Adaptive Cell Outage Compensation in Self-Organizing Networks

I. de-la-Bandera*, P. Muñoz*, I. Serrano† and R. Barco*

***Abstract*—Within Self-Organizing Networks (SON), the Cell Outage Compensation (COC) functionality is one of the most important use cases in Self-Healing in mobile communication networks. The state-of-the-art has proposed different COC techniques, each of them to be indistinctly applied to all cells in outage. Conversely, this paper presents an important improvement of the COC function by adapting different COC strategies to different cell outage situations. With this objective, a novel COC methodology is proposed. When a cell outage occurs in a network, a detailed analysis of the faulty situation is carried out. The result of this analysis allows to classify the degradation produced by the cell outage in the neighboring cells. Depending on this degradation, different COC algorithms should be applied to each affected neighboring cell. In addition, as another contribution, some COC algorithms based on handover parameters modifications have been applied to a cell outage compensation problem. Results have shown that, by adapting the strategy to the outage impact on neighboring cells, the proposed method outperforms classic strategies.**

***Index Terms*—LTE, Self-Healing, Cell Outage Compensation, Self-Organizing Networks (SON), Fuzzy Logic Controller.**

I. INTRODUCTION

SELF-ORGANIZING Networks (SON) functions constitute an essential part of the current mobile communication network standards developed by the 3rd Generation Partnership Project (3GPP) such as LTE (Long Term Evolution) [1]. SON are based on automating management tasks in order to reduce operational expenditures (OPEX) and capital expenditures (CAPEX) [2]. This feature will predictably be one of the most important elements in the 5th Generation (5G) of mobile communications networks [3]. These new networks will increase significantly in complexity and size so that SON functions will be essential to cope with the management of such complex networks.

SON are classified into three groups: Self-Configuration, Self-Optimization and Self-Healing. Self-Healing [4] aims to detect and diagnose network failures in an automatic manner. When a problem is detected, a compensation and recovery functions may be activated. Most Self-Healing use cases defined by the 3GPP [5] are related to the Cell Outage Management (COM). This function is composed of Cell Outage Detection (COD) and Cell Outage Compensation (COC). Several works that cope with these two issues can be found in the literature. As for the COD functionality, different algorithms based on different inputs can be found. Specifically, the COD algorithm can use as input a set of alarms and Key Performance Indicators (KPIs) [6] or information presented in the neighbor cell lists [7].

Regarding COC, one of the main difference between differet algorithms is the control parameter used for the compensation. Thus, the main control parameters presented in the literature are: antenna tilt ([8], [9]), the uplink target received power level (P0) ([8], [10]), reference signal power ([8], [11]) and transmission power of the base stations ([12]). It is important to point out that operators usually are unwilling to modify the transmission power of the base stations since these changes may produce coverage holes. Specifically, in [8] the authors evaluate the different parameter (i.e. reference signal power, P0 and antenna tilt) and analyze their effectiveness in different scenarios. In that study, the cell outage causes a coverage hole but the compensation can be made focusing on improving coverage or throughput. The obtained results show that the P0 and the antenna tilt are the most effective strategies in improving coverage, while P0 is the most effective in improving throughput. The objective of [9] is to increase the coverage area of the compensating cells in the outage area. The carried out modifications are based on propagation measurements. The COC algorithm presented in [10] improves the coverage and quality in the outage area. The authors of [12] apply a COC algorithm to an irregular network (i.e. cellular network in which base station positions, power levels and coverage areas are highly inhomogeneous). Finally, a distributed COC algorithm is presented in [11]. Compared to a centralized management architecture, the distributed algorithm can enhance the management efficiency and continue active when the management node fails.

It is also possible to find in the literature compensation methods that modify more than one parameter at the same time. In [13], an algorithm based on reinforcement learning that compensates an outage by simultaneously modifying the antenna tilt and the transmission power of the base station is proposed. The authors present a comparison between the modification of both parameters and the compensation using each parameter separately. The conclusion is that the method that combined both parameters obtained the best results.

In addition to the previous works, some authors propose to apply Coverage and Capacity Optimization (CCO) algorithms to cell outage problems. The control parameter most commonly used to carry out the compensation in these works is the antenna tilt [14] [15] [16] [17]. The authors of [14] present an algorithm with two phases. The objective of the first phase is the antenna tilt optimization. In the second phase the antenna tilt is fine-tuned in order to adapt to dynamics of the network

*Universidad de Málaga. 29071. Málaga, Spain. Email: {ibanderac, pabloml, rbm}@ic.uma.es

†Ericsson. 29590 Campanillas, Málaga, Spain. Email: inmaculada.serrano@ericsson.com

such as the failure of a neighboring cell. In [15], different strategies based on reinforcement learning are proposed. Each proposed strategy is analyzed in different network situations: deployment, normal operation and cell outage. The authors of [16] present a heuristic variant of the gradient ascent method that allows to optimize the antenna tilt even in a cell outage situation. Finally, there are other works that simultaneously modify more than one parameter in order to improve the results. For instance, in [17], an optimization method based on the modification of the antenna tilt and an offset related to the cell selection algorithm is proposed.

All previous works assume that the main effect produced by the cell outage is a coverage hole. Thus, the main objective of these algorithms is to cover the outage area by increasing the coverage area of the neighboring cells. This can be done mainly by modifying the antenna tilt or the transmission power of the base stations. However, the effects caused by an outage problem depend on the type of scenario and the network conditions. For instance, in a network with a high level of overlapping between cells, a cell outage problem may not result in a coverage hole. In these network conditions, a cell outage might produce mobility problems between the neighboring cells or overload problems if the amount of traffic absorbed by the neighboring cells is excessive. Furthermore, in these scenarios, a cell outage may produce different effects in different neighboring cells at the same time. Therefore, when an outage problem does not produce a coverage hole and the degradation observed in the neighboring cells is not related to lack of coverage, the state-of-the-art COC methods may not be effective.

This paper proposes to adapt the COC function to each particular cell outage failure depending on the different effects that a cell outage may produce in the neighboring cells. Once a cell outage is detected, a detailed analysis of the effects produced in the neighboring cells is carried out. Based on the results of this analysis, it is possible to determine the set of cells that will take part in the compensation and the control parameter to be modified on a cell-basis in order to adapt the compensation to the specific problem detected in the neighboring cells. Thus, the COC function is focused on mitigating the concrete degradation caused by the cell outage. First, in this paper, in order to show that different types of cell outages should be compensated in a different way, a sensitivity analysis has been carried out. The sensitivity study aims to show that a given COC strategy may not be the most appropriate one in all cell outage situations. In particular, this paper considers three different types of degradations that can be produced by a cell in outage (i.e. coverage hole, load congestion and mobility problem). In addition, three different COC strategies based on modifying different control parameters (i.e. antenna tilt and handover margin (HOM)) are considered. Second, three different COC fuzzy algorithms based on the modifications of the previous control parameters are proposed. Antenna tilt modifications has been widely used for outage compensation in the literature. Conversely, to the best of authors' knowlegde, handover (HO) parameters have not previously been used with this purpose. Typically, the modification of the HO parameters has been used for other SON functions, such as HO process optimization [18] or load balancing in case of congestion [19].

The main contributions of this paper can be summarized as follows:

- Analysis of cell outages in order to classify the kind of degradation produced in the neighboring cells. Based on this analysis, the cells in charge of the compensation and the control parameters to be modified can be automatically selected.
- A novel COC methodology that includes the application of a novel COC algorithm based on the degradation produced by the cell outage. The proposed COC methodology is able to adapt the compensation to different neighboring cell degradations at the same time, e.g. one neighboring cell suffering congestion and another one with a coverage hole.
- A novel algorithm for COC based on HO parameter modifications.

The rest of this paper is organized as follows. Section 2 introduces the problem and the considered system variables (i.e. control parameters and system measurements). Section 3 describes the proposed COC methodology. Section 4 presents the sensitivity analyses and the results obtained in a realistic scenario. Finally, the conclusions are included in Section 5.

II. System model

A. Problem formulation

A cell is in outage when it cannot carry traffic due to a failure. Therefore, the first effect of a cell outage is that users in the coverage area of the faulty cell lose their connection. However, depending on the network conditions, different situations may occur in the problematic area. In some cases, when the level of overlapping between the neighboring cells is low, the cell outage may produce a coverage hole. Affected users only might recover their connection if some compensation action is taken. Conversely, if the level of overlapping between the neighboring cells is high, it is possible that most affected users could recover their communication by establishing a new connection with a neighboring cell without any compensation action. In this situation, the cell outage may not result in a coverage hole since the neighboring cells are able to absorb most traffic from the faulty cell. However, depending on the amount of absorbed traffic, neighboring cells could become overloaded. In addition, the outage may produce new neighborly relationships. If the HO parameters are not correctly configured between these new neighbors, a mobility problem could be also produced by the outage. The objective of the compensation algorithm in these two last cases (i.e. overload and mobility problem) will not be to recover the lost traffic but to mitigate the overload or mobility problem.

In this work, three different situations are considered:

- Cell outage that results in a coverage hole (*Coverage_outage*): This situation occurs in scenarios where the overlapping areas between cells are very limited and/or the outage affects a large geographical area (e.g. when a whole site is down). Thus, the problematic area presents an important number of users that lose their connection.

- Cell outage that produces a congestion problem (*Load_outage*): In this case, when the outage occurs, most users move to neighboring cells. This scenario conditions lead to a congestion problem due to the traffic absorbed by the neighboring cells.
- Cell outage that produces a mobility problem (*Mobility_outage*): When a cell outage occurs and neighboring cells cover the problematic area, new neighborly relationships appear. If the mobility parameters are not well configured between these new neighbors, different mobility problems can occur. One of these problems is the HO ping-pong [20]. An HO ping-pong event occurs when two HOs are executed between the same two cells in a short time period.

A real network usually presents a very irregular scenario. In such a scenario, the level of overlapping between neighboring cells or the load of the cells may be very different depending on the considered area. For that reason, when a cell or a group of cells (e.g. a whole site) is in outage, the neighboring cells of the cells in outage may present different types of degradation. When this occurs, the COC algorithm to be applied to each neighboring cell should be different. In this work, a scenario that combines more than one of the outage situations described above is also considered.

B. Control parameters

As described before, one of the most commonly used parameters in COC is the antenna tilt angle. This parameter is actually effective when the outage causes a coverage hole in the network. In order to consider the antenna tilt modifications as part of the COC methodology, the vertical antenna radiation pattern ($A_V(\theta)$) should be modeled [21]. The following expression represents the model considered in this work:

$$A_V(\theta) = -min[12(\frac{\theta - \theta_{etilt}}{\theta_{3dB}})^2, SLA_v], \quad where -90^\circ \leq \theta \leq 90^\circ \tag{1}$$

where θ is the angle of inclination between the user and the eNodeB, θ_{3dB} is the vertical half-power beamwidth, θ_{etilt} is the electrical antenna downtilt (i.e. the angle of inclination of the transmitting antenna with respect to the horizontal plane) and SLA_v is the side lobe level in dB relative to the maximun gain of the main beam.

However, if the negative effects experienced by the neighboring cells are not related to a coverage degradation, antenna tilt modifications may not produce any improvement. For these other situations, HO parameters modifications are considered. One of the most widely used HO algorithms is that based on the A3 event defined by the 3GPP [22]. This event determines the condition that must be fulfilled to execute an HO, i.e. the expression (2) must be fulfilled for a certain time period given by the Time To Trigger (TTT) parameter.

$$(RSRP_j) \geq (RSRP_i + HOM(i,j)) \tag{2}$$

where $RSRP_i$ and $RSRP_j$ are the Reference Signal Received Power (RSRP) measured by the user from cells i and j, respectively, and $HOM(i,j)$ is the HOM defined between the cell i and its adjacent j.

A specific value of the $HOM(i,j)$ and the symmetric $HOM(j,i)$ allow to determine a certain HO hysteresis (HOH) that avoid unnecessary HOs. The HOH calculation is obtained as follows:

$$HOH(i,j) = HOM(i,j) + HOM(j,i) = HOH(j,i) \tag{3}$$

In addition, these two parameters (i.e. $HOM(i,j)$ and $HOM(i,j)$) can be used to apply a certain offset (HOoffset) that modifies the HO performance with load balancing purposes. Thus, HOM modifications can be made with different objectives: to modify the HOH or the HOoffset. On the one hand, $HOM(i,j)$ and the symmetric $HOM(j,i)$ can be jointly tuned for load balancing purposes (i.e. HOoffset changes). In this case, the two parameters should be modified with the same magnitude but opposite sign [19]. This kind of changes allows to modify the serving area of cells i and j, while maintaining the HOH to avoid unnecessary HOs in the overlapped area between both cells. On the other hand, to adjust the HOH, the two parameters (i.e. $HOM(i,j)$ and $HOM(j,i)$) should be modified with the same magnitude and the same sign. For instance, a low value of the HOM favors a user to perform an HO to a neighboring cell although it may produce an increase in unnecessary HOs (and consequently, an increase in HOs ping-pong) due to signal fluctuations, Fig 1(a). Conversely, the HOM may be configured to a higher value in order to avoid these unnecessary HOs, Fig. 1(b). In this paper, HOoffset modifications are used in case of a *Load_outage* situation and HOH changes are used in case of *Mobility_outage*.

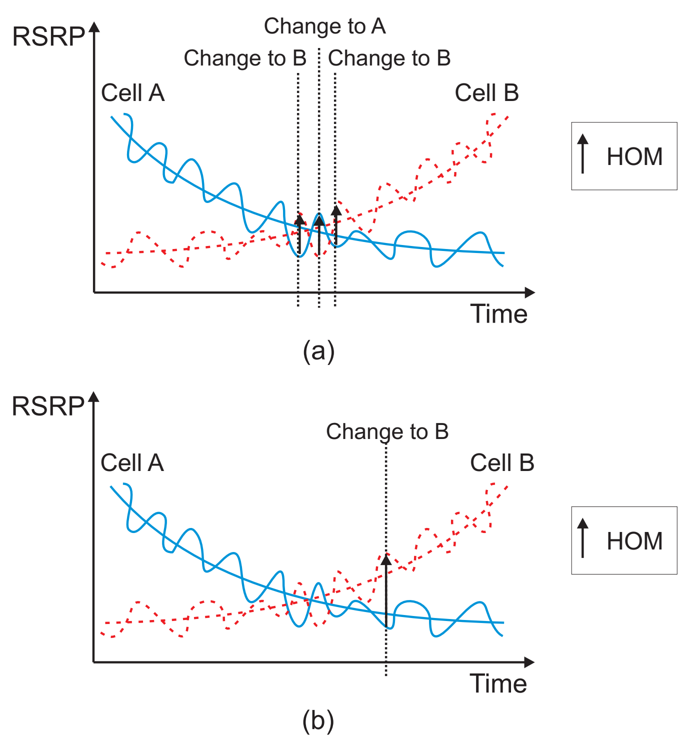

Fig. 1. HO process with a small (a) and a big (b) HOM

C. System measurements

A set of performance indicators has been selected in order to analyze the proposed algorithms. Some of these KPIs constitute the inputs of the algorithms and allow to decide when a control parameter modification is needed and when the performed changes lead the network to the optimal performance. The selected KPIs are the following:

- Accessibility. This KPI indicates the capability of a cell to accept new connections. When a user requests a new connection to a certain cell, it may be blocked if the cell does not have enough available resources. The following expression indicates how to calculate this KPI:

$$Accessibility = 1 - \frac{N_{blocked}}{N_{attempts}} \tag{4}$$

where $N_{blocked}$ is the number of blocked connections and $N_{attempts}$ is the total number of connections attempts.
- Retainability. This indicator represents the capability of a cell to maintain active connections under different environment conditions. Its calculation depends on the number of dropped connections in a cell. When a user abnormally loses its connection due to problems in the connection quality or coverage, it is considered a dropped connection. The retainability can be expressed as:

$$Retainability = \frac{N_{succ}}{N_{drops} + N_{succ}} \tag{5}$$

where N_{succ} is the number of successfully finished connections and N_{drops} is the number of dropped connections.
- HO ping-pong Ratio, HPR. This KPI shows the percentage of HO ping-pong occurred in a certain adjacency, calculated as the ratio between the number of HO ping-pong and the total number of HO executed. This KPI can be calculated as follows:

$$HPR = \frac{N_{HO\_PP}}{N_{executed}} \tag{6}$$

where N_{HO_PP} is the number of HO ping-pong occurred in a certain adjacency and $N_{executed}$ is the number of successfully HO executed in that adjacency. In particular, the N_{HO_PP} for a certain adjacency (i, j) is obtained from the total number of outgoing HO from cell i and the number of outgoing HO from cell j that return as incoming HO to cell i in a certain time period (ping-pong period).
- Percentage of blocked connections due to a lack of coverage (Block_Cov). This indicator measures the percentage of connections affected by a lack of coverage. A user is considered to be out of the coverage area of a cell if the best signal level received from that cell is below the minimum required signal value. If the user is out of the coverage area of the strongest cell in the scenario, the user is considered to be blocked due to a lack of coverage. The received signal is represented by the RSRP. The Block_Cov for a certain cell is obtained by dividing the number of blocked connections due to a lack of coverage among the total number of connections that measure that cell with the highest RSRP value in the scenario. The following expression represents this KPI:

$$Block\_Cov = \frac{N_{blocked}}{N_{measured}} \tag{7}$$

where $N_{blocked}$ is the number of blocked connections occurred in a cell and $N_{measured}$ is the total number of users that measured the cell as the strongest cell.

III. Cell Outage Compensation methodology

The COC methodology proposed in this paper is activated once a new cell outage problem is detected. This detection is carried out by the COD functionality, which is out of the scope of this paper. In general, by monitoring alarms and KPIs from each cell it is possible to detect most cell outages. However, there are some particular cases for which the availability of KPIs is lost but the cell is still alive. In these cases, extra information such as neighbor cell lists or HO-related data is needed to discriminate both cases. For example, the algorithm described in [23] assumes that when the number of incoming HOs measured in neighboring cells becomes zero, the cell under study is likely to be in outage.

Fig. 2 shows the different phases of the proposed COC methodology. When the COD algorithm detects a new cell outage problem, the cell outage analysis is carried out. This phase allows to analyze the kind of degradation produced in the neighboring cells by the cell outage. Depending on the kind of degradation detected, the most appropriate COC algorithm is selected for each neighboring cell.

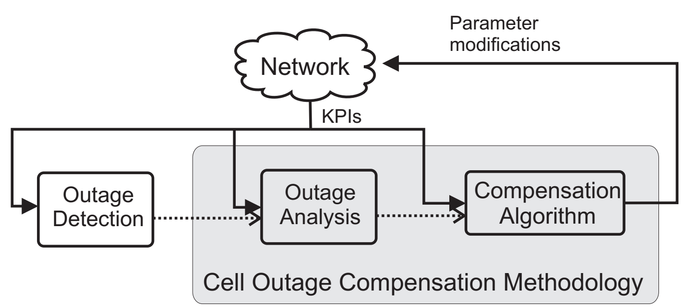

Fig. 2. Cell Outage Compensation Methodology

The following sections present each phase of the methodology.

A. Cell outages analysis

In order to apply an adaptive COC method, it is essential to classify each cell outage situation when it is detected. Consequently, the most appropriate COC algorithm will be selected depending on the degradation caused in the neighboring cells by the cell outage. The proposed method analyses whether there is any degradation in the neighboring cells at the time of the cell outage and which KPIs are most affected. With that aim, the KPIs of the neighboring cells are correlated with a reference signal [24], which represents the cell availability along time of the cell in outage (this reference signal can be defined as the unit step function with the jump discontinuity corresponding to the first hour of the cell outage). In this work, the Pearson correlation coefficient (r) is used:

$$r = \frac{N\sum xy - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[N\sum x^2 - \left(\sum x\right)^2\right]\left[N\sum y^2 - \left(\sum y\right)^2\right]}} \quad (8)$$

where x is the original signal for a certain KPI, y is the reference signal and N is the number of samples considered for both signals.

In addition to the correlation, KPI value is compared to a threshold. This threshold allows to determine if the detected degradation is higher enough to be compensated. A different threshold must be defined for each KPI. This threshold can be automatically calculated by the average of the specific KPI over a long time in a cell or over many cells in the network, assuming that most of the time there are no problems in the cells. A possible alternative method for the analysis might be to use only the threshold, without the correlation. However, in a live network, 1) KPIs usually experience important variations (i.e. spurious values) during the normal behavior, and 2) the normal values can vary from cell to cell and also depending on the network conditions. Therefore, on the one hand, the correlation method allows to avoid false positives and correctly detect degradation patterns in the neighboring cells' performance. Then, on the other hand, the defined threshold allows to determine whether this degradation is enough to be considered problematic.

Consequently, to determine if a certain KPI is degraded due to the cell outage, the correlation coefficient obtained for that KPI is compared to a threshold (i.e. a high value of the correlation coefficient for a certain KPI indicates that the KPI is degraded by the cell outage). Subsequently, the value of the degraded KPI is compared to a defined threshold to determine if the level of the degradation is higher enough to be compensated. Based on the affected KPIs (Table I), the degradation produced by the cell outage in a certain neighboring cell is classified in the three different types described in Section 2: *Coverage_outage*, *Load_outage* and *Mobility_outage*. For the sake of clarity, the following analysis of the three situations is explained considering that a certain cell outage affects all the neighboring cells in the same way.

When a *Coverage_outage* has occurred, a coverage hole is produced in the outage area. In this situation, most of the users in the coverage area of the faulty cell lose their connection. The neighboring cells absorb only a small part of the affected users. The main degradation detected in the neighboring cells is an increase in the Block_Cov. The only way to increase the number of users absorbed by the neighboring cells is extending their coverage area. The most appropriate solution for this situation is to perform tilt modifications in order to cover the outage area. Therefore, in the case of *Coverage_outage*, the COC algorithm should be based on tilt modifications (COC_TILT) and the selected cells for the compensation should be the neighboring cells affected by the coverage hole.

When the outage problem is a *Load_outage*, the neighboring cells usually absorb most of the affected connections. Thus, the percentage of users out of coverage may be very low. However, a congestion problem may affect the neighboring cells when the amount of absorbed traffic is high enough. In this case, an increase of the coverage area would not significantly affect the percentage of absorbed traffic since most traffic has already been absorbed and may worsen the congestion problem. In this situation, the objective of the compensation algorithm should be to mitigate the congestion problem. The most suitable method for this scenario is a COC algorithm based on HOoffset (COC_HOoffset). The objective of this algorithm is to reduce the serving area of the affected cells and increase the serving area of their own neighboring cells. In this way, the congestion may be reduced. The selected cells in this case should be the neighboring cells of the cell in outage (i.e. the cells affected by the congestion) and their own neighboring cells.

Finally, a cell outage may produce a mobility problem in its neighboring cells (i.e. *Mobility_outage*). As in the case of *Load_outage*, this kind of cell outage may not result in a coverage hole. Most of the affected traffic can be absorbed by the neighboring cells without any compensation action. Unlike *Load_outage* situation, in this case, the neighboring cells do not experience a congestion problem. Since the neighboring cells cover the outage area, new neighborly relationships may appear. This situation may produce mobility problems if the HO parameters are not correctly configured between these new neighboring cells. One typical mobility problem that may appear is the HO ping-pong problem due to a wrong value of the HOH. HOH changes (COC_HOH) allow to reduce the number of HOs ping-pong. The selected cells for the compensation are the affected neighboring cells of the cell in outage.

As described before, in these two last cases (i.e. COC_HOoffset and COC_HOH), the control parameter used is the HOM.

TABLE I
OUTAGE ANALYSIS

Type of outage	Degraded KPI	Parameter
Coverage_outage	Block_Cov	Tilt
Load_outage	Accessibility	HOoffset
Mobility_outage	HPR	HOH

As described before, a cell outage may affect different neighboring cells in a different way. In this case, one cell outage may produce different outage situations depending on the considered neighboring cell. In addition, a neighboring cell may suffer different types of degradation simultaneously due to the cell outage. The COC algorithm should adapt the compensation of each neighboring cell to the detected outage situation. In the case that a cell experiences different types of degradation, the COC actions may be prioritized.

B. Cell Outage Compensation algorithms

This section presents the three compensation algorithms applied in this work to the cell outage problem. All the algorithms are based on Fuzzy Logic. This technique is especially suitable to be applied to cellular networks since it allows to take decisions from imprecise information. In addition, the use of linguistic terms in the definition of Fuzzy Logic systems favors that the operator's experience can be easily applied to the problem. In particular, three Fuzzy Logic Controllers (FLC) have been defined, one for each compensation algorithm. All of them are according to Takagi-Sugeno approach [25]. Fig. 3 presents the main blocks that constitute an FLC. The first stage, *fuzzifier*, is in charge of transforming the numerical input values into fuzzy inputs. This transformation is based on several membership functions. These membership functions are defined for each input of the FLC and determine the degree of membership of any numerical input to different fuzzy sets. A linguistic term represents each defined fuzzy set. In this work, the terms High, Medium and Low are used. The values of the degree of membership can be between 0 and 1. The next step is the inference engine which is based on a set of IF-THEN rules. Based on these rules, this block calculates the output fuzzy sets. Specifically, depending on the input fuzzy sets, different rules may be activated with different degree of truth (α). In addition, each rule produces a certain output (i.e. a constant value with an associated linguistic term, o). As result, a fuzzy output, $\alpha \cdot o$, is generated for each rule. The definition of these rules is based on the knowledge and experience of human experts and with the specific objective to perform the appropriate compensation. Finally, the *defuzzifier* calculates the output crisp value from the results of the previous stage. In particular, depending on the rules' outputs and the activated rules with the corresponding degree of truth, the final crisp output is obtained as a weighted average as follows:

$$output = \frac{\sum_{i=1}^{N} \alpha_i \cdot o_i}{\sum_{i=1}^{N} \alpha_i} \tag{9}$$

where N is the number of rules, o_i is the output for the rule i and α_i is the degree of truth of the rule i.

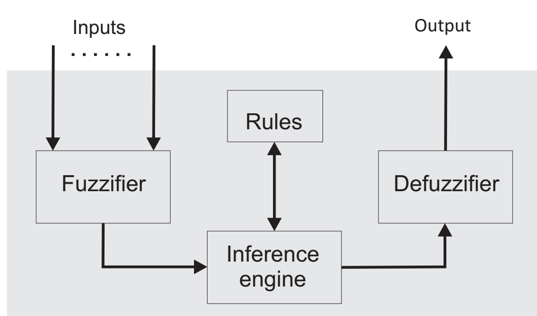

Fig. 3. Block diagram of a Fuzzy Logic Controller

The difference between the three algorithms presented in this paper are the considered inputs and outputs, the fuzzy sets and the rules. The configuration details for each method are explained in the following sections.

1) COC_TILT algorithm: In this case, the objective of the algorithm is to increase the coverage area of the neighboring cells in order to cover a coverage hole. The FLC is executed for each selected neighboring cell. The considered inputs are the Block_Cov and the Accessibility. The output of the FLC is the increment that must be applied to the antenna tilt of each neighboring cell. Fig. 4 shows the membership functions defined for each input. Three fuzzy sets have been defined for Block_Cov (i.e. Low, Medium and High) and two fuzzy sets have been defined for Accessibility (i.e. Low and High). The values selected for the different thresholds are similar to the typical limits accepted by network operators. Table II presents the set of rules that has been defined where L is Low, M is Medium and H is High. As for the fuzzy outputs, Negative means a decrease of the antenna tilt of $1°$ (i.e. uptilt), Null means no change in antenna tilt and Positive means an increase of the antenna tilt of $1°$ (i.e. downtilt). For instance, rule 1 can be read as: 'IF (Block_Cov is Low) AND (Accessibility is Low) THEN ($\Delta Tilt$ is Positive)'. Each rule has been defined with a certain objective. Rules 4 and 6 are activated when compensation changes are needed (i.e. when the cell is suffering coverage problems but not congestion). Rule 1 is activated when the absorbed traffic begins to produce a congestion problem. Rules 3 and 5 avoid changes in order to not worse the Accessibility. Finally, rule 2 is in charge of maintaining the compensation situation once it is achieved. The obtained output crisp values are rounded to -1, 0 or 1 (standing for Negative, Null or Positive, respectively) and the tilt values are limited to avoid excessive changes or possible instabilities in mobile networks. Specifically, the antenna tilt values are limited to $[0° - 12°]$.

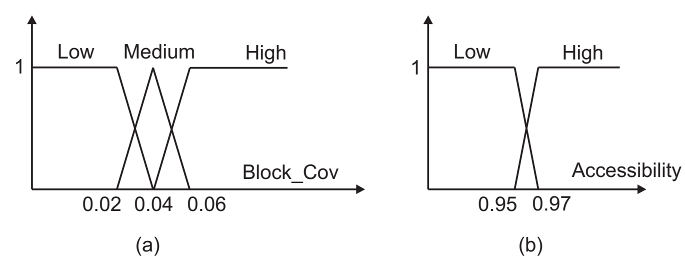

Fig. 4. Membership functions for (a) Block_Cov and (b) Accessibility fuzzy inputs

TABLE II
FLC RULES FOR COC_TILT ALGORITHM

No	$Block\_Cov$	$Accessibility$	$\Delta Tilt$
1	L	L	Positive
2	L	H	Null
3	M	L	Null
4	M	H	Negative
5	H	L	Null
6	H	H	Negative

2) COC_HOoffset algorithm: This algorithm has been defined to perform modifications in the service area of the cells without modifying the hysteresis. This means that all modifications applied to $HOM(i,j)$ should be applied with equal magnitude and opposite sign to $HOM(j,i)$, as explained in Section 2. The objective of this algorithm is to balance the load between the neighboring cells of the cell in outage (which have absorbed the traffic from the outage area) and their own neighboring cells. These last cells should not be neighbors of the cell in outage. Hereafter, each neighboring cell of the cell in outage will be called 'serving cell' and its neighboring cells will be called 'adjacent cells'. The FLC is executed for each pair of serving and adjacent cell. The considered inputs are the Accessibility for the serving cell, the Accessibility for the adjacent cell, the current value of $HOM(s, a)$ and the Retainability for the adjacent cell. Fig. 5 shows the membership functions defined in this case. Two fuzzy sets have been defined for both KPIs: Low and High. The values selected for the different thresholds related to Accessibility and Retainability are similar to the typical limits accepted by network operators. As for the $HOM(s, a)$, the parameter is considered High if the value is above 1 and Low if the value is below -1. A Low $HOM(s, a)$ value facilitates the HOs from the serving cell to the adjacent cell. Table III presents the set of rules that has been defined where L is Low and H is High. Rule 5 is activated when a load balance is needed, independently of the current HOM value. In the case that the adjacent cell experiences problems related to Accessibility (rules 1 and 2) or Retainability (rules 4 and 5), only if the situation is produced by an excessive modification of the HOM (rules 2 and 5), a Positive change is applied. Finally, rule 6 maintains the compensation situation once it is achieved. The output of the FLC, ΔHOM, represents the modification to be applied to $HOM(s, a)$. The same modification with opposite sign must be applied to $HOM(a, s)$. The obtained output crisp values are rounded to -1, 0 or 1 dB (Negative, Null, Positive, respectively) and the HOM values are limited to [-12 - 12] dB.

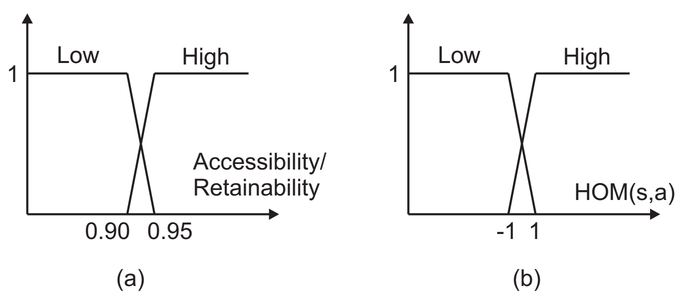

Fig. 5. Membership functions for (a) Accessibility and Retainability and (b) $HOM(s, a)$ fuzzy inputs

TABLE III
FLC RULES FOR COC_HOM ALGORITHM

No	Acc (s)	Acc (a)	HOM (s,a)	Ret (a)	ΔHOM (s,a)
1	-	L	H	-	Null
2	-	L	L	-	Positive
3	-	H	H	L	Null
4	-	H	H	L	Positive
5	L	H	-	H	Negative
6	H	H	-	H	Null

3) COC_HOH algorithm: The objective of this algorithm is to modify the HOH in order to improve the HO performance between the neighboring cells when a cell outage occurs. Thus, the modifications should be applied to $HOM(i, j)$ and $HOM(j, i)$ with the same sign and magnitude. The FLC is executed for each degraded adjacency between the neighboring cells of the cell in outage. The considered inputs are the $HPR(i, j)$ per adjacency and the Retainability for cell i and for cell j. Fig. 6 presents the membership functions. As in the previous case, two fuzzy sets have been defined: Low and High. The values for the different thresholds have been selected according to the performance of the considered scenario in a normal situation. Table IV shows the set of rules that has been defined where L is Low and H is High. Rule 8 produces the HOM changes when a compensation is needed. Rules 4, 6 and 7 are activated when a reversion is needed if any cell begins to experience a Retainability degradation and the HPR is low. Rules 1, 2 and 3 avoid changes if any cell suffers a Retainability degradation although the HPR is high. Finally, rule 5 maintains the compensation situation once it is achieved. The output, ΔHOM, represents the increment that must be applied to $HOM(i, j)$ and $HOM(j, i)$. The obtained output crisp values are rounded to -0.5, 0 or 0.5 dB (Negative, Null, Positive, respectively) and the HOM values are limited to [0 - 12] dB.

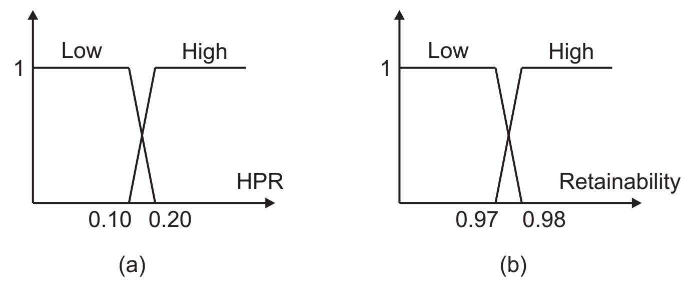

Fig. 6. Membership functions for (a) HPR, (b) Retainability fuzzy inputs

TABLE IV
FLC RULES FOR COC_HOH ALGORITHM

No	HPR (i,j)	Ret (i)	Ret (j)	ΔHOM (i,j)
1	H	L	L	Null
2	H	H	L	Null
3	H	L	H	Null
4	L	H	L	Negative
5	L	H	H	Null
6	L	L	H	Negative
7	L	L	L	Negative
8	H	H	H	Positive

IV. Performance Analysis

A. Simulations setup

A dynamic LTE system level simulator has been used in this work in order to analyze the effectiveness of the proposed COC methodology. The LTE simulator has been implemented in MATLAB and it is based on that presented in [26]. However, unlike the regular scenario in [26], the simulated scenario considered in this work is composed of 75 tri-sectorized cells and corresponds to a real LTE network that is currently in use. Table V presents the main configuration parameters of the simulations. In general, the simulations consist of a set of simulation loops. The considered KPIs are estimated at the end of each loop. Based on the KPIs values, it is possible to propose a control parameter modification that will be applied in the next loop. Each loop is composed of a set of simulation steps. Each step simulates 100ms of real time. During each step the main radio resource management functions (i.e. HO, Cell Selection, Admission Control and Packet Scheduler) are executed. The duration of each loop is set to 30000 steps (i.e. 50 minutes) in order to ensure reliable statistics. It is important to point out that these times can be reduced when the algorithm is applied to a real network. In this case, each execution of the COC algorithm can be performed once the KPIs are updated. The periodicity of updating the KPIs in a real network can be less than an hour (e.g. 15 minutes) so that the total time to achieve a compensation situation can be reduced.

TABLE V
SIMULATION PARAMETERS

Parameter	Configuration
Cellular layout	Real scenario, 75 cells (25 eNBs)
Carrier frequency	2.0 GHz
System bandwidth	1.4 MHz
Propagation model	Okumura-Hata Log-normal slow fading, $\sigma_{sf} = 8$ dB correlation distance=50 m
Channel model	Multipath fading, ETU model
Mobility model	Random direction, 3 km/h
Service model	Full Buffer, poisson traffic arrival
Base station model	Tri-sectorized antenna, SISO, Azimuth beamwidth=70° Elevation beamwidth=10° $P_{TX_{max}}$ =43 dBm
Scheduler	Time domain: Round-Robin Freq. domain: Best Channel
Handover	Triggering event = A3 Measurement type = RSRP Initial HOM = 2 dB TTT = 100 ms ping-pong period = 5 s
Radio Link Failure	$SINR < -6.9\ dB$ for 500 ms
Time resolution	100 TTI (100 ms)

Fig. 7 shows the simulated scenario in a normal situation. Specifically, the figure presents the RSRP received from the strongest cell in each point of the scenario. The different cells are numerated to facilitate the understanding of the tests.

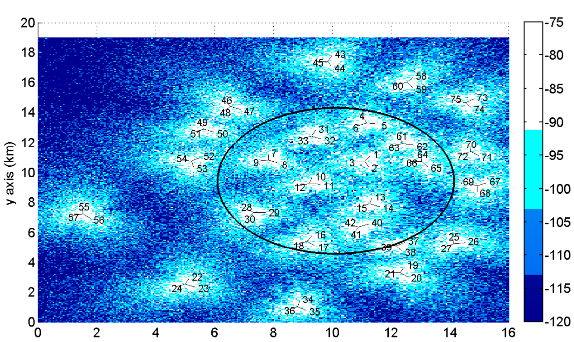

Fig. 7. RSRP values in the simulation scenario (dBm)

B. Sensitivity analysis

State-of-the-art COC algorithms, which are based on power or tilt modifications, are devised to specifically solve coverage problems. However, as described along this paper, when an outage problem occurs in a network different effects may appear, not limited to coverage holes. Consequently, a sensitivity analysis has been carried out in order to illustrate that a certain COC algorithm may not be appropriate for a concrete outage case. The selected outage situations are those explained in Section 2. For the sake of clarity, in this section it is assumed that a certain cell outage causes the same degradation in all of its neithboring cells. The different effects produced by a cell outage depend on the network conditions in the outage area. Thus, cells 10, 11 and 12 (Fig. 7) have been selected to suffer a cell outage that produces a coverage hole, since this site has the largest serving area in the considered network. Conversely, when cells 1, 2 and 3 (Fig. 7) are in outage, the outage area is automatically covered by the neighboring cells so that the outage does not cause a coverage hole. In this case, two different situations may occur depending on the network conditions during normal performance. On the one hand, it is possible that the neighboring cells that have absorbed the traffic from the outage area suffer a congestion problem. This situation may occur if the amount of traffic in the normal situation is high enough and the new absorbed traffic exceeds the limit of the cells. In addition, the quality of the radio channel of the new connections served by neighboring cells will be worse than in the normal situation. As a consequence, the link adaptation in LTE will lead to a higher consumption of radio resources, increasing the probability of congestion. It is important to point out that, although in the normal situation the amount of traffic may be high, the network performance does not present any congestion problem. On the other hand, a mobility problem may happen. When a cell outage occurs, new neighborly relationships appear. The HO process performance may be degraded if the HO parameters are not correctly configured for these new neighbors. In all cases, the considered set of neighboring cells are the neighbors in the first tier.

The sensitivity analysis carried out consists of applying different control parameters modifications to these three outage situations. The considered control parameters are the antenna tilt and the HOM (used for HOoffset and HOH modifications). The default configuration of the network parameters are based on the actual values used in the live network considered in this work. Thus, the default value of the HOM is 2 dB (HOH equal to 4 dB) and the antenna tilt is configured to values between 2° and 7°. The default average load is 80% of occupation approximately. As described before, the degradation produced by the cell outage depends on the network conditions. For that reason, it is necessary to slightly change some configuration parameters in order to facilitate the occurrence of the different kind of degradations. Thus, the initial value of the HOM in the case of *Mobility_outage* is configured equal to zero (HOH equal to zero) and the antenna tilt is equal to 7° for the selected cells (i.e. neighboring cells of the cells in outage). In the case of *Coverage_outage* the default value of the antenna tilt for the neighboring cells is configured to 9° in order to facilitate the occurrence of the coverage hole. Finally, the initial load of the neighboring cells in the case of *Load_outage* is 95% of occupation approximately. It is important to point out that these changes do not cause any problem in the network during the normal behavior (i.e. when no cell outages occur).

During the tests, the antenna tilt is reduced 1° per simulation loop (i.e. uptilting) and the HOM is modified 1 dB per simulation loop in the case of *Load_outage* and 0.5 dB per simulation loop in the case of *Mobility_outage*.

The following figures (Fig. 8-Fig. 10) show the results obtained in the sensitivity analysis. Each figure corresponds to a different outage situation and shows the value of the most significant KPIs in each outage case. The average value for the neighboring cells is presented. In all cases, the simulation consists of three phases. First, a normal behavior of the network is simulated. KPI values during this phase are considered as the baseline. Second, a cell outage is simulated. In this phase, no compensation actions are applied. It allows to analyze the degradation produced by the outage. Finally, in the third phase, the sensitivity analysis is carried out. During this phase, incremental changes are applied to the corresponding parameter (i.e. antenna tilt angle or HOM).

Fig. 8 shows the obtained results in the case of *Coverage_outage*. The final values achieved for each parameter are: 1° for the antenna tilt, 5.5 dB for $HOM(i,j)$ and $HOM(j,i)$ in the HOH case and 9 dB for $HOM(i,j)$ and -5 dB for $HOM(j,i)$ in the HOoffset case. In this situation, the considered KPIs are Block_Cov and Accessibility. When a cell outage occurs, the percentage of blocked connections increases significantly indicating that a coverge hole has been produced. Results show that only the antenna tilt modification allows to achieve a compensation situation similar to the normal behavior. After uptilting, the neighboring cells absorb almost all the traffic from the outage area reducing the percentage of users without coverage. It can be seen that the tilt modifications causes a decrease in the Accessibility. However, this decrease is quite smaller than the achieved benefit.

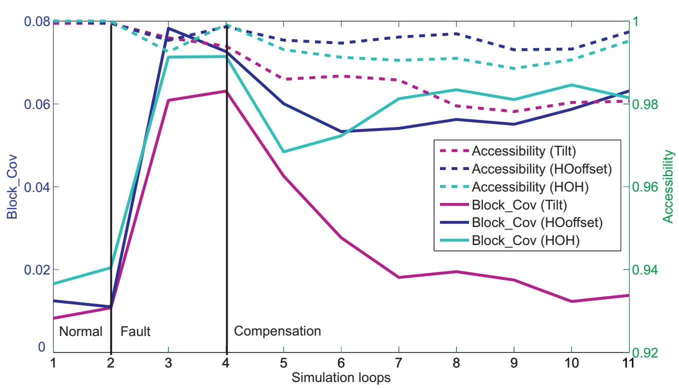

Fig. 8. Sensitivity analysis results for *Coverage_outage*

In the case of a *Load_outage* situation, the accesibility is the most important KPI. Fig. 9 presents the Accessibility and the Retainability of two groups of cells. On the one hand, cells of Group A are the neighboring cells in the first tier of the cells in outage. These cells are those with the congestion problem after the outage. On the other hand, cells of Group B are the neighboring cells of the congested cells. Regarding Section 3.2.2, cells of Group A are considered as serving cells and cells of Group B are considered as adjacent cells. Fig. 9 shows the Accessibility for cells in Group A and the Retainability for cells in Group B (the most significant KPI has been chosen for each group of cells). The final values achieved for each parameter are: 0° for the antenna tilt, 6.5 dB for $HOM(i,j)$ and $HOM(j,i)$ in the HOH case and 11 dB for $HOM(i,j)$ and -7 dB for $HOM(j,i)$ in the HOoffset case. In this outage situation, the neighboring cells (i.e. Group A) automatically cover the outage area. This fact causes a congestion problem in these neighboring cells that are absorbing traffic from the outage area. The important decrease presented in the Accessibility indicates the congestion problem. In this situation, the compensation method that achieves a compensation situation similar to the normal behavior is the one based on HOoffset modifications. The HOoffset modifications carry out a load balancing between the two groups of cells. These changes may also cause a degradation of the Accessibility of the cells in Group B although this degradation is negligible. The main negative effect produced by this method is a degradation in the Retainability of cells in Group B.

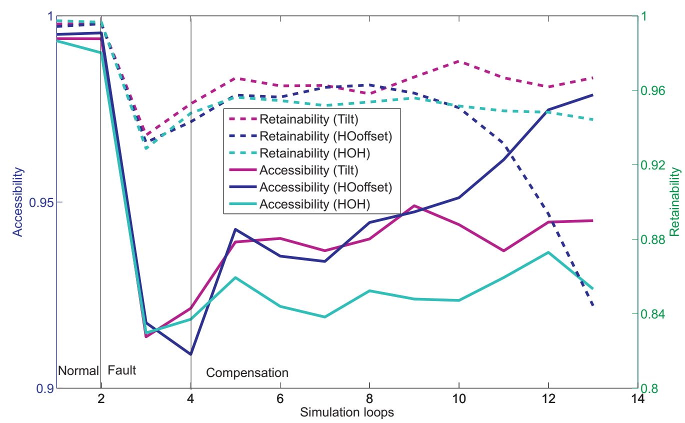

Fig. 9. Sensitivity analysis results for *Load_outage*

Finally, Fig. 10 shows the results obtained for the *Mobility_outage* case. The final values achieved for each parameter are: 0° for the antenna tilt, 4.5 dB for $HOM(i,j)$ and $HOM(j,i)$ in the HOH case and 9 dB for $HOM(i,j)$ and -5 dB for $HOM(j,i)$ in the HOoffset case. When the outage occurs, an important increase of the HPR between some new neighbors is observed. This increase is caused when there are HO parameters misconfigured. This problem is negligible during the normal behavior of the network because, if there is not an outage problem, there are not HOs between these cells. In a *Mobility_outage* situation, only an increase of the HOH allows to reduce the HPR. In this case, it is important to consider that a high value of the HOH may lead to a decrease in the connection quality and, consequently, a decrease in the Retainability. However, Fig. 10 shows that the improvement of the HPR is achieved before the Retainability is degraded.

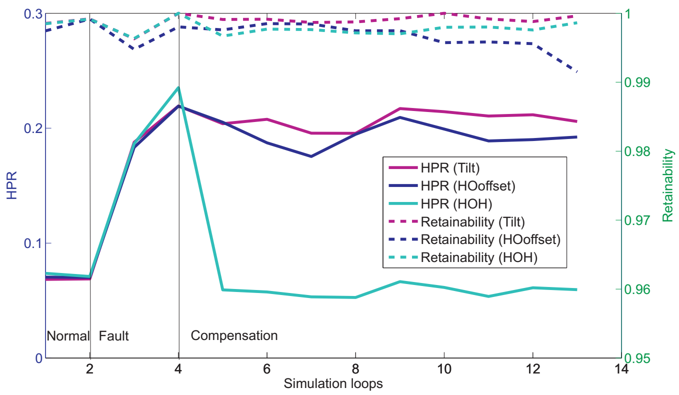

Fig. 10. Sensitivity analysis results for *Mobility_outage*

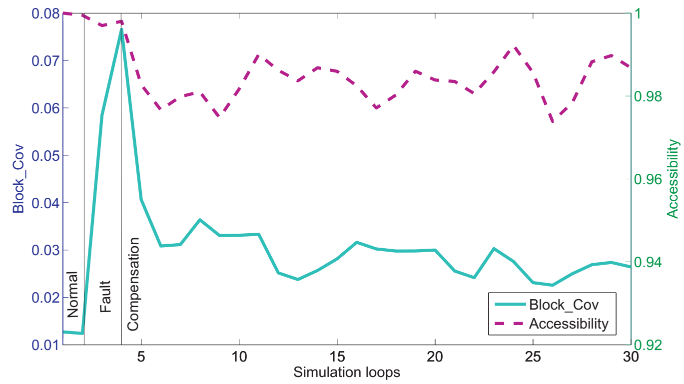

Fig. 11. Results for the COC_TILT algorithm

C. Algorithms performance

The previous sensitivity analysis has been shown that different outage situations should be compensated by the modification of different parameters. Specifically, for the outage situations considered in this work, the *Coverage_outage* should be compensated by antenna tilt modifications, the *Load_outage* should be compensated by HOoffset modifications and, finally, the *Mobility_outage* can be successfully compensated by modifying the HOH. This section presents the results obtained when each proposed FLC-based COC algorithm is applied to the corresponding outage situation. In this case it is also assumed that each outage situation causes the same degradation in the neighbors of the cells in outage. Like in the sensitivity analysis, the simulation consists of three phases; normal behavior, fault and compensation. During the last phase, the COC algorithm initiates the compensation process and achieves a stable compensation situation.

Fig. 11 shows the results obtained in the application of the COC_TILT algorithm to a *Coverage_outage* problem. The figure presents the average value for the neighboring cells for the KPIs Block_Cov and Accessibility. The cell outage failure affects cells 10, 11 and 12 (Fig. 7) and the selected neighboring cells are neighbors in the first tier (i.e. cells 8, 15, 28 and 29). During the compensation, the minimum achieved value for the antenna tilt is 6°. In the normal situation, this site covers an extensive area. When the cell outage occurs, an important percentage of users suffers lack of coverage. When the compensation is activated, this percentage decreases significantly. This decrease is achieved by uptilting the degraded neighboring cells to absorb the users in the outage area. While neighboring cells are accepting new users, its Accessibility may be degraded. The proposed algorithm achieves a balanced situation with a significant decrease of the Block_Cov and a slight degradation of the Accessibility.

As for the *Load_outage* problem, Fig. 12 presents the results. The cells in outage are cells 1, 2 and 3. In this case, the outage failure causes a congestion problem in cells 11, 13, 63 and 66 (i.e. Neighbors Group A). The set of cells selected to carry out the compensation are 12, 14, 15, 61, 62, 64 and 65 (i.e. Neighbors Group B). The applied algorithm (i.e. the COC_HOoffset algorithm) performs modifications similar to a load balancing algorithm. Thus, the main KPIs that should be considered in this test is the Accessibility and the Retainability of both groups of cells (i.e. Accessibility of cell in Group A and Retainability of cells in Group B), Fig. 12. It can be seen that the algorithm improves the Accessibility of the neighboring cells of Group A (i.e. cells with the congestion problem) without degrading the Retainability of the cells used for the compensation (i.e. Neighbors Group B). The maximum modification applied to HOM is 8 dB (i.e. 10 dB for $HOM(i, j)$ and -6 dB for $HOM(j, i)$).

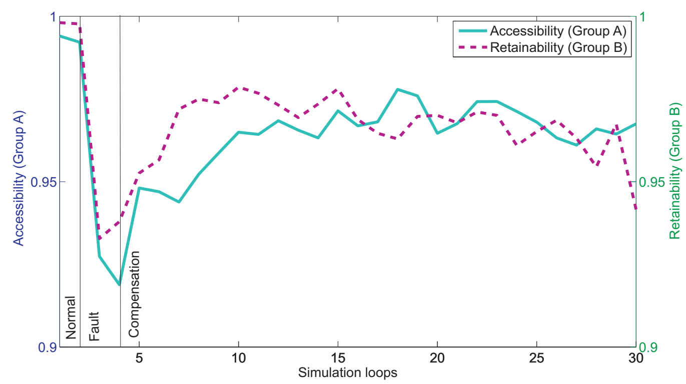

Fig. 12. Results for the COC_HOoffset algorithm

Finally, the COC_HOH algorithm has been tested. This algorithm has been applied to a *Mobility_outage* failure. As described in the previous section, for this test the network load has been configured with the default value to avoid a congestion problem. Thus, the mobility problem can be analyzed. In addition, the HOH for the neighboring cells has been configured to zero. Fig. 13 presents the average value of HPR and the Retainability for the degraded neighboring cells (i.e. cells 10, 32, 63 and 66 in the first tier). By increasing the HOH value between the affected cells it is possible to reduce the HPR. A value closer to that of the normal situation is achieved in the first iterations of the algorithm avoiding a degradation in the Retainability. The maximum value achieved for the HOH is 2 dB.

Finally, a last test has been carried out. As described in Section 1, the objective of this work is to adapt the COC algorithm to each cell outage failure characteristics. In a real network, when a cell outage occurs, it is expected that different neighboring cells area affected in a different way depending on

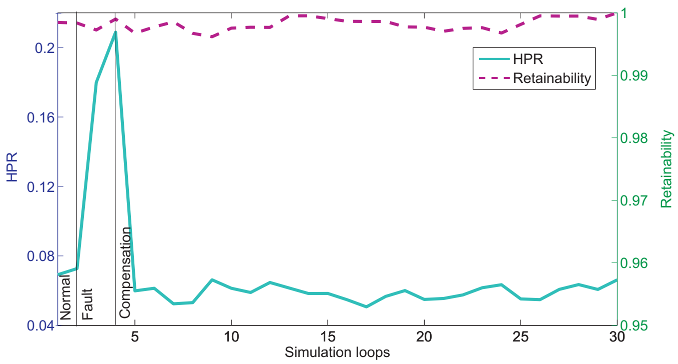

Fig. 13. Results for the COC_HOH algorithm

the network conditions. For the sake of clarity, in the previous tests it has be assumed that a cell outage affects in the same way all the neighboring cells. Thus, different strategies have been analyzed. In this last test, a more realistic failure situation is presented. Specifically, a cell outage in cells 10, 11 and 12 is studied. This cell outage may cause different degradation in each neighboring cell. Once the specific degradation is detected for each neighboring cell, the corresponding COC algorithm will be applied in the concrete neighbor in the cases that it is needed.

The configuration of this test is similar to that used in the *Coverage_outage* test with a hot-spot near cells 13 and 15. These conditions allow to simulate a cell outage that will cause a coverage hole in the outage area and a congestion problem in cells 13 and 15.

Once the cell outage occurs, the analysis of the degradation is carried out. For each neighboring cell, the correlation of the reference signal and each considered KPI (i.e. Block_Cov, Accessibility and HPR) is calculated. Table VI shows the obtained results. According to these results and considering degradation when the correlation coeficient is higher than 0.9, it can be concluded that cells 8, 13, 15 and 29 may be affected by the coverage hole; cells 13 and 15 may be suffering a congestion problem; and cells 3, 8 and 13 may present a mobility problem. These results must be completed with the comparison to the defined thresholds. To select a certain neighboring cell as degraded cell the value of the Block_Cov has to be higher than 0.06, the value of the Accessibility has to be lower than 0.96 and the value of HPR has to be higher than 0.2. Thus, after comparing to the thresholds, the analysis determines that cells 8 and 29 are affected by the coverage hole, while cells 13 and 15 experience a congestion problem. The rest of neighbors in the first tier are not significantly affected. Fig. 14 and Fig. 15 show the obtained results. Specifically, Fig. 14 shows the average value of the KPIs Block_Cov and Accessibility for cells 8 and 29. For these cells, the COC_TILT algorithm has been applied achieving a reduction of the Block_Cov by uptilting these cells. The negative effect is a reduction of the Accessibility. In order to avoid this negative effect, the COC_HOoffset could be applied once the Accessibility degradation appears. Fig. 14 does not consider this alternative.

Simultaneously, cells 13 and 15 are affected by a congestion problem (Fig. 15). Following the same nomenclature that in previous tests, these two cells are considered Neighbors Group A and the set of cells used to reduce the congestion are Neighbors Group B (i.e. cells 2, 3, 14, 29, 40, 42, 69, 72). In this case, the COC_HOoffset algorithm is applied to compensate the congestion problem. Along iterations, the Accessibility of the affected cells is increased but a slight degradation of the Retainability of the cells from Group B is produced. However, the achieved Retainability values remain in an acceptable margin.

TABLE VI
CORRELATION RESULTS FOR THE ANALYSIS PHASE

	Block_Cov	Accessibility	HPR
Cell 2	0.08	0	0.47
Cell 3	0.69	0	-0.94
Cell 8	0.99	-0.61	-0.92
Cell 13	0.98	-0.97	-0.91
Cell 15	0.95	-0.98	-0.75
Cell 28	0.61	0	-0.67
Cell 29	0.95	-0.61	-0.54

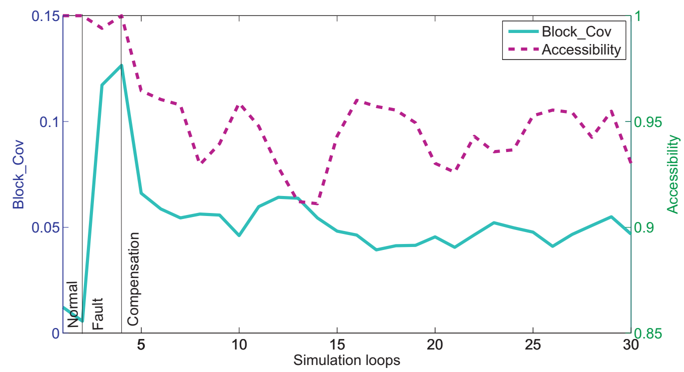

Fig. 14. Results for coverage hole problem

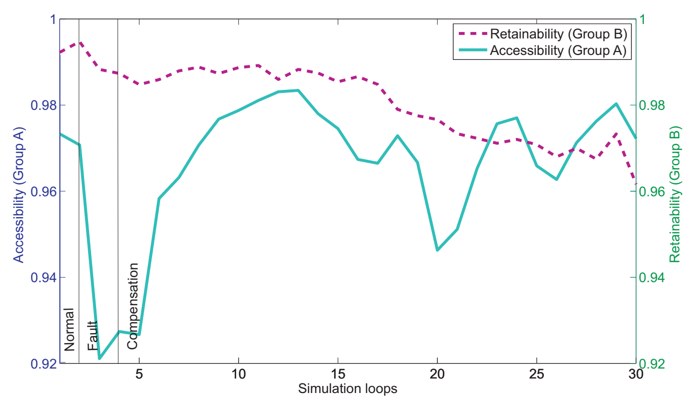

Fig. 15. Results for congestion problem

V. CONCLUSIONS

A novel Cell Outage Compensation (COC) methodology has been proposed in this paper. The presented methodology is based on adapting the COC algorithm to each cell outage failure. When a cell outage occurs, a detailed analysis of the fault is carried out. This analysis determines the set of affected neighboring cells and the type of degradation caused by the cell outage. Depending on this degradation, different COC algorithm should be applied to each neighboring cell. In particular, three different cell outage situations are considered in this work: one related to coverage degradation, another related to load congestion degradation and the last one related to a mobility problem. The different COC algorithm considered in this paper are based on modifications of antenna tilt, handover margin and handover hysteresis. A sensitivity analysis has been carried out in order to show how different types of cell outage situations should be compensated by modifying different control parameters. Results show that for each cell outage problem only one COC strategy achieves a successful compensation situation. In addition, based on the previous results, three COC algorithms based on Fuzzy Logic have been applied to different cell outage failures. In all cases, the COC algorithm allows to compensate the degradation produced by the cell outage without affecting other cells of the scenario. Finally, a more realistic scenario has been tested. In this case, the cell outage causes different types of degradation in the neighboring cells simultaneously. Results show that the proposed COC methodology successfully compensate the fault situation.

Acknowledgment

This work has been partially funded by Optimi-Ericsson, Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovación y Empresa, ref. 59288; and Proyecto de Investigación de Excelencia P12-TIC-2905), the Spanish Ministry of Economy and Competitiveness (TEC2015-69982-R) and ERDF.

References

[1] "3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2," 3rd Generation Partnership Project (3GPP), TS 36.300, 2015.

[2] "Telecommunication management; Self-Organizing Networks (SON); Concepts and requirements," 3rd Generation Partnership Project (3GPP), TS 32.500, 2014.

[3] A. Imran and A. Zoha, "Challenges in 5G: how to empower SON with big data for enabling 5G," *Network, IEEE*, vol. 28, no. 6, pp. 27–33, Nov 2014.

[4] R. Barco, P. Lázaro, and P. Muñoz, "A unified framework for self-healing in wireless networks," in *IEEE Communications Magazine*, Dec 2012, pp. vol.50 (12), pp.134–142.

[5] "3GPP, Telecommunication management; Self-Organizing Networks (SON); Self-healing concepts and requirements," 3rd Generation Partnership Project (3GPP), TS 32.541, 2014.

[6] H. Sanneck, P. Szilagyi, and C. Frenzel, "Sub-cell level, multi-layer degradation detection, diagnosis and recovery," Oct. 3 2013, wO Patent App. PCT/EP2012/055,282.

[7] C. Müller, M. Kaschub, C. Blankenhorn, and S. Wanke, "A Cell Outage Detection Algorithm Using Neighbor Cell List Reports," in *Proceedings of the 3rd International Workshop on Self-Organizing Systems (IWSOS) 2008, Lecture Notes in Computer Science (LNCS) 5343*, December 2008, pp. 218–229.

[8] M. Amirijoo, L. Jorguseski, R. Litjens, and R. Nascimento, "Effectiveness of cell outage compensation in LTE networks," in *Consumer Communications and Networking Conference (CCNC), 2011 IEEE*, Jan 2011, pp. 642–647.

[9] M. Asghar, S. Hamalainen, and T. Ristaniemi, "Self-healing framework for LTE networks," in *Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2012 IEEE 17th International Workshop on*, Sept 2012, pp. 159–161.

[10] Z. Jiang, P. Yu, Y. Su, W. Li, and X. Qiu, "A cell outage compensation scheme based on immune algorithm in LTE networks," in *Network Operations and Management Symposium (APNOMS), 2013 15th Asia-Pacific*, Sept 2013, pp. 1–6.

[11] W. Li, P. Yu, M. Yin, and L. Meng, "A distributed cell outage compensation mechanism based on rs power adjustment in lte networks," *Communications, China*, vol. 11, no. 13, pp. 40–47, Supplement 2014.

[12] L. Kayili and E. Sousa, "Cell outage compensation for irregular cellular networks," in *Wireless Communications and Networking Conference (WCNC), 2014 IEEE*, April 2014, pp. 1850–1855.

[13] J. Moysen and L. Giupponi, "A reinforcement learning based solution for self-healing in lte networks," in *Vehicular Technology Conference (VTC Fall), 2014 IEEE 80th*, Sept 2014, pp. 1–6.

[14] R. Razavi, "Self-optimisation of antenna beam tilting in LTE networks," in *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th*, May 2012, pp. 1–5.

[15] R. Razavi, S. Klein, and H. Claussen, "A fuzzy reinforcement learning approach for self-optimization of coverage in LTE networks," *Bell Labs Tech. J.*, p. 153175, 2010.

[16] H. Eckhardt, S. Klein, and M. Gruber, "Vertical antenna tilt optimization for LTE base stations," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, May 2011, pp. 1–5.

[17] A. Fehske, H. Klessig, J. Voigt, and G. Fettweis, "Concurrent load-aware adjustment of user association and antenna tilts in self-organizing radio networks," *Vehicular Technology, IEEE Transactions on*, vol. 62, no. 5, pp. 1974–1988, Jun 2013.

[18] P. Muñoz, R. Barco, and I. de la Bandera, "On the potential of handover parameter optimization for self-organizing networks," *Vehicular Technology, IEEE Transactions on*, vol. 62, no. 5, pp. 1895–1905, Jun 2013.

[19] P. Muñoz, R. Barco, and I. de la Bandera, "Optimization of load balancing using fuzzy q-learning for next generation wireless networks." *Expert Syst. Appl.*, vol. 40, no. 4, pp. 984–994, 2013.

[20] "Self-configuring and self-optimizing network (SON) use cases and solutions (Release 9)," 3rd Generation Partnership Project (3GPP), TS 36.902, 2011.

[21] "3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects," 3rd Generation Partnership Project (3GPP), TS 36.814, 2010.

[22] "3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification," 3rd Generation Partnership Project (3GPP), TS 36.331, 2015.

[23] I. de la Bandera, R. Barco, P. Muñoz, and I. Serrano, "Cell outage detection based on handover statistics," *Communications Letters, IEEE*, vol. PP, no. 99, pp. 1–1, 2015.

[24] I. de-la-Bandera, P. Muñoz, I. Serrano, and R. Barco, "Improving Cell Outage Management through data analysis," *Submitted, IEEE Wireless Communications Magazine*, 2016.

[25] T. Ross, "Fuzzy logic with engineering applications," *Wiley*, 2010.

[26] P. Muñoz, I. de la Bandera, F. Ruiz, S. Luna-Ramírez, R. Barco, M. Toril, P. Lázaro, and J. Rodríguez, "Computationally-Efficient Design of a Dynamic System-Level LTE Simulator," *Intl Journal of Electronics and Telecommunications*, vol. 57, no. 3, pp. 347 –358, 2011.