

Mitigating Macro-Cell Outage in LTE-Advanced Deployments

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Abstract—LTE network service reliability is highly dependent on the wireless coverage that is provided by cell towers (eNB). Therefore, the network operator’s response to outage scenarios needs to be fast and efficient, in order to minimize any degradation in the Quality of Service (QoS). In this paper, we propose an outage mitigation framework for LTE-Advanced (LTE-A) wireless networks. Our framework exploits the inherent design features of LTE-A; it performs a dual optimization of the transmission power and beamforming weight parameters at each neighbor cell sector of the outage eNBs, while taking into account both the channel characteristics and residual eNodeB resources, after serving its current traffic load. Assuming statistical Channel State Information about the users at the eNBs, we show that this problem is theoretically NP-hard; thus we approximate it as a convex optimization problem and solve for the optimal points using an iterative algorithm. Contrary to previously proposed power control studies, our framework is specifically designed to alleviate the effects of sudden LTE-A eNB outages, where a large number of mobile users need to be efficiently offloaded to nearby towers. We present the detailed analytical design of our framework, and we assess its efficacy via extensive NS-3 simulations on an LTE-A topology. Our simulations demonstrate that our framework provides adequate coverage and QoS across all examined outage scenarios.

I. INTRODUCTION

Mobile network operators strive to provide highly reliable and efficient network connectivity, in order to guarantee long-term QoS. However, such guarantees can be compromised by network outage events, where one or more network elements suddenly become unavailable. In this paper, we tackle the problem of adaptively reconfiguring the network in scenarios with eNB outages in LTE-Advanced (LTE-A) macro-cell deployments. Outage is defined as an interruption in the coverage and service of an LTE base station called eNodeB (or alternatively, eNB) to the User Equipments (UEs) associated to its cell. One or more eNBs, covering cell sectors, suddenly go down among a set of eNBs in the topology. Outage causes the network’s QoS to be degraded as a result of which any associated UE’s performance is affected. We primarily focus on the case of LTE-A [1], [2] since it is a mobile network technology that is being widely deployed around the world and is expected to dominate the broadband network market within the next few years [3]. In this context, an eNB outage can typically occur due to: (a) planned maintenance, or (b) unexpected events such as bad weather conditions. With planned maintenance, the operator in many cases needs to take the eNB offline in order to apply a hardware/software upgrade or perform certain repair operations. Moreover, during severe weather conditions such as hurricanes and heavy snow storms, eNB radio transmitters can be badly damaged. In both such cases, the eNB becomes unavailable and thus, its associated UEs get immediately disconnected. Depending on network planning and resource availability, some of these UEs may be able to attach to neighbor sectors. However, due to poorer SINR

conditions, the newly re-attached users are likely to experience poorer performance. Even worse, some users may not be able to attach to any neighbor eNB; this may be due to either very low SINR, or due to the fact that all candidate neighbor eNBs already operate at full capacity. Therefore, during eNB downtime, the operator must adaptively re-configure the Radio Access Network (RAN) topology settings in order to restore the reliable connectivity to users, but limiting the extent of compromise on user performance.

The challenge in tower outage mitigation: Previous work in the area of RAN optimization has studied configuration of transmission power as well as beamforming weights at eNBs, once UEs are associated to them. Assuming the allocation of a set of UEs to their respective eNBs, existing literature discusses RAN optimization by proposing algorithms for power and precoding weight adjustments towards optimizing a system utility [4]. One approach requires minimizing the transmission power and/or beamforming weights on the eNBs adequate enough for the transmission link to be strong with the UEs (characterised by an SINR threshold). The other approach requires maximizing the weighted sum rate by choosing optimal transmission power or beamforming weights such that they do not exceed a pre-defined threshold [4], [5]. However, in the context of outage of one or more eNBs, a group of UEs (associated to them) facing service interruption is re-associated to appropriate neighbor eNBs among the remaining ones in service. Cutting-edge outage mitigation needs to take one step further in configuring operational parameters; besides optimizing radio coverage, operators need to also satisfy application service requirements, thereby meeting the customer traffic demands across the network. This suggests that during a tower outage, the RAN needs to be reconfigured such that: (a) users that experience outage can be served by neighbor cells; (b) the QoS requirements for such users are still met, even during outage; and (c) the operator does not compromise the performance of other attached users that do not experience eNB outage. These requirements pose new challenges in addressing the problem of adaptive outage mitigation in LTE-A macro-cell deployments. Increasing coverage so as to re-associate UEs requires increase in transmission power at the eNBs. However blindly increasing the transmission power of nearby sectors in order to cover connectivity holes from eNB outage is not the wisest choice; it can cause excessive levels of co-channel interference thereby degrading QoS. The link stability of the re-associated UEs must be strong and their QoS requirements in terms of finite buffer traffic subscription are required to be satisfied. To the best of our knowledge, these challenges are not adequately discussed in existing literature.

Our Contributions: In this paper, we address the above challenges by designing an online outage mitigation framework for re-associating UEs facing outage to alternate LTE-A eNB cell

sectors. Our framework is based on the concept of *closed-loop service quality management* where real-time outage correlation data along with eNB configuration parameters are provided to a centralized RAN controller. To suit a more general case, our framework assumes imperfect channel knowledge of the UEs at the eNB; hence, it maintains a statistical distribution of the Channel State Information (CSI) at the transmitters. Our contributions in this paper are multi-fold:

- *Design* : To the best of our knowledge, our paper is the first to design an outage mitigation framework for LTE-A systems with Carrier Aggregation (CA) and 2D/3D beamforming.

- *Service Model*: Our framework for optimal re-association of UEs facing outage is novel in that we consider the UEs' quality of service requirements in addition to conventional factors such as channel characteristics of the UEs from the eNBs and the traffic load at the eNBs.

- *Optimization* : We establish that the outage mitigation problem is NP-Hard and we approximate it to be solved via convex optimization techniques. The RAN controller runs an iterative reconfiguration procedure for optimizing transmission power and 3D beamforming weights on serving eNBs to re-associate UEs facing outage. By doing so, our framework maximizes the network coverage with higher link stability and the aggregate QoS from the serving eNBs for all UEs, especially the ones facing outage. Contrary to previous work dealing with traditional power control, our design is custom-fit for outage scenarios.

- *Evaluation* : We implement our outage mitigation solution in NS-3 [6] and perform extensive simulations on a sectorized macro-cell topology. Our simulations demonstrate that our reconfiguration framework outperforms the existing traditional power allocation techniques in terms of mitigating outage through the net QoS satisfaction and achievable throughput.

Related Work: There is substantial existing literature which talks about transmit power and beamforming weight configurations in telecommunication systems. We highlight and elucidate the most relevant and compare them with our proposed work. In [7], the authors propose a joint optimization of beamformers in a MIMO multi-cell setting. They focus upon minimizing the total weighted transmission power and the maximum per-antenna power across base stations, such that the link between any base station - UE pair meets a certain threshold. They use an important result in [8], which shows that the SINR constraint that requires the link to satisfy a pre-defined threshold value can be modelled as a convex constraint using second-order cone programming. Using this, they model the problem as a convex optimization problem via Lagrangian duality theory and propose an iterative algorithm that converges to optimality. The key difference in our paper is the impact caused by the frequency-selective OFDMA sub-channels considered in our MIMO OFDM system. Similarly, a dual optimization technique for transmission power and beamforming weights using antenna arrays is given in [5]. They however do not model the problem as a convex optimization but propose an iterative convergence algorithm for optimizing beamforming weights and transmit power that meets the SINR thresholds for operating links. The objective function is different in our case, as we focus on optimizing the effective coverage in a topology that accounts for dynamic outages. Moreover, they do not account for QoS guaran-

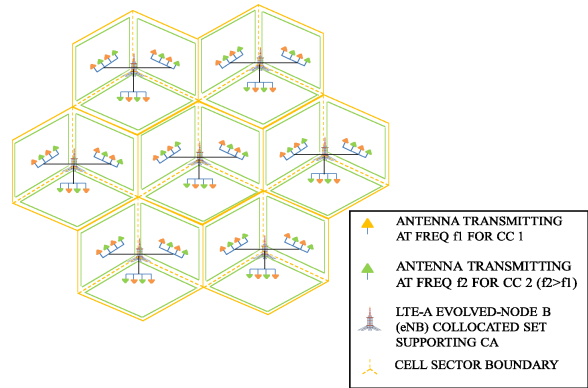


Fig. 1. Modeled macro-cell LTE-A deployment, where each site hosts 3 MIMO-capable sectors with 120-degree angle separation.

tees in their optimization. In [9] and [10], the authors consider maximizing the weighted sum rate objective function subject to power thresholds. This problem is however non-convex (similar to our original problem without approximation) and the authors devise a joint optimization strategy to optimize the linear beam vectors across coordinated cells and independently-modulated resource slots that address the frequency diversity in OFDMA systems. They present an iterative algorithm that attempts to solve the first-order optimality conditions of the non-convex problem, which gives us insights for deriving the first order optimality conditions.

II. SYSTEM MODEL DESCRIPTION

In this section, we discuss the design space of our system model and we elaborate on the set of design assumptions.

A. Design Space Description: We consider M collocated sets of sectorized LTE-A eNBs; i.e., each sector is associated with a separate eNB, as modelled in [11]. Hence there are $3M$ sectorized eNBs. Since the considered eNBs are LTE-A, they can perform Carrier Aggregation (CA) of up to five 20-MHz Component Carriers (CC) concurrently, which means their aggregate bandwidth can be up to a maximum bandwidth of 100 MHz [12]. In addition, the eNBs are equipped with 2D and 3D beamforming capabilities (CoMP), wherein higher signal gains are achieved across specific directions by adjusting the phase and weights of multi-antenna transmissions. Each eNB covers a sector (area of coverage), so any collocated set has 3 sectorized eNBs with angular orientations of 0° , 120° and 240° , respectively, as shown in Fig. 1. The figure also shows deployment of 2 Component Carriers (CCs) on every sectorized eNB. Each CC covers one cell, which is a group of users in the sector area. The covered area of the 2 cells for each eNB could be somewhat different based on the frequency, power, and antenna configuration.

In general, each collocated set of sectorized eNBs serves one set of cells, and each sectorized eNB is deployed with C inter-band aggregated Component Carriers (CCs) [12] $\mathcal{C} = \{\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_C\}$ belonging to frequencies $\{f_1, f_2, \dots, f_C\}$.

Each eNB m has $N_{m,c}$ transmit antennae for any CC \mathcal{C}_c that emit signals at the corresponding frequency f_c , and each transmit antenna has N_a antenna elements. The number of transmit antennae for any eNB m is given by $N_m = \sum_{c=1}^C N_{m,c}$ and the total number of transmitter antennae

is $N_T = \sum_{m=1}^{3M} N_{m,c}$. Let K be the total number of User Equipments (UEs) in the system. We consider the UEs to be scheduled on all the CCs. Let $N_{k,c}$ be the total number of receiver antennae for signals corresponding to CC \mathbb{C}_c at any UE k . The number of receiver antennae for any UE k is given by: $N_k = \sum_{c=1}^C N_{k,c}$ and the total number of receiver antennae is given by $N_R = \sum_{k=1}^K \sum_{c=1}^C N_{k,c}$. We assume that $N_R \geq N_T$.

• **MIMO-OFDM:** We consider a linear MIMO OFDM system [13] in which the given frequency-selective channels in any CC \mathbb{C}_c is converted into a set of B fixed parallel flat fading sub-channel Physical Resource Blocks (PRBs). The transmission across the PRBs of any CC in the aggregated carrier follows an equal power allocation scheme. We assume the fading characteristics to be resolved to the granularity of sub-channel PRBs and hence, we have B random fading values on any CC \mathbb{C}_c . 3D MIMO introduces a vertical dimension in transmitting antennae by accounting for the heights of the eNBs and the UEs. For any eNB m and UE k , the respective channel coefficient matrix has three dimensions per PRB which are: (i) the number of transmitting antennae on the eNB m at the corresponding CC c , (ii) the number of receiver antennae on the UE k receiving signals corresponding to CC \mathbb{C}_c , and (iii) the number of elevation antenna elements N_a per transmit antenna that accounts for the height of the eNB m and UE k . However, the receiver antennae has conventional 2D MIMO characteristics. The channel coefficients between eNB m and UE k over any PRB b out of the B PRBs of any CC \mathbb{C}_c is represented by a 3D matrix $\mathbf{H}_{k,m}(b)$, given by the dimensions $N_{k,c} \times (N_{m,c} \times N_a)$. Let $\mathbf{W}_{k,m}(b)$ and $\mathbf{Z}_{k,m}(b)$ denote the corresponding transmit beamformer and receive combiner weights, respectively.

• **Modeling of Radio Channel Characteristics:** The received signal for any UE k from any eNB m over a PRB b is [14]:

$$\begin{aligned} y_k(b) &= \mathbf{Z}_{k,m}^H(b) \mathbf{H}_{k,m}(b) \mathbf{W}_{k,m}(b) x_{k,m}(b) + \\ &+ \sum_{\substack{m'=1; \\ m' \neq m}}^{3M} \sum_{\substack{k'=1; \\ k' \neq k}}^K \mathbf{Z}_{k,m'}^H(b) \mathbf{H}_{k,m'}(b) \mathbf{W}_{k',m'}(b) x_{k',m'} + \mathbf{Z}_{k,m}^H(b) n_{k,c}. \end{aligned} \quad (1)$$

The noise $n_{k,c}$ experienced by the UE k over any CC c is an independent and identically-distributed Gaussian random variable with mean $\mu_c = 0$ and variance $\sigma_{N,c}^2$. The first term on the RHS in Eqn. 1 indicates the intended signal from eNB m to UE k , the second term indicates the inter-cell interference from any eNB $m' \neq m$ to UE $k' \neq k$ and the third term is the receiver noise after combining signals. Since PRB orthogonality in OFDMA guarantees any 2 UEs to be allocated mutually exclusive PRBs, when simultaneously scheduled, intra-cell interference is eliminated in Eqn. 1. For transmission of data symbols to any UE k over PRB b of CC c from eNB m , we assume that all $N_{m,c}$ transmitter antennae jointly process transmission of data symbols to the UE. Let $s_{t,k}(b) \in \mathbb{C}^{N_k(c)}$ be the data symbol transmitted from antenna t to UE k over all receiver antennae $N_k(c)$. Let $S_{t,k}(b) \in \mathbb{C}^{N_k(c) \times N_k(c)}$ be the transmission co-variance matrix [15]. So, we have: $S_t(b) = E\{s_t(b) \cdot s_t(b)^H\}$. The co-variance of the transmitted symbols over any PRB b is the power spectral density of transmitter t over CC c given

by $\text{psd}_{t,c} = P_{t,c}/B$. Here, B is the total number of PRBs of any CC in the aggregated carrier and $P_{m,c} = \sum_{t=1}^{N_m(c)} P_{t,c}$ is the total transmission power of the eNB m . Here, $\mathbf{rank}\{S_{t,k}(b)\}$ is the number of independent data streams from transmitter t over PRB b . And $\mathbf{tr}\{S_t(b)\} = \text{psd}_{t,c}$. Hence, the transmission from eNB m to UE k over PRB b of CC c is given by $x_{m,k}(b) = \sum_{t=1}^{N_m(c)} s_t(b)$. Thus, the power spectral density of eNB m over CC c is:

$$\begin{aligned} |x_{k,m}(b)|^2 &= \sum_{t=1}^{N_m(c)} \mathbf{tr}\{S_t(b)\} = \sum_{t=1}^{N_m(c)} \mathbf{tr}\{E\{s_t(b) \cdot s_t(b)^H\}\} \\ &= \sum_{t=1}^{N_m(c)} \text{psd}_{t,c} = \text{psd}_{m,c}. \end{aligned} \quad (2)$$

The SINR for any UE k associated to any eNB m , $\omega_{k,m}(b)$, is given by: $\omega_{k,m}(b) =$

$$\frac{|\mathbf{z}_{k,m}^H(b) \mathbf{H}_{k,m}(b) \mathbf{w}_{k,m}(b)|^2 \cdot \text{psd}_{m,c}}{\sum_{\substack{m'=1; \\ m' \neq m}}^{3M} \sum_{\substack{k'=1; \\ k' \neq k}}^K |\mathbf{z}_{k,m'}^H(b) \mathbf{H}_{k,m'}(b) \mathbf{w}_{k',m'}(b)|^2 \cdot \text{psd}_{m',c} + \sigma_{N,c}^2 \cdot \|\mathbf{z}_{k,m}^H(b)\|^2} \quad (3)$$

B. Outage and Mitigation: We assume that one or more of the eNBs in a topology dynamically face outage. As a result, the UEs that experience outage stop sending/receiving any control or data traffic to/from eNBs that are not transmitting. Our goal is to mitigate the adverse impact of outage. This can be done by re-associating the UEs to other operating eNBs in the neighborhood, upon appropriate re-configuration of transmit power and beamforming parameters. Next, we elucidate the strategies required for mitigation.

Let \mathcal{X}_o be the set of UEs facing outage. Let \mathcal{M}_k be the set of eNBs from which any UE $k \in \mathcal{X}_o$ receives signals with a Reference Signal Received Power (RSRP) [16] greater than a pre-defined threshold. An RSRP value experienced by any UE from any eNB that is greater than a lower-bound threshold indicates that the UE is within the coverage area of the eNB. In this case, the UE could *possibly* consider re-associating to this eNB, while facing outage. Let \mathcal{M} be the set of eNBs such that $\mathcal{M} = \bigcup_{k \in \mathcal{X}_o} \mathcal{M}_k$. For every eNB $m \in \mathcal{M}$, \mathcal{X}_m is the set of UEs which the eNB serves with a RSRP greater than a threshold, signifying that \mathcal{X}_m consists of UEs lying within the coverage of m . This includes UEs already being served by m . Now the eNBs in \mathcal{M} need to be able to pull over the maximum possible set of UEs currently facing outage.

When UEs get re-associated due to an outage, the performance of the re-associated UEs are certainly impacted. In addition, UEs in nearby sectors are also impacted. This is illustrated in Fig. 2 which is a result from our simulations which are described in detail later. The figure shows the CDF of \log_{10} SINR(in dB) as against each of the 250 UEs considered for simulation under (i) a no outage and (ii) varying sector outage scenarios. The topology with distribution of UEs is shown in Fig. 3, where the red circles represent UEs and the stars represent eNBs. The simulation parameters are given in Table I. A monotonously increasing curve (passing nearly through the middle) represents the SINR CDF of the UEs under no outage. And the remaining curves (deviating from

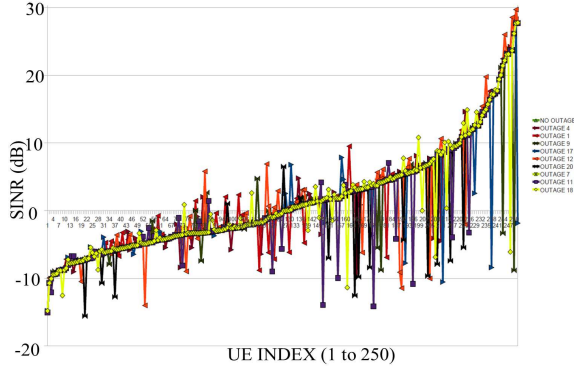


Fig. 2. SINR CDF

the baseline) represent the SINR CDF of the UEs for all topologies containing at least one sector outage. A large number of UEs face decline in the performance due to outage (shown by curves pointing downwards in the slope) as they were apparently associated to the eNBs experiencing service interruption, whereas a few other UEs associated to the neighboring sectors get higher channel gains (shown by the points above the baseline curve) due to the reduction of interference. Hence, this motivates the reconfiguration of transmission power and beamforming weights across serving eNBs (not experiencing outage) to be driven by the need to not only extend coverage to UEs in the neighboring sectors that face outage but also to accommodate the varying channel gains of the UEs associated to their respective cell sectors.

Maximizing coverage requires increasing the transmission power across the eNBs. However, this is expected to cause interference to other UEs. So, the reassociation of outage UEs to other alternative eNBs must be done while minimizing the inter-cell interference. Choosing adequate beamforming weights across the transmit antennae, apart from their power, guarantees the desired SINR for the UEs. This is equivalent to maximizing the coverage (that requires higher RSRP and thus, higher transmission power) with minimum inter-cell interference (with appropriate beamforming weights). The novelty of this work is that it considers the transmission power increment on the eNB to be based on its residual radio resources after serving current traffic load. The rationale behind this is that if an eNB in \mathcal{M} is facing exhaustion of its radio resources as a result of serving a large number of users or a higher traffic subscription, then it cannot accept and effectively serve any UE in \mathcal{H}_o facing outage. To the best of our knowledge, our work is the first to incorporate current traffic load characteristics of the eNBs along with the radio channel characteristics of the UEs for selection of appropriate transmission power and beamforming vector weights to mitigate outage. With this approach, the transmission power and the related beamforming vector weights of any eNB in \mathcal{M} are varied, in direct proportion to the residual radio resources on the eNB that are available, after serving the current traffic on a per-LTE-frame basis.

III. OPTIMAL MITIGATION STRATEGY FORMULATION

As discussed, the goal of our outage mitigation technique is to minimize, in the mean square sense, the beamforming

weights corresponding to the maximum transmission power so as to be able to successfully reassociate as many outage-impacted UEs as possible, as discussed in section II. The success of a reassociation is based on whether the QoS requirements for the UE-subscribed traffic are satisfied. Increasing the eNB transmission power to the *maximum-possible* limit helps in getting higher RSRP values (based on the transmission power) for the UEs, thereby, maximizing coverage. Decreasing the beamforming weights to a *minimum-possible* limit that satisfies the required link stability (characterised by SINR threshold) reduces interference to UEs in neighboring cell sectors. In essence, appropriately steering the directional beam over frequency-selective PRBs to intended UEs decreases the inter-cell interference. For brevity, we term the process of minimizing the beamforming weights corresponding to a maximum transmission power as *optimizing the effective signal coverage* from the remaining eNBs. Optimizing coverage should adhere to power constraints for each eNB and is subject to SINR and traffic guarantees. As stated above, SINR guarantee requires the link stability between a UE facing outage and any other serving eNB, considered for re-association, to be greater than a pre-defined threshold. Traffic guarantees require the QoS requirements of the UE-subscribed traffic (in terms of per-frame finite buffer rate) to be satisfied for any associated/re-associated UE using the residual PRBs available in the eNB. This is a joint optimization strategy, as the choice of transmission power and appropriate beamforming vectors on any eNB affects the performance of UEs associated to eNBs in the neighboring sectors. Let $\mathcal{W} = \bigcup_{\forall m; \forall k; \forall b} \mathbf{W}_{k,m}(b)$ represent the set of all 3D unit-norm beamforming vector weights. In addition, let $\mathcal{P} = \bigcup_{\forall m; \forall c} P_{m,c}$ represent the set of all eNB transmission powers corresponding to the set \mathcal{M} of eNBs and the CCs \mathcal{C} of the aggregated carrier. Given this, we formulate our joint optimization as follows:

$$\begin{aligned} & \underset{\mathcal{W}}{\text{Minimize}} \quad \max_{\mathcal{P}} \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{k \in \mathcal{H}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2 \cdot \frac{P_{m,c}}{B} \\ & \text{subject to} \quad \mathbf{tr}\left\{ \sum_{k \in \mathcal{H}_m} |\mathbf{W}_{k,m}(b)|^2 \cdot \text{psd}_{m,c} \right\} \leq P_{\text{Th}}(m, c); \\ & \quad \omega_{k,m}(b) \geq \omega_{\text{Th}}; \quad \sum_k V_{k,m}(c) \leq B; \\ & \quad \|\mathbf{W}_{k,m}(b)\|_2^2 \leq 1; V_{k,m}(c) \in \{0, 1, 2, \dots, B\} \end{aligned}$$

Here, $\text{psd}_{m,c}$ is as mentioned in Eqn. 2, $P_{\text{Th}}(m, c)$ is the upper-bound threshold on the transmission power; the first constraint ensures that the power thresholds are not violated. $\omega_{k,m}(b)$ is as mentioned in Eqn. 3 and ω_{Th} is the lower-bound threshold SINR per PRB that is required by any UE associated to an eNB; the second constraint guarantees meeting the required SINR threshold. For practical purposes, we assume $\omega_{\text{Th}} \gg 1$, $V_{k,m}(c)$ is the required number of PRBs in any CC \mathcal{C}_c to serve traffic for UE k by eNB m ; the third constraint guarantees that the QoS traffic demands of any associated/re-associated UE are met upon association/reassociation. And the last constraint ensures integrality in the allocation of PRBs from any CC to the UEs.

■ **THEOREM 1:** *The choice of optimal transmission power and beamforming weights on any eNB m is NP-Hard.*

The above optimization problem is hard to solve as it is difficult to estimate the value of $V_{k,m}(c)$ due to the stochastic random variables $\mathbf{H}_{k,m}(b)$ (considering statistical CSI) associated with each b in CC \mathbb{C}_c . It is hard to determine the value of $V_{k,m}(c)$ for even 2 UEs. Previous works have modeled the problem of choosing optimal transmission power or beamforming weights of each eNB in a multi-cell beamforming scenario, subject to SINR constraints, as a convex optimization problem. However, since our work additionally includes the QoS constraint based on the residual frequency-selective PRBs at the eNB, they cannot be directly applied here.

–**Proof:** If we prove the NP-hardness for a simpler single-cell version of the same problem, then the NP-hardness property will also apply for our “harder” multi-cell problem as well. For this, let us consider the following decision version: *Given the set of all UEs facing outage, is there a feasible configuration of transmission power P_m and beamforming weights $W_{k,m}$, $\forall k$ across eNB m , resulting in a successful association/re-association of K_o UEs, where $k = 1, 2, \dots, K_o$ and $K_o \leq |\mathcal{K}_m|$.*

First, to claim that the problem is in NP, we should prove that a Yes/No answer to the corresponding decision problem can be verified in polynomial time. Given \mathcal{P}^* and \mathcal{W}^* , the computed set of transmission powers and beamforming weights across eNBs needed to associate K_o UEs, it takes only a linear time to determine the feasibility in terms of $V_{k,m}(c)$ and to verify that the sum of allocated PRBs from eNB m does not exceed the total number of PRBs B . It again takes only a linear time to determine the feasibility in terms of computing $\omega_{k,m}(b)$ for all B PRBs on eNB m for each associated UE k and to verify that $\omega_{k,m}(b) \geq \omega_{\text{Th}}, \forall b : 1 \leq b \leq B$.

Next, to show that the problem is NP-Hard, we must reduce a known NP-complete problem to our problem in polynomial time. Let us take an instance of the NP-Complete Subset sum problem [17], whose decision problem is stated as follows: “Given an instance of non-negative integers s_1, s_2, \dots, s_n and an integer t , is there a subset of these numbers with a total sum t ”. This decision problem is proven to be NP-complete. We will provide a reduction in polynomial time to the decision problem of our version as follows: As B is the total number of PRBs on any CC of any eNB, $t \implies B$. The PRB allocation is done based on the given finite-buffer QoS requirement for each UE k , given by R_k . So, $s_k \implies R_k$. Clearly, the successful allocation of K_o UEs to any eNB m is possible *if and only if* the B PRBs can support the net traffic requirement of all these UEs, given by $\sum_{k=1}^{K_o} s_k$. So, a Yes answer to this decision problem indicates a Yes answer to allocating K_o UEs, based on the configuration of transmission power and beamforming weights on each eNB m . This impacts its SINR for any UE k , which further determines the rate and hence, the number of PRBs allocated to the UE. ■

Approximation: Since we prove that the independently-modulated PRBs makes the problem hard, we approximate the problem so that it could be solved using convex optimization techniques. Accordingly, the 3rd constraint is approximated as follows:

$$\overline{V}_{k,m}(c) \cdot \beta \cdot \log_2(1 + \overline{\omega}_{k,m}(c)) = R_k \implies$$

$$\overline{V}_{k,m}(c) = \frac{R_k}{\beta \cdot \log_2(1 + \overline{\omega}_{k,m}(c))} \simeq \frac{R_k}{\beta \cdot \log_2(\overline{\omega}_{k,m}(c))} \leq \theta_k B \quad (4)$$

where $\overline{\omega}_{k,m}(c)$ is the exponential effective SINR average [18] from CC c of eNB m to UE k and $\overline{V}_{k,m}(c)$ is the expected number of PRBs to be allocated from CC \mathbb{C}_c of eNB m to UE k , as shown in Eqn. 5. The approximation of $\log(1+x) \approx \log x$ is a commonly-studied approximation [19] and the approximation is within 1 bit ($\log(1+x) - \log x < 1$; for $x > 1$). For $\overline{\omega}_{k,m}(c)$ we have:

$$\overline{\omega}_{k,m}(c) = \frac{\mathbf{G}_{k,m}(c) \cdot P_{m,c}}{\sum_{m' \neq m} \mathbf{G}_{k,m'}(c) \cdot P_{m',c} + \overline{\sigma}_{N,c}^2} \quad (5)$$

where $\mathbf{G}_{k,m}(c)$ is the expected wideband channel gain between eNB m and UE k over CC \mathbb{C}_c . The approximation gap for this is elucidated in [18] and [20]. From the 2nd constraint, as it is required for the resulting SINR across each PRB to be greater than the threshold SINR, the exponential effective SINR average $\overline{\omega}_{k,m}(c) \gg 1$ and so $1 + \overline{\omega}_{k,m}(c) \simeq \overline{\omega}_{k,m}(c)$. Also, this exponential effective SINR average varies for different UEs associated to the eNB. This results in different values of $\overline{V}_{k,m}(c)$ across different UEs. So, imposing the constraint that $\sum_k \overline{V}_{k,m}(c) \leq B$ for each UE k associated to the eNB m makes it difficult to get a closed-form expression for the total number of PRBs allocated to all associated UEs from eNB m on CC \mathbb{C}_c and to check if it does not exceed B . To handle this problem, we introduce a new fractional variable θ_k based on the scheduler (such as the Proportional-Fair scheduler, Round-robin scheduler, etc.) [21] that assigns each CC in the aggregated carrier of the eNB with its portion of the finite-buffer per-frame UE-subscribed traffic that it should serve, schedules the traffic portion on the corresponding PRBs of the CC and allocates them to the UEs. Based on the required traffic, instantaneous achievable throughput and past-achieved throughput from the CC of any eNB to a UE, the scheduler determines how many PRBs should be allocated from that CC to the UE. This helps in estimating the fraction of PRBs which the scheduler decides to allocate to the UE. The value of the number of PRBs is also impacted by the total number of UEs associated to the corresponding cell. There is however no guarantee that the total number of PRBs allocated to the UE by the scheduler would ascertain meeting its QoS requirements. That is the duty of our constraint to ensure it. So, the third constraint (upon approximation) is written as $\overline{V}_{k,m}(c) \leq \theta_k B$.

A critical aspect of this approximation is that the equation does not essentially capture frequency-selectivity across the CC c , but rather chooses a wideband Channel Quality Indication (CQI) reporting. On the other hand, this helps in approximating the problem as a convex optimization problem and deriving a near-optimal solution. However, the principle of frequency-selectivity in PRBs is accounted for, when we determine the near-optimal 3D beamforming weight matrices \mathcal{W} , as detailed in Lemma 2 and in the next section.

–**LEMMA 1:** *The optimization problem with approximated constraints is convex with respect to the choice of transmission powers across eNBs.*

We analyze the formulation in terms of joint optimization of both \mathcal{P} and \mathcal{W} . Let us split the formulation into two sub-problems. The first sub-problem is the **maximization objective**

by choosing the optimal transmission power for each eNB.

$$\begin{aligned} \mathcal{P}^* &= \arg \max_{\mathcal{P}} \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{K}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2 \cdot \frac{P_{m,c}}{B} \\ \text{subject to: } & \mathbf{tr}\{ \sum_{k \in \mathcal{K}_m} |\mathbf{W}_{k,m}(b)|^2 \cdot \text{psd}_{m,c} \} \leq P_{\text{Th}}(m, c); \\ & \omega_{k,m}(b) \geq \omega_{\text{Th}}; \quad \bar{V}_{k,m}(c) \leq \theta_k B. \end{aligned} \quad (6)$$

Recall that $\mathbf{W}_{k,m}(b)$ here is the beamforming weight value when outage happens, since the starting point of our optimization procedure happens at outage. With respect to this maximization objective, the objective function is a linear function of the transmission power. A linear function is both convex and concave. Thus, the objective with respect to transmission power involves the maximization of a concave function. The left hand side of the first constraint is a linear and hence, a convex function of the transmission power. Hence, the first constraint is convex. The second constraint may appear non-convex; however, constraints of this type can be transformed into a second-order cone constraint and thus convex [8], [7]. Thus, the left hand side of the second constraint can be written as a concave function of the transmission power. The left hand side of the third constraint is a convex function as log of the expected SINR is also concave. The log of expected SINR, based on wideband CQI reporting that uses one SINR value for the entire CC from Eqn. 5, is present in the denominator in Eqn. 4, as discussed above, and is hence convex. Therefore, the maximization objective to optimize the transmission power in Eqn. 6 is a convex optimization problem.

–LEMMA 2: *The optimization problem with approximated constraints is convex with respect to the beamforming weights across eNBs.*

The second approximated sub-problem is the **minimization objective** by choosing the appropriate beamforming weights for each optimal transmission power obtained from the previous sub-problem.

$$\begin{aligned} \mathcal{W}^* &= \arg \min_{\mathcal{W}} \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{K}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2 \cdot \frac{P_{m,c}^*}{B} \\ \text{subject to } & \|\mathbf{W}_{k,m}(b)\|_2^2 \leq 1 \\ & \omega_{k,m}(b) \geq 2 \frac{R_k}{\bar{V}_{k,m}(c) \cdot \beta} - 1; \end{aligned} \quad (7)$$

As discussed earlier, the optimal transmission power used in Eqn. 7 is the one obtained from solving the optimization problem in Eqn. 6, based on the expected SINR from wideband CQI reporting. However, with the optimal set of transmission power values \mathcal{P}^* obtained from the first sub-problem, the beamforming weights are obtained on a per-PRB basis using sub-band CQI reporting. Recall that $P_{m,c}^*$ is the optimal transmission power allocated for CC c of eNB m (as obtained from the previous phase), and $\bar{V}_{k,m}(c)$ is the approximated number of PRBs allocated from the CC to any UE k . We need to choose the minimum possible beamforming weights for each of the $\bar{V}_{k,m}(c)$ PRBs allocated from CC \mathcal{C}_c of eNB m to UE k . This, when coupled with per-UE minimum-acceptable SINR requirements, results in the SINR-based constraint, as shown above in Eqn. 7. Hence, the approximated constraint

that couples both traffic and signal guarantees is obtained from the following:

$$\bar{V}_{k,m}(c) \cdot \beta \cdot \log_2(1 + \omega_{\text{Th}}) \approx R_k; \quad \omega_{\text{Th}} \approx 2 \frac{R_k}{\bar{V}_{k,m}(c) \cdot \beta} - 1 \quad (8)$$

If $\omega_{k,m}(b) \geq \omega_{\text{Th}}$, this results in the above constraint in Eqn. 7 (proved to be convex from [8]).

IV. OPTIMIZATION OF TRANSMISSION POWER AND BEAMFORMING WEIGHTS

Having shown that the approximated mitigation strategy is a convex optimization problem, strong duality holds. Hence, the solution can be characterized via its Lagrangian. The rationale in this optimal reconfiguration of the transmission power and beamforming weights on each eNB is to make the coverage from each CC of the eNB is proportional to the number of residual PRBs. The Lagrangian is applied in two phases, \mathcal{L}_1 and \mathcal{L}_2 for the transmission power and beamforming weights, respectively.

A. Transmission power Optimization

Here, we increase the transmission power of each eNB based on its residual PRBs so that the coverage from each of them is increased due to a higher resulting RSRP value for the UEs. This reconfiguration impacts the SINR of the UEs (contributing to both the signal and interference factors) which in turn affects satisfaction of their QoS. Hence, we must iterate through the reconfiguration values so as to reach the optimal point of signal coverage, where there is maximum possible reassociation of UEs. The high-level overview of the procedure before divulging intricate details is as follows: The procedure initially starts with the maximum possible transmission power on each eNB that maximizes coverage due to increased RSRP. But this contributes to interference in a multi-cell setup which does not help in successful reassociation. So, at every iteration, the transmission power on each eNB is reduced based on the interference it contributes to neighboring sectors, until we get an upper bound on the transmission power of each eNB that maximizes coverage. The procedure stops at this optimal point, characterized by the first-order Karush-Kuhn-Tucker (KKT) conditions [9], [7]. Referring to the corresponding objective in Eqn. 6, the primal variable to be optimized in the first phase is $P_{m,c}$ and the lagrangian dual variables (for the constraints in the primal problem) include $\lambda_{m,c}$, $\mu_{m,c}$ and $\kappa_{m,c}$. By applying the Lagrangian, we get:

$$\begin{aligned} \mathcal{L}_1(\mathcal{P}, \lambda, \mu, \kappa) &= \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{K}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2 \cdot \frac{P_{m,c}}{B} \\ &- \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \lambda_{m,c} \left(\sum_{\substack{\forall k \in \mathcal{K}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2 \cdot \frac{P_{m,c}}{B} - P_{\text{Th}}(m, c) \right) \\ &+ \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{K}_m; \\ \forall b \in \mathcal{C}_c}} \mu_{m,c} (\omega_{k,m}(b) - \omega_{\text{Th}}) \\ &- \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{k \in \mathcal{K}_m} \kappa_{m,c} (\bar{V}_{k,m}(c) - \theta_k B) \end{aligned} \quad (9)$$

Now, from Eqn. 3, we can write:

$$\omega_{k,m}(b) - \omega_{\text{Th}} = \frac{|\mathbf{Z}_{k,m}^H(b) \cdot \mathbf{H}_{k,m}(b) \cdot \mathbf{W}_{k,m}(b)|^2 \cdot P_{m,c}}{B \cdot \omega_{\text{Th}}} - \sum_{\substack{(m',k') \neq \\ (m,k)}} |\mathbf{Z}_{k,m'}^H(b) \cdot \mathbf{H}_{k,m'}(b) \cdot \mathbf{W}_{k',m'}(b)|^2 \cdot \frac{P_{m',c}}{B} - \sigma_{N,c}^2 \|\mathbf{Z}_{k,m}^H(b)\|^2 \quad (10)$$

Similarly, we have:

$$\bar{V}_{k,m}(c) - \theta_k B = \frac{\mathbf{G}_{k,m}(c) \cdot P_{m,c}}{B \cdot (2^{\frac{R_k}{\beta \cdot \theta_k \cdot B}} - 1)} - \sum_{m',c} \mathbf{G}_{k,m'}(c) \cdot \frac{P_{m',c}}{B} - \sigma_{N,c}^2 \|\mathbf{Z}_{k,m}^H(b)\|^2 \quad (11)$$

We do not show the entire step of derivation for the final closed-form expression of \mathcal{L}_1 due to space constraints. However, by re-arranging as shown in Eqn. 15 and setting the gradient of \mathcal{L}_1 with respect to $P_{m,c}$, $\frac{\partial \mathcal{L}_1}{\partial P_{m,c}}$, equal to zero, we obtain the following set of equalities which form the first-order conditions required for optimality:

$$\begin{bmatrix} \lambda_{m,c} \\ \mu_{m,c} \\ \kappa_{m,c} \end{bmatrix}^H \left[- \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} \frac{\sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2}{\omega_{\text{Th}}} \cdot \frac{|\mathbf{Z}_{k,m}^H(b) \cdot \mathbf{H}_{k,m}(b) \cdot \mathbf{W}_{k,m}(b)|^2}{\omega_{\text{Th}}} \right] = \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} \frac{\mathbf{G}_{k,m}(c)}{2^{\frac{R_k}{\beta \cdot \theta_k \cdot B}} - 1} + \sum_{m' \neq m} \begin{bmatrix} \lambda_{m',c} \\ \mu_{m',c} \\ \kappa_{m',c} \end{bmatrix}^H \left[- \sum_{\substack{\forall (k',m') \\ \neq (k,m)}} |\mathbf{Z}_{k',m}^H(b) \cdot \mathbf{H}_{k',m}(b) \cdot \mathbf{W}_{k,m}(b)|^2 \right] + \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} \mathbf{W}_{k,m}(b)$$

The complementary slackness conditions are given by:

$$\lambda_{m,c} \left(\sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2 \cdot \frac{P_{m,c}}{B} - P_{\text{Th}}(m,c) \right) = 0 \\ \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} \mu_{m,c} (\omega_{k,m}(b) - \omega_{\text{Th}}) = 0 \\ \sum_{\forall k \in \mathcal{X}_m} \kappa_{m,c} (\bar{V}_{k,m}(c) - \theta_k B) = 0 \\ \lambda_{m,c} \geq 0, \mu_{m,c} \geq 0, \kappa_{m,c} \geq 0 \quad (12)$$

The equalities and complementary slackness, shown above, along with the constraints in the transmission power sub-problem in Eqn. 6 form the KKT conditions, required for optimality. From the first-order conditions for optimality, we construct our iterative procedure as follows: Let the terms on the LHS of the matroid be written as $\lambda_{m,c}(t)$, $\mu_{m,c}(t)$ and $\kappa_{m,c}(t)$ and the terms on the right be written as $\lambda_{m',c}(t-1)$, $\mu_{m',c}(t-1)$ and $\kappa_{m',c}(t-1)$. Starting from $\lambda_{m,c} = 0$, $\mu_{m,c} = 0$

and $\kappa_{m,c} = 0$, the iterative procedure is based on the expression in the matroid, which is of the following form:

$$\Upsilon_{m,c}(t) \Xi = \Upsilon_{m',c}(t-1) \Psi + \Omega$$

The value of the dual variables obtained at each iteration are used to find the corresponding primal variable $P_{m,c}$ at that iteration. This can be written in standard function, as follows:

$$\Upsilon_{m,c}(t) = \Xi^{-1} (\Upsilon_{m',c}(t-1) \Psi + \Omega) = f_{m,c}(\Upsilon_{m',c}(t-1)). \quad (13)$$

Any expression that can be written in the above standard form is proven to converge. We avoid elaborate discussions on convergence due to space constraints and the reader is referred to [7], [5] for pertinent details. At convergence, we will have $P_{m,c}^*$, i.e., the optimal transmission power for eNB m on CC c .

B. Beamforming Weights

Here, we reduce the beamforming weights corresponding to each transmission power $P_{m,c}^*$, we obtain for every eNB in the previous stage, while still maintaining a strong, stable link between the eNB-UE pair. This helps in reducing the inter-cell interference among eNBs. The rationale here is to determine the appropriate beamforming weights for every PRB on each CC in the eNBs, thereby retaining the frequency-selectivity of the OFDMA-modulated CC. The computation is based on the optimal transmission power for each eNB m on CC c obtained from the previous Lagrangian phase, $P_{m,c}^*$, along with the estimated number of PRBs for every reassocated UE given by $\bar{V}_{k,m}(c)$ and the SINR $\omega_{k,m}(b)$. Referring to the objective function in Eqn. 7, the primal variable to be optimized here is $\mathbf{W}_{k,m}(b)$ and the dual variable considered here is $\zeta_{k,m}(b)$.

$$\mathcal{L}_2(\mathcal{W}, \zeta) = \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} |\mathbf{W}_{k,m}(b)|^2 \cdot \frac{P_{m,c}^*}{B} - \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} \zeta_{k,m}(b) \left(\frac{\omega_{k,m}(b)}{2^{\frac{R_k}{\beta \cdot \bar{V}_{k,m}(c) \cdot \beta}} - 1} - 1 \right) \quad (14)$$

After substitution from Eqn. 3 into $\omega_{k,m}(b)$ like what is shown in Eqns. 10 and 11 and then, rearranging, we have:

$$\mathcal{L}_2(\mathcal{W}, \zeta) = \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} \sigma_{N,c}^2 \zeta_{k,m}(b) \|\mathbf{Z}_{k,m}^H(b)\|^2 + \sum_{\substack{\forall m \in \mathcal{M}; \\ \forall c \in \mathcal{C}}} \sum_{\substack{\forall k \in \mathcal{X}_m; \\ \forall b \in \mathcal{C}_c}} \mathbf{W}_{k,m}(b) \frac{P_{m,c}^*}{B} \left(1 - \frac{|\mathbf{Z}_{k,m}^H(b) \cdot \mathbf{H}_{k,m}(b)|^2 \cdot \zeta_{k,m}(b)}{B (2^{\frac{R_k}{\beta \cdot \bar{V}_{k,m}(c)} - 1}}) \right) - \sum_{\substack{(m',k') \neq \\ (m,k)}} |\mathbf{Z}_{k',m}^H(b) \cdot \mathbf{H}_{k',m}(b)|^2 \cdot \zeta_{k',m'}(b) \mathbf{W}_{k,m}^H(b) \quad (15)$$

Similarly, the first-order optimality conditions for KKT, obtained by equating the gradient of \mathcal{L}_2 in 15 with respect to the beamforming weight $\mathbf{W}_{k,m}(b)$ to zero, include the following equalities:

$$\frac{|\mathbf{Z}_{k,m}^H(b) \cdot \mathbf{H}_{k,m}(b)|^2 \cdot \zeta_{k,m}(b)}{B \left(2^{\frac{R_k}{\beta \cdot V_{k,m}(c)}} - 1 \right)} = 1$$

$$- \sum_{\substack{(m', k') \neq \\ (m, k)}} |\mathbf{Z}_{k',m'}^H(b) \cdot \mathbf{H}_{k',m'}(b)|^2 \cdot \zeta_{k',m'}(b) \quad (16)$$

The corresponding complementary slackness conditions are similar to Eqn. 12, referring to the constraints in Eqn. 7. This expression can also be written in standard function shown in Eqn. 13. And with a similar reasoning, it converges to an optimal point $\mathbf{W}_{k,m}^*(b)$ [7], [5] i.e., the appropriate transmit beamforming weight for any PRB b from eNB m to UE k .

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed framework. We present our computer simulation setup followed by our results.

Simulation setup: We use the open source LTE/EPC Network simulator (LENA) M5 release, based on the discrete-event Network Simulator NS3 [6]. The salient features of this simulation model include a complete implementation of uplink and downlink PHY and MAC layers (e.g. Adaptive Modulation and Coding (AMC), path loss models, and channel state information feedback). We extended the simulator to support: (i) RSRP-based association of UEs to the eNBs, (ii) Log-normal shadowing between each eNB-UE pair and (iii) Frequency-dependent path loss exponent for computation in inter-band CA. We simulate our framework over a 21-sector hexagonal grid with sets of 3 collocated sectored eNB cell sites with directional antenna, as shown in Fig. 3. 7 collocated eNB sets (21 cell-sectors with 3 cells per set) are deployed in the following coordinates : (1700,4250), (3400,4250), (850,2550), (2550,2550), (4250, 2550), (1700, 850), (3400, 850) with an average inter-cell site of 1.732 km. Each eNB is equipped with 2 inter-band CCs, belonging to 748 MHz and 2125 MHz. We perform extensive simulations for three cases:

- (i) Scenario A with outage of a single sector at the center of the hexagon,
- (ii) Scenario B with the outage of a collocated set of eNBs and
- (iii) Scenario C with the outage of 3 cell sectors randomly distributed over the network.

Simulation parameters are detailed in Table I. Each simulation result is based on an average of 50 instances of the various random variates (user placement, log-normal fading, traffic model). The users are uniformly distributed across the topology. The number of traffic applications used by a UE follows a binomial distribution, i.e. there is a non-zero probability for any UE to subscribe for any number of traffic applications (incl. 0), up to a maximum subscription number. The choice of subscribing to any traffic application by any UE follows a uniform distribution. We consider upto 1000 UEs in the simulation for all the 3 scenarios. Based on 3GPP standards, the maximum number of UEs that can be associated to any cell is 320 as this is the maximum possible association of UEs to any cell; this is because the longest supported interval for Sounding Reference Signal (SRS) periodicity to multiplex users

TABLE I
NS3 SIMULATION PARAMETERS

Parameter	Value
Macro eNB Tx power range	45-50 dBm
Macro eNB height	32 m
UE height	1.5 m
Antenna	Directional, sectored
Orientations	0°, 120°, 240°
Beamwidths	30° – 70°
Antenna Gain	10-15 dBm
Path Loss model	Log-Distance
Distance-dependent pathloss exp.	3.52
Frequency-dependent pathloss exp.	2.16
SINR threshold	35 dBm
Fading distribution	Log-normal ($\mu = 0, \sigma = 6.5\text{dB}$)
Macro inter-site distance	1.732 km
Operating central band frequencies	748 MHz, 2125 MHz
Bandwidth of the CCs	10 MHz (50 PRBs)
Maximum number of UEs	1000
User distribution	Uniform across cell
UE Traffic subscription	Binomial
Distribution of traffic choices	Uniform
Scheduling algorithm	Proportional-Fairness
PHY AMC decoding	AmcMirror model
Supported Modulation schemes	QPSK, 4QAM, 16QAM, 64QAM

for sending their uplink SRS values is 320 ms. With respect to traffic subscription, the UEs subscribe to traffic applications with finite buffer QoS requirements of 32 kbps, 128 kbps and 512 kbps, following a binomial distribution with a maximum of 2 traffic subscriptions per UE. The choice of traffic applications follows equal probabilities. The Table I contains the values used for the parameters and a range of values, specifically for the transmission power and beamforming weights parameters. The near-optimal transmission power and beamforming weights used are obtained from this range through a numerical evaluation of our optimization procedure.

There are 2 key main parameters considered for evaluation:

- **Fraction of successfully-reassociated outage UEs** : The fraction of UEs facing outage who have been re-associated successfully and served for their QoS requirements.
- **Aggregate achievable throughput of outage UEs** : This is the estimated aggregate throughput of all the re-associated UEs, based on their instantaneous Modulation and Coding Scheme (MCS) values, while considering the allocation of the entire aggregated carrier (all PRBs on all sub-frames) to each UE. It indicates the quality of the radio channel made available to the UEs facing outage. The evaluation is carried out for the 3 scenarios A, B and C. We evaluate and compare our proposed optimization approach against two other approaches. One of them (SINR only) is only based on SINR constraints that requires the link stability to be greater than a threshold, without caring about the residual network bandwidth. The other approach (residual resource only) is a channel-agnostic load-balancing technique based on the number of residual PRBs available on each eNB. eNBs having larger residual PRBs are likely to attract more outage UEs for reassociation. In Figs. 4, 5, 6, the fraction of successfully-reassociated outage UEs is evaluated by varying the number of UEs across the simulation topology from 100 to 1000 for scenarios A, B and C respectively. Our method outperforms the other two, in all 3 scenarios in terms of guaranteeing QoS. It reports a successful reassociation of 45%, as against 26% and 23% over

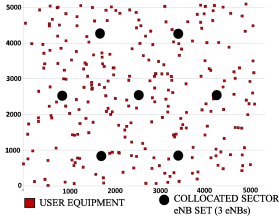


Fig. 3. Topology

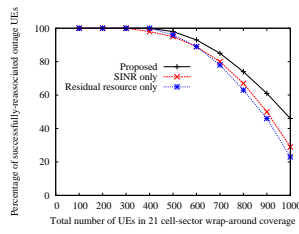


Fig. 4. Scenario A

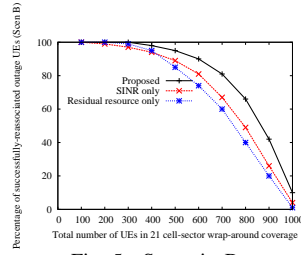


Fig. 5. Scenario B

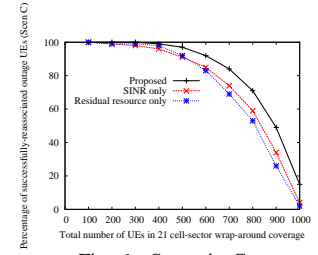


Fig. 6. Scenario C

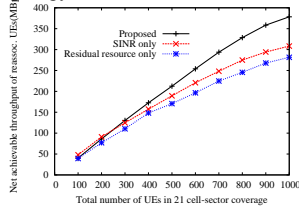


Fig. 7. Scenario A

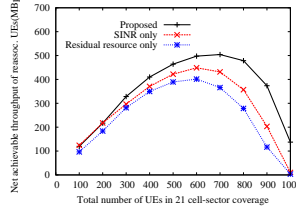


Fig. 8. Scenario B

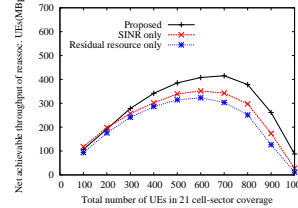


Fig. 9. Scenario B

the existing techniques for scenario A in Fig. 4 for a highly dense network deployment with 1000 UEs. In Scenarios B and C corresponding to Figs. 5 and 6, our technique guarantees 10% and 15% of successful reassociation in the worst case. This is in comparison with the existing SINR-based approach yielding 4% in both the scenarios and load balancing yielding 1% and 2% in the scenarios, respectively. The curves decrease as we keep increasing the number of UEs in the simulation topology. More UEs create more traffic and so, there are fewer residual PRBs on each eNB. Hence, the fraction of successfully-reassociated UEs keeps decreasing.

In Figs. 7, 8, 9, the achievable throughput of outage UEs is evaluated against the number of UEs across the simulation topology for all the 3 scenarios and compared with the above existing techniques. The curves in scenarios B and C show an increase upto a certain point, following which, there is a decrease. This is because initially there are fewer UEs facing outage. As long as there is a higher fraction of successful reassociation, the net aggregate achievable throughput increases with the increase in the number of UEs in the topology. When the fraction of successful reassociation of outage UEs decreases, the aggregate throughput keeps decreasing even as the UEs get denser as fewer UEs exhibit successful reassociation (seen from previous results). Hence, as seen in Figs. 8 and 9, the aggregate achievable throughput increases upto a certain point, beyond which, it starts decreasing as the network gets denser and the QoS requirements of all outage UEs cannot be satisfied. The improvements are around 20%-25% half-way through and rises to more than 75% as the network gets highly denser with more than 800 UEs in the topology. However, this trend in the curves (increase upto a point, and then, decrease) is not observed in scenario A as only one outage, happening in the central eNB sector, keeps the fraction of successful reassociation to a reasonable level. Therefore, the trend of the net achievable throughput aggregate is increasing with the number of UEs. In all the three scenarios, our proposed dual optimization outperforms existing techniques by 20%.

VI. CONCLUSION

We presented a framework for mitigating the adverse impact of dynamic outages in LTE-Advanced macro deployments with sector base stations. Our framework performs an optimal recon-

figuration of the transmission power and beamforming weights of the serving base stations in the neighborhood of the ones facing outage. The unique aspect of our mitigation framework is the reassociation of users facing outage to alternate base stations that not only provide them with adequate channel gains but also possess enough residual resources to meet the QoS requirements of their subscribed traffic. We model the problem as an NP-hard problem and perform a reasonable approximation to solve it via convex optimization techniques in two phases. We evaluate our mitigation framework using exhaustive simulations.

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