Fronthaul Cell Outage Compensation for 5G Networks

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***Abstract*—5G networks are expected to bring the gigabits per second throughput level per user to reality by 2020. This is done using a combination of new and well known technologies such as Cloud Radio Access Networks (C-RAN), Self-Organizing Networks, Ultra Dense Networks, massive MIMO and millimeter waves. In new RAN architectures, C-RAN has been viewed as a promising 5G architecture which centralizes baseband processing units and virtualizes them into a resource pool. The baseband units are connected to the Remote Radio Heads via a high speed fronthaul links. Failure of any 5G cell site fronthaul means the loss of hundreds of gigabits, or even terabits. In this article, we present a novel cell outage compensation approach using new Self-Healing Radios (SHRs) added to each cell site in the 5G network. These SHRs operate only in case of fronthaul/backhaul failure of any cell site in the network. A new software defined controller is introduced to handle the self-healing procedures. The article also introduces a high level simulation study that is carried out to assess the proposed approach. The simulation results confirm the advantages of the proposed approach in terms of the degree of recovery from failures.**

***Index Terms*—5G, C-RAN, COC, Fronthaul, Self-Healing, Self-Healing Radios.**

I. Introduction

THE main objective of 5G networks is to achieve the gigabits per second throughput level with high reliability and "limitless" connectivity from everything to everything, anytime, and anywhere. Many new and/or well-known technologies are proposed to be integrated in the 5G architecture such as Cloud Radio Access Networks (C-RAN), massive MIMO, millimeter Waves (mmW), Software Defined Networking (SDN), Self-Organizing Networks (SONs), dense heterogeneous networks (HetNets).

C-RAN is a cloud computing based newely adapted cellular network architecture that is highly expected to be integrated in future cellular standards. Each conventional Base Station (BS) consists of a Baseband Unit (BBU), which is responsible of the baseband processing, and radio heads which are responsible of the radio frequency functionalities. By separating the radio heads, which are now called Remote Radio Heads (RRHs), from the BBU, the baseband processing is migrated to the cloud and connected to the RRHs via high speed fronthaul links giving rise to the so called C-RAN. C-RAN provides several advantages compared to the conventional RANs such as faster network deployment and system performance improvement. Even more, by the interworking of SDN with C-RAN in 5G networks, C-RAN can gather more information to perform better global tasks and decisions [1].

It is expected that 5G data traffic will increase up to 1000 folds over that of 4G, implying that the 5G backhaul/fronthaul capacity has to carry significant amount of traffic. These high rates pose new requirements for backhaul/fronthaul links [2]. Achieving data rates on the order of 10 or 100 Gbps for access communications or fronthaul links is possible only if the available bandwidth is within 1 GHz, which is available only in the mmW bands [3]. Although 5G requires a multiple gigabits per second, tens or hundreds of megabits per second need to be guaranteed with very high availability and reliability in case of failures.

Adding new network elements, optimizing these elements and mitigating the effect of the different potential failures is one of the most challenging tasks facing any network operator. The automation of these tasks is referred to as SON. The SON is defined as the network which has the capability to dynamically adapt changes in the network in order to optimize its performance. The need for SONs arise from the fact that in future networks, the number of nodes is increasing at a rapid rate. Moreover, it is also because of the introduction of a high degree of heterogeneity and complexity, that such SONs could save a lot of operational expenditure.

SON defines three areas: self-configuration (plug and play network elements), self-optimization (automatically optimize network elements and parameters) and self-healing (automatically detect and mitigate failures). For the use of SON in 5G networks, the reader is referred to [4].

Self-healing is the execution of actions that keep the network operational and/or prevent disruptive problems from arising. Self-healing is done in two steps: Cell Outage Detection (COD) and Cell Outage Compensation (COC). The COD is to detect and classify failures, while minimizing the detection time. The COC executes actions to mitigate or, at least, alleviate the effect of the failure. If the failure time exceeds a certain threshold, it is considered as a permanent failure and a site visit by the operator personnel is needed [5]. Detecting cell outage in 3G and 4G (before adapting SON to 4G) was doable but it may take up to several hours, thus resulting in salient degradation in the network performance. Hence automatic detection and compensation of failures in 5G networks is mandatory. In this article, we focus on fronthaul failures and how to mitigate these failures.

Self healing has been addressed by quite a few research works until 4G and in 5G networks it is still an unexplored area. The authors in [6] addressed a variety of survivability issues, challenges, and mechanisms in multihop wireless networks. In [7] the authors surveyed the literature over the period of the last decade on the SONs as applied to wireless networks including self-healing. The authors in [8] presented a novel cell outage management framework for HetNets. They used an algorithm for COC which uses reinforcement learning algorithm, which adjust the antenna gain and transmission power of the surrounding BSs.

II. The proposed HetNet C-RAN Architecture

The new proposed HetNet C-RAN architecture consists of the BBU pool and RRHs of different types of cells where the small cells (SCs), i.e., picocells and femtocells, are co-located within the macrocell footprint as shown in Fig. 1. Each macrocell is supposed to use fractional frequency reuse to avoid interference with other macrocells. The SDN concept was included for the network flexibility and the Software Defined Wireless Network Controller (SDWNC), which is co-located within the cloud, is used mainly to control the whole process of COC.

The different types of cell sites are fronthauled using different types of links. Macrocell is always connected to the BBU pool using fiber link(s). Picocells are connected to the BBU pool or to the macrocell either by using fiber or wireless point to point links. Femtocells can be fronthauled using any of the mentioned links in addition to coaxial cable, hybrid fiber-coaxial or copper pairs. If the former links are used, the Internet Service Provider (ISP) must have a low latency high speed connection to the cloud. This C-RAN architecture is also compatible with the conventional BSs which are not C-RAN based.

It should be noted that the heterogeneity in this architecture is in two directions. One direction is that the C-RAN serves heterogeneous types of cell sites (macrocells, picocells and femtocells). The second direction is the different wired and wireless types of fronthaul connections.

III. The Proposed COC Approach

The conventional and well known approach for COC is to optimize the capacity and coverage of the outage zone by adjusting the antenna gain and transmission power of the neighboring BSs. The disadvantage of this approach is that changing antenna tilt and power of the neighboring BSs will degrade the performance of the users served by these BSs. Moreover, the neighboring BSs will consume a considerable time (compared to 1 ms) to change their power and antenna tilt. The proposed COC approach will not change the antenna tilt or the power of the neighboring cell sites. We propose to add a new radio, which is named Self-Healing Radio (SHR), to each cell site in the network. When a failure occur to the fronthaul/backhaul of any cell site, the failed cell site will acquire its fronthaul/backhaul connection from the neighboring cell sites using the SHRs. The neighboring cell will help the failed cell if it has available resources which are not used by its users. The detailed approach is discussed in Section IV.

The network always operates in the normal mode (no failure) which may last for hours or days. The network is monitored for detection of any failure by the SDWNC. In case of failure, the COC strategy will be activated by the SDWNC within a few milliseconds. System repair, which will be done by the operator maintenance personnel, can typically be done within 12 hours and in this case, the COC approach will provide recovery that satisfies the minimum rate requirements in the failure region. Switching back to normal operation is performed in multiple of milliseconds and it is triggered by the SDWNC which will deactivate all SHRs for all cell sites.

There are many challenges and issues that had been addressed to provide a reliable network architecture which is able to mitigate any fronthaul failure such as the bands used for the macrocell tier and the SCs tier, the SHRs band, how to control the whole COC process and using pre-planned femtocells to help in the healing process. These issues are addressed below.

A. C-RAN Architecture

C-RAN architecture consists of three main components:

1) BBU pool which is composed of a set of servers, storage and switches. The BBU assignment for each RRH could be centralized or distributed. In our architecture we are considering the centralized implementation due to its advantages (flexible resource sharing, energy efficiency and interference avoidance).

2) RRHs are located at the remote cell sites. They transmit the radio frequency signals in the downlink and forward the baseband signals in the uplink for further processing in the BBU pool. They include radio frequency amplifier, up/down conversion mixer, analog-to-digital and digital-to-analog conversion.

3) Fronthaul Links can be wired or wireless. Although wireless fronthaul is cheaper and faster to deploy than wired, the best choice is the high speed optical fiber but microwave or mmW are also considered (reader is referred to [10] for an overview of possible wired and wireless backhaul/fronthaul technologies). Fronthaul antennas can be installed on top of roofs in urban areas and on top of hills in rural areas to ensure the existence of Line-of-Site (LOS) propagation. Also the reader is referred to [11] for more information regarding integrated fronthaul/backhaul architecture in 5G.

By implementing C-RAN, 5G network will gain many advantages such as: 1) The equipment needed at the cell site is only RRHs, power supply and backup batteries which will result in shorter installation and repair time. 2) The cell site will consume less energy (no need for air conditioning) 3) The ease of communication between BBUs in the cloud will provide better performance for mobility management, interference cancelation and coordinated multi-point communication, which is expected to provide higher capacity and improve cell-edge coverage.

Backhaul failures of regular BSs is one type of many failures that can occur in BSs of 4G networks. But, after simplifying the BSs in C-RAN into the RRHs and migrating all processing units (BBUs) to the cloud, fronthaul failures is the failure that has the most impact on the operation of the C-RAN 5G network.

B. Millimeter Waves (mmW) Band

The mmW bands are typically sub-band free and high frequency reuse is possible due to very narrow directed beams.

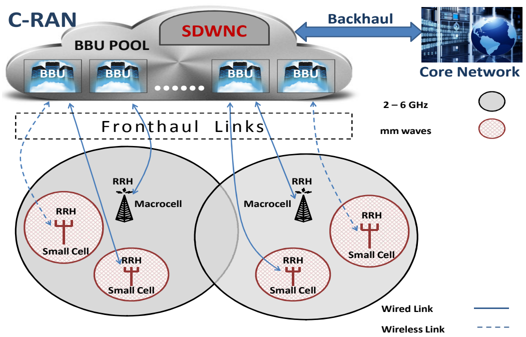

Fig. 1 : The System Model

The so-called light spectrum licensing scheme provides lower total cost of ownership and lower cost per transmitted bit than the microwave bands.

Using mmW bands in 5G networks has already been proposed in the literature. The mmW band is used in short range LOS communications. It is not used in long distance communications due to the high attenuation and oxygen absorption of these waves [3]. The wireless fronthaul and access links are assumed to be out-of-band, that is, there is no interference between them. This will provide the 5G users with the target data rates, and SCs will rely on high-gain beamforming to mitigate pathloss [12].

The macrocell situation is complicated due to its wide area coverage. Using mmW with macrocells is still under intensive research because of the high attenuation associated with wide coverage area. As it is well known from 4G networks, 80% of network traffic is used indoor and only 20% is used outdoor [13]. The 20% outdoor traffic will be carried out by the macrocell and the outdoor SCs. This trend is expected to continue in 5G, this means that the traffic carried out by the macrocell in 5G networks is much lower than that carried by SCs.

In our proposed solution, mmW is used only in fronthaul connections and in SCs access links between SCs and users equipment (UEs). However, the macrocell will use the traditional cellular band (2 - 6 GHz) for communications with its UEs. The motivations behind using this band are better coverage, lower penetration loss and eliminating the interference issue between SCs tier and macrocell tier. The only limitation of this band is its bandwidth but using massive MIMO, carrier aggregation and other technologies, can facilitate the achievement of macrocell gigabits per second throughput.

C. SHRs Band and Cognitive Radio Concept

The SHRs can use 1) mmW band, 2) The traditional cellular band, or 3) A new dedicated band. For the mmW band, it is difficult to be used because of the NLOS path between SHRs. Dedicating a portion of the traditional cellular band, which is also used by the macrocell, to the SHRs communication will affect the band utilization because SHRs are only activated if fronthaul failures occur; otherwise this portion of the band will not be used. Finally, using a dedicated band (licensed for self-healing communicationS only) will dramatically increase the capital expenditure and also this band will not be fully utilized.

Cognitive Radio (CR) concept is one of the promising technologies for solving telecom problems such as spectrum scarcity or in case of disasters [14]. Our proposed solution is to use the CR for SHRs communications which optimizes the use of the available spectrum. The band used is the same as the second solution where a portion of the traditional cellular band will be dedicated to the SHRs. The main difference is that when SHRs are inactive, this portion will be available for the macrocell to use it as a secondary user. Therefore, if the macrocell is starved for bandwidth, it will sense the SHRs dedicated channels and if it is free then the secondary user (macrocell) will use the vacant channels until the primary users (SHRs) are activated. Once the primary user (SHR) is active (this means that a failure has occurred), the macrocell will vacate these channels.

Furthermore, in our model, the macrocell can avoid wasting time in spectrum sensing by acquiring the SHRs channel occupancy information from the SDWNC. If there is no failure, the macrocell will use the reserved portion of the band without sensing. If a failure happen, the SDWNC will immediately request from the macrocell to vacate the SHRs channels to be used by the primary users (SHRs). This will save the sensing power and time (at least 10% of the transmission time) and will also increase the reliability of using CR in 5G networks.

D. Femtocells Used

As it is known from 4G, the femtocells may be deployed by network users; In this case they are randomly placed and are called Random Femtocells (RFs) or femtocells may be deployed by the operator in pre-planned locations to enhance the capacity or to cover dead zones; In this case they are called Pre-planned Femtocells (PFs).

The main difference between the 4G PFs and the proposed 5G ones is that the latter are used mainly to self-heal the failed cell sites. In addition, they can be used also for capacity enhancement and dead zones coverage. The only constraint is that they must be located within the SHRs footprint of the target cell site and it is preferable that the PF be connected to a fiber fronthaul to guarantee the gigabits per second 5G throughput which will be used mainly to heal the failed cell sites and also for serving its own users.

E. Software Defined Wireless Network Controller (SDWNC)

The SDWNC is co-located within the cloud to gather the needed information in a fast and reliable way. The SDWNC is a mandatory component in our architecture as it acts as the supervisor, decision maker and administrator for all self-healing procedures applied to all network cell sites. The reader is referred to [15] for more details about SDN in wireless networks.

The co-location of the SDWNC in the cloud will help it to take optimal decisions in order to decide how to recover from fronthaul failures. This reduces the amount of information

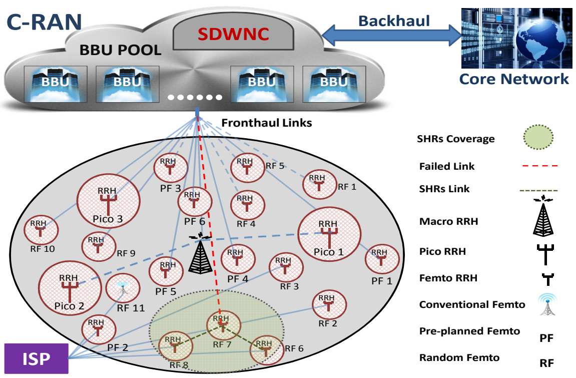

Fig. 2: SC failure mitigation process

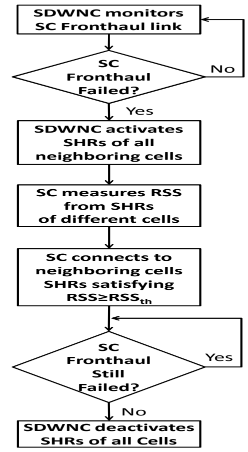

Fig. 3: SC failure mitigation flow chart

needed to be exchanged which will allow optimal recovery in a very short time.

The SDWNC activates SHRs for all cell sites in vicinity of the failed cell site. It also deactivates the SHRs after the failure is repaired. In addition, it deactivates the SHRs of the cells that are not participating in the self-healing process to save their power from being wasted.

IV. Self-Healing Procedures

Fig. 1 shows the whole network but in Fig. 2 we show a zoom in to one of the macrocells coverage where each macrocell is associated with three PFs (one in each sector) and each picocell is associated with one PF. There are no PFs associated with RFs. This is because macrocells and picocells are serving a large number of users compared to the RFs. The latter will search for nearby SHRs, in case of failure, in order to heal their failed fronthaul link. This proposed C-RAN architecture is compatible with the conventional BSs which are not C-RAN based. RF 11 in Fig. 2 shows an example of a BS backhauled from the ISP.

When a certain cell site fronthaul fails, it will automatically activate its own SHRs, but will be totally disconnected from the SDWNC and in this case the cloud, macrocell or ISP (depending on which one was fronthauling this cell site) will report to the SDWNC the failed cell details. The SDWNC will then activate the SHRs of all cell sites in the region surrounding the failed cell site. The process of detecting the failure and SHRs activation must be done within a very short time.

The failed cell will try to connect to the healing cell sites via SHRs according to a certain priority order depending on the cell site type, available resources and the Received Signal Strength (RSS). The failure of a fronthaul link may be permanent or transient. Our COC approach works with both, and the only difference is that in the case of a permanent failure, the SDWNC, after a certain threshold time, will inform the operator that there is a failure which requires maintenance personnel to embark on a field visit to the failed cell site. It should be noted that our proposed COC scheme can be classified as a hybrid approach according to the definition given in [6].

A. *Single Failure Scenario*

Single failure means that only one cell site fronthaul failed in the network. In this case, the SC will trigger the self-healing mode where it will activate its own SHRs and then try to connect to other cell sites' SHRs which are activated by the SDWNC. Following a priority order, the SC will first try to connect to a macrocell, then PFs, then picocell and finally RFs. RFs are assigned the lowest priority because they are personal properties and the operator will have to compensate the owners of these RFs.

The flow chart in Fig. 3 shows the SC fronthaul failure mitigation process where the SDWNC always monitor the network to detect any fronthaul failure. If the fronthaul of any cell site failed, the failed SC will immediately activate its SHRs and at the same time the SDWNC will activate SHRs of all neighboring cell sites. At this point the failed SC will use its SHRs to measure the RSS levels from all neighboring cell sites and will update a list of healing cell sites with measured RSS levels higher than a certain RSS threshold. The failed SC will use priorities to decide which cell sites' SHRs it will connect to. The SDWNC will continue to monitor the failed fronthaul link and when the failed link returns to work properly, the SDWNC will deactivate SHRs of all cell sites in the failure region and the network returns to operate in normal operation.

An example of failure scenario is shown in Fig. 2, where the fronthaul link of RF 7 failed. The failed RF will apply the priority order described above, but because it is out of SHRs' coverage of the macrocell, PFs and nearby picocells, it will connect to the SHRs of RF 6 and RF 8 to mitigate its fronthaul failure. Once the failure is repaired, the SHRs will be deactivated by the SDWNC and RF 7 will return to serve its users using its own fronthaul link.

The failure of the macrocell fronthaul is not considered as a single failure because this will immediately cause the failure of all SCs fronthauled from the macrocell causing multiple failures in the network.

B. *Multiple Failures Scenario*

A multiple failures scenario refers to the situation where two or more fronthaul failures occur at the same time in the same region. There are two cases studied here.

1) SCs Fronthaul Failure: This case can be seen as the failure of two or more SCs in the same region. The procedures in the flow chart above can be used to mitigate these failures when implementing the proposed algorithm for each failed cell site. For example, if two SCs failed, the SDWNC will activate the SHRs of cell sites in their region and each failed cell site will activate its SHRs and try to connect to the healing cell sites and as the number of failures increases the probability of healing each failed cell will depend on the number of nearby healing cell sites which can provide the temporary fronthauling connections. Thus, as expected in 5G networks, the dense deployment of SCs will enhance the performance of our self-healing approach especially in the multiple failures case.

2) Macrocell Fronthaul Failure: The macrocell plays a vital role in HetNets where in addition to its main function, coverage for outdoor users, it provides wireless fronthaul links to other SCs that can't directly reach the cloud. In our architecture, two picocells acquire there fronthauling from the macrocell. Fig. 4 shows an example of the macrocell fronthaul failure and the mitigation process. The macrocell fronthaul failure (the solid red line) immediately results in the failure of two fronthaul links (Pico 1 and Pico 2). As can be seen from Fig. 4, the self-healing process will mitigate the effect of failure for the fronthauled picocells and the macrocell. The picocells will be recovered first using PFs and RFs in their vicinity. For example, Pico 1 will be recovered by PF 1, RF 1 and RF 3. Similarly, Pico 2 will be recovered by PF 2, RF 9 and RF 11.

The next step, macrocell fronthaul recovery, will be done from two sources. The first source is using the mmW links between the macrocell and recovered picocells. The second source is the recovery from femtocells in its SHRs footprint. As shown in Fig. 4, PF 4, PF 5, PF 6, and RF 4 provide the temporary fronthaul connections. Aggregating all received traffic, the macrocell will be able to guarantee the minimum requirements to its users until the failure is repaired, regardless of how long the failure will remain. A heuristic algorithm for the detailed macrocell self-healing procedures can be found in [9].

V. Simulation Model

Simulations were carried out for one macrocell with a footprint of radius 500m in an urban area. Within the macrocell footprint there are 6 picocells, 9 PFs and 50 RFs randomly distributed over the entire area. The fronthaul rate to the macrocell is 100 Gbps, to the picocells is 10 Gbps, to the PFs is 5 Gbps and finally to the RFs is heterogeneous and distributed among the RFs as follow; 50% of RFs with rate of 200 Mbps, 40% of RFs with rate of 500 Mbps and 10% of RFs with rate of 1 Gbps.

The performance of our self-healing approach is evaluated in terms of Degree of Recovery (DoR) from failure. The DoR of a certain BS is defined as:

$$DoR = \frac{Sum\ of\ recovered\ rates\ from\ other\ cell\ sites}{Original\ input\ rate\ of\ the\ failed\ cell\ site}$$

where the original input rate of the failed cell site is the same as the input rate of that cell site except for the macrocell

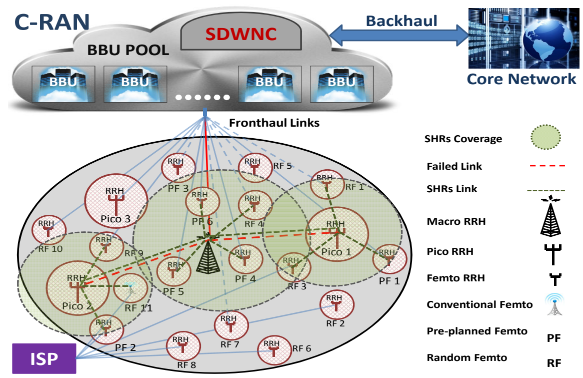

Fig. 4: Macrocell failure mitigation process

because it fronthauls other picocells, so the actual input rate for the macrocell depends on the number of macrocell fronthaul connections.

VI. Simulation Results

In this section, we study the performance of our proposed COC algorithm by investigating the effect of increasing the number of SHRs on the DoR of the failed cell sites. Two scenarios are considered; single failure and multiple failures. First, we assess the DoR of the macrocell failure which is the worst case and is considered as multiple failures. The DoR is evaluated with respect to the number of SHRs in both macrocell and picocells. Second we assess the DoR of RF in case of single failure with respect to the number of SHRs in RFs and picocells.

Fig. 5 addresses the failure scenario of macrocell fronthaul. It shows the DoR of macrocell when the number of SHRs of macrocell and picocells is increased from 1 to 4. When the number of SHRs in picocells is fixed, the DoR increases with the increase of SHRs in macrocell. On the other hand, when fixing the number of SHRs in the macrocell and increasing them in picocells, the DoR will also increase. However, increasing the number of picocells' SHRs has a great influence on the DoR of the macrocell. For example, fixing macrocell SHRs to 1 and increasing picocell SHRs from 1 to 4 can improve the macrocell DoR by approximately 50%, but fixing picocell SHRs to 1 and increasing macrocell SHRs from 1 to 4 will improve the DoR by less than 10%. The DoR significantly depends on the number of SHRs in picocells because in addition to recovering from surrounding femtocells, it recovers also from the recovered picocells using the already deployed LOS links between picocells and macrocell. It is obvious that the incremental increase in the DoR decreases with increasing the SHRs.

Fig. 6 addresses the failure scenario of a femtocell fronthaul. It shows the DoR of a femtocell when the number of SHRs of femtocells and picocells is increased from 1 to 4. As can be seen clearly from the figure, as the femtocells SHRs increases the DoR of femtocells increases. However, the number of SHRs in picocells has a slight or even no effect on the DoR of the failed femtocell. This shows that the DoR of femtocells is not directly dependent on the number of SHRs in picocells

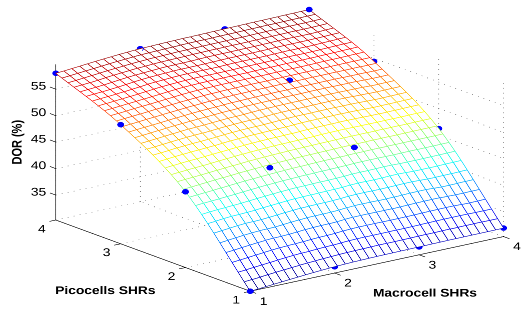

Fig. 5 : Macrocell DoR vs. number of SHRs in the macrocell and picocells.

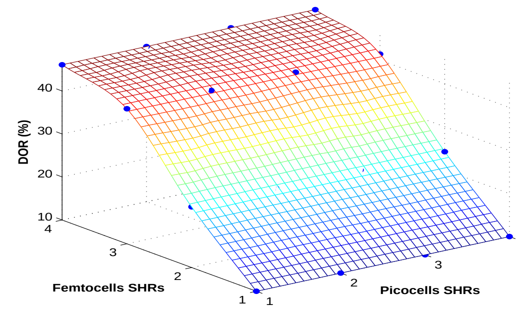

Fig. 6 : Femtocell DoR vs. number of SHRs in the femtocells and picocells

but it is dependent on the number of cell sites located within the failed femtocell's SHRs coverage area, regardless of the cell site type.

It is clear that using 2 SHRs in femtocells we can recover up to 20% of the original rate of the failed femtocell fronthaul link. Using 3 SHRs in femtocell will recover around 40%. Further increase of the SHRs will not increase the DoR by a significant percentage.

The price of RRHs ranges from \$2000 for macrocell to \$100 for femtocell (this is an approximate market price taken from different vendors) and the price of a typical cellular transceiver is much less than these values. So adding more SHRs to macrocells or picocells will not dramatically increase the capital expenditure. For femtocells only 1 or 2 SHRs can be added to keep its price low. The operator will pay for the extra cost of the SHRs if the user agrees to be involved in the self-healing process. Otherwise, the user will purchase the regular femtocell (without SHRs). From the DoR results and the approximate cost stated above, it is recommended to equip each macrocell sector with 3 SHRs, and use 4 SHRs per picocell. The latter plays a crucial rule in recovering the macrocell fronthaul failure. Using 2 SHRs per femtocell is sufficient to guarantee the minimum requirements in the presence of failures, as confirmed by the results.

VII. Conclusions

The new technologies proposed for use by 5G networks are C-RAN, massive MIMO, mmW, SDWN, etc. Applying all these and other technologies to 5G will increase the fronthauling load. In this article, we propose a scheme to guarantee a minimum throughput to 5G users in the presence of temporarily or permanently fronthaul failures. A novel pre-planned reactive cell outage compensation approach is presented to mitigate the fronthaul failure effects and its main concepts can be summarized as follows:

• Two tier C-RAN architecture with SCs use mmW band for connecting their users, and macrocell uses traditional cellular bands for macrocell users access.

• SDWN implementation provides flexible network operation where the SDWNC, which is co-located in the cloud, monitors and implements the self-healing procedures and acts as a database for the macrocell to avoid spectrum sensing during the CR phase.

• SHRs are considered as the main component in the COC process where SHRs are activated only in case of fronthaul failure only.

Performance was evaluated using system simulation and it shows that at least 20% of the fronthauling rate can be guaranteed during the fronthaul failure of any cell site type.

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