2}\right) + \cdots + 2, \\ \text{if } x \text{ is even}. \end{cases} \tag{11}$$

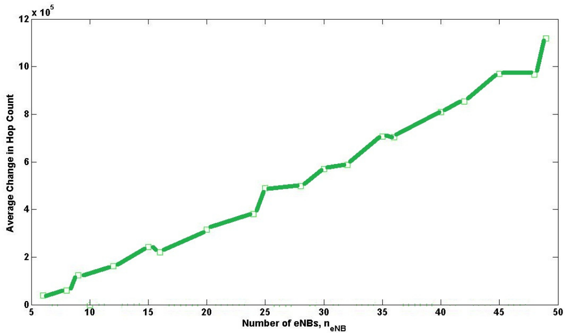

Figure 6. *Average Change in Hop Count*

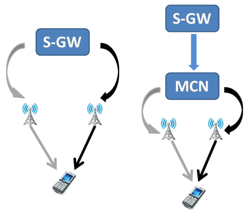

Figure 7. CoMP data can be distributed to the eNBs through the MCN

A plot of this cost function is presented in Fig. 6. Here, the *Average Change in Hop Count* has been shown as a function of the n_{eNB}. The value of λ_r was constan at 10^5 per unit time. As n_{eNB} increases, we have more number of hops required to reach the destination as L too increases. Also, more number of rings implies greater distances on average betwen eNBs. Hence, the almost linear graph of α_H.

IV. APPLICABILITY IN LTE, LTE-A

LTE and LTE-Advanced propose a multitude of features and services like flat IP structure, backward compatibility with other 3GPP technologies, multiple-point transmission and reception and hence it is imperative that they are to be serviced by an appropriate topology. We now look at some of the features of 3GPP Rel. 8+ and how the above discussed topologies fare.

A. *Fostering CoMP*

Coordinated Multiple Point Transmission and Reception (CoMP) is the new technique in LTE Advanced considered to improve the coverage of high data rates, the cell-edge throughput and the system throughput [11]. We have two kinds of CoMP operation in the downlink (DL) - Joint Processing (JP) and Coordinted Scheduling (CS)/Coordinated Beamforming (CB).

CoMP in the DL requires transmission of data to each eNB and clock synchronization between these eNBs. If the HRT is employed, then transmitting user data to each eNB in the Joint Processing in DL become easier. The data just has to be forwarded to the approriate MCN, as shown in Fig. 7 and the MCN will then route the data to the eNBs in the vicinity of the UE.

Also the high level of synchronization required in Dynamic Cell Selection can be achieved, as shown in

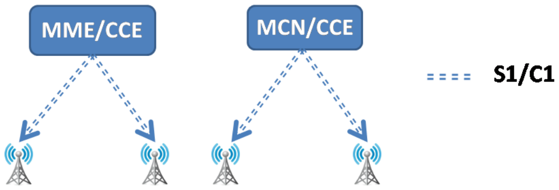

Figure 8. Synchronization of eNBs can be simplified by having an MCN perform the role of a CCE

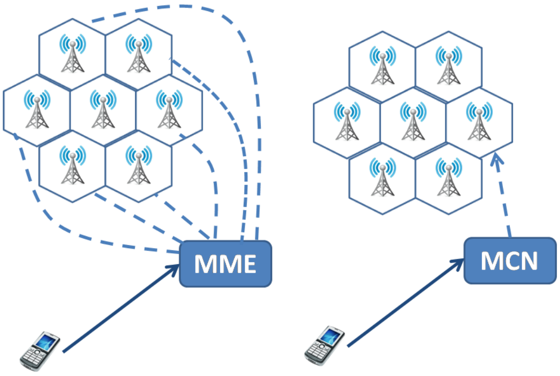

Figure 9. Tracking Area reduced to a single cell from a group of cells

Fig. 8, by having the MCNs perform the role of a CoMP Coordination Entity (CCE) serving the eNBs of its ring [12].

B. *Load on MMEs and SGWs*

The MME is the chief control node in the LTE access network. Due to the flat IP structure, with very few network elements, the MME and the SGW have a host of functions. Some of the functions of the MME are: idle mode UE tracking, bearer activation and SGW choice for a UE. The MME also provides the control plane function for mobility with 2G/3G access networks apart from various other functions [10].

Using the HRT, some of the control plane functions of the MME are transferred to the MCN of each ring. The intra-EUTRAN UE idle mode tracking is now done by the local MCN as follows. Instead of the MME, it is the MCN that knows the location of the UE in LTE_IDLE state and the Tracking Area (TA) can be reduced to the local ring. In fact, the TA is reduced to a single cell, as the bandwidth of links between eNBs can now support it, as the X2 links have been substituted by S1. This helps reduce latency incurred in locating the UE to a cell, when DL data for that UE arrives and also reduces load on the MME. The Fig. 9 illustrates this advantage - while the MME tracks to a group of cells, the MCN tracks it to a single cell.

Also, the selection of an SGW by an MME that takes place at the time of a UE's initial attach and at the time of intra-LTE handover can be instead performed by the local ring as follows: The MCN of each ring of the HRT can store a list of potential SGWs present in the neighbourhood and depending on the current location of the UE (which, has been established above with the granularity of a cell), the appropriate SGW can be selected, without going to the MME. However, once the UE goes out of a ring's purview, the MME has to select the correct ring, from where, once again the SGW list is used.

The SGW is another important network element in LTE. Some of its functions are, routing user data packets, acting as the mobility anchor for the user plane during handovers, and also as the interface to the packet data network.

Once again, if the HRT is employed, the MCN can serve as the mobility anchor in case of inter-eNB handovers between eNBs of the same ring instead of the SGW. If the handover is between eNBs of different rings, then the SGW comes into the picture.

The Table IV-B summarizes and compares the features of the two topologies, based on the current work carried out.

TABLE I
RESULTS FOR THE TWO TOPOLOGIES - RT AND HRT

Parameter/Service	RT	HRT
CoMP	UE data is sent to all eNBs separately	Single transmission to MCN sufficient
Synchronization	Need for a separate node	MCNs perform the role of a sync gateway
Idle Mode Tracking	MME has to track all UEs	MCN takes over the function
The Tracking Area Granularity	Group of Cells	Single Cell
SGW Selection	Selection by MME	Selection by MCN
Mobility Anchor	Performed by MME	Performed by MCN
Average eNBs lost	Very high	Very low
Average Bandwidth per Link	Low	High
Topology Rigidity	eNB assimilation is easy	eNB assimilation is difficult

V. CONCLUSION AND FUTURE WORK

We have proposed an alternate RAN topology for the LTE system, the Hierarchical Ring Topology (HRT) and considered its performance. This topology was compared with the current E-UTRAN topology (RT) in terms of robustness and this comparison was in terms of the number of towers lost in the event of link failures. The HRT performed on an average 2 orders of magnitude better than the RT.

A test of flexibility in network topologies was proposed in the form of the average hop count change. Performance of the HRT for this parameter was analyzed. Also, the use of the HRT in alleviating signal load on the MMEs and SGWs, and in helping foster CoMP service in LTE Advanced, has been argued upon.

In future, we wish to comprehensively determine the load handling capabilities of the propsed topology. Furthermore, extensive simulations have to be conducted for further comparison of the topologies. We also wish to work on developing a framework for estimating total link cost in a real scenario. Also, the performance of various hybrid topologies in 4G-like scenarios has to be well understood in order to satisfy provider and subscriber ends' requests.

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