# LTE-ADVANCED SELF-ORGANIZING NETWORK CONFLICTS AND COORDINATION ALGORITHMS

HAFIZ YASAR LATEEF, ALI IMRAN, MUHAMMAD ALI IMRAN, LORENZA GIUPPONI, AND MISCHA DOHLER

*Hafiz Yasar Lateef is with Qatar Mobility Innovations Center.*

*Ali Imran is with the University of Oklahoma.*

*Muhammad Ali Imran is with University of Surrey.*

*Lorenza Giupponi is with Centre Tecnolgic de Telecomunicacions de Catalunya.*

*Mischa Dohler is with King's College London.*

## ABSTRACT

Self-organizing network (SON) functions have been introduced in the LTE and LTE-Advanced standards by the Third Generation Partnership Project as an excellent solution that promises enormous improvements in network performance. However, the most challenging issue in implementing SON functions in reality is the identification of the best possible interactions among simultaneously operating and even conflicting SON functions in order to guarantee robust, stable, and desired network operation. In this direction, the first step is the comprehensive modeling of various types of conflicts among SON functions, not only to acquire a detailed view of the problem, but also to pave the way for designing appropriate Self-Coordination mechanisms among SON functions. In this article we present a comprehensive classification of SON function conflicts, which leads the way for designing suitable conflict resolution solutions among SON functions and implementing SON in reality. Identifying conflicting and interfering relations among autonomous network management functionalities is a tremendously complex task. We demonstrate how analysis of fundamental trade-offs among performance metrics can lead us to the identification of potential conflicts. Moreover, we present analytical models of these conflicts using reference signal received power plots in multi-cell environments, which help to dig into the complex relations among SON functions. We identify potential chain reactions among SON function conflicts that can affect the concurrent operation of multiple SON functions in reality. Finally, we propose a self-coordination framework for conflict resolution among multiple SON functions in LTE/LTE-Advanced networks, while highlighting a number of future research challenges for conflict-free operation of SON.

## INTRODUCTION

Given that network densification is emerging as the dominant capacity enhancement theme in both existing and future cellular networks, operational complexity and operational expenditure (OPEX) are bound to increase. Another challenging feature of the future cellular landscape is that more and more network nodes will be deployed impromptu. Consequently, self-organizing network (SON) functions are being considered an essential feature to ensure the technical as well as financial viability of emerging and future cellular networks. This is reflected by identification of key SON use cases by Next Generation Mobile Network consortium (NGMN) [1] and their ongoing standardization by the Third Generation Partnership Project (3GPP). As a result of the stark demand from operators, and endorsements by the standardization body, research on developing SON functions for the use cases identified by NGMNs and 3GPP has gained significant momentum in both academic and industrial circles. For a detailed review of the state-of-the-art SON functions, the reader is referred to [2, 3].

Although many individual SON solutions for each NGMN use case promise gain with respect to its intended key performance indicators (KPIs) as discussed in [2], different SON functionalities can have a range of conflicts when working concurrently in the same network. Such conflicts may compromise the overall gain of SON and may also undermine system stability. Since networks are becoming denser and more heterogeneous, and SON functionalities have to be exploited on a wide scale, the analysis of potential conflicts generated by the numerous autonomous functionalities in heterogeneous networks can be extremely challenging. Therefore, self-coordination among conflicting SON functions is essential in order to enable stable network operation with tight operator control over the network behavior. Self-coordination among conflicting SON functions is thus understandably endorsed by the 3GPP System Architecture (SA) group (SA5) in 3GPP Release-11 [4].

Despite its significance and implications, the problem of self-coordination has not been deeply investigated in literature. Here, we highlight the main contributions. The Socrates project team took the first step in this direction and organized selected inter-related parameters that could cause parametric conflict into basic groups [5–7].

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Initial challenges of characteristics, parametric, and measurement conflicts when integrating SON functions into next generation wireless networks were then described in [8]. However, none of these works provide comprehensive identification, annotation, and classification of SON function conflicts. Some self-coordination mechanisms for SON are described in [9]. However, [9] does not identify the application of these self-coordination mechanisms for specific SO function conflicts. In [10], for the first time the authors identified and categorized SON function conflicts based on different criteria such as the network deployment, the KPIs, the measurement and logical dependencies, and the output parameters' direction/magnitude. This is a very interesting first step toward self-coordination; however, the resolution of SON conflicts requires a deeper analysis, modeling, and classification, as we describe in the rest of the article.

The state-of-the art work on SON conflict classification has mainly focused on hard classification where each SON conflict is categorized into exactly one category. Such hard classification ignores the fact that a SON conflict may arise due to intricate and rather indirect interactions deriving from more than one conflicting condition and therefore will have attributes of more than one type of conflict. To overcome this difficulty, we propose hybrid classification, which includes fuzzy classification in addition to hard classification. In this fuzzy classification approach different conflicts can have different degrees of membership to various categories, depending on the underlying nature of conflict. We refer to this new classification methodology as soft classification. The overall soft and hard classification of conflicts is referred to as hybrid classification. Our hybrid classification framework also includes another novel SON conflict classification called nested conflicts. Specifically, some of the SON function conflicts may occur as a reaction to other SON function conflicts. We categorize such chain reactions among SON function conflicts in the nested conflicts category. In this article, we provide a comprehensive hybrid classification of SON function conflicts. It is worth mentioning here that the proposed hybrid classification of SON function conflicts acts as a key enabler for not only identification of the root cause of the conflicts but also the design of efficient self-coordination solutions. To the best of the authors' knowledge, such comprehensive hybrid classification of SON conflicts does not exist in open literature.

In order to overcome the tremendous difficulty of identifying the potential conflicts in the complex and intricate future heterogeneous network scenarios, we propose and demonstrate a method to analytically identify potential conflict based on fundamental trade-offs already well known in cellular network literature. We also present another method to model the SON function conflicts using 3GPP handover triggering event equations and reference signal received power (RSRP) plots in multi-cell environments. Building on these developments, we outline a hybrid self-coordination scheme and provide mechanisms for conflict-free operation of SON functions. The conflict identification schemes and coordination mechanisms provided in this article are generally valid for a range of SON function conflicts. However, in order to provide insights into the addressed problem, in different sections we discuss specific SON function conflict examples as proof of concepts.

The rest of the article is organized as follows. Analytical modeling of SON function conflicts is presented in the following section. A hybrid classification of SON function conflicts and chain reactions among SON function conflicts is then presented. A hybrid self-coordination mechanism based on 3GPP architecture is proposed after that. The performance evaluation of the proposed hybrid self-coordination solution is also presented. Finally, our conclusion and future work are presented.

## Analytical Modeling of Self-Organizing Function Conflicts

The identification of potential conflicts among miscellaneous SON functions in a cellular heterogeneous network, which might be operating concurrently to optimize same network parameters and metrics at different spatial and temporal scales, is extremely complex [2]. In order to find a proper approach for anticipation and subsequent mitigation of these conflicts, it is first essential to understand the nature and origin of the potential conflicts. Exploitation of the fundamental knowledge of the trade-offs between several desirable performance metrics is one possible approach for the identification of underlying conflicts, as we show through an analysis of energy efficiency (EE) and spectral efficiency trade-off [11, 12]. In the following we first provide an example of how to identify potential conflicts from the analytical perspective. Then we devote two subsections to the analytical description of the generation of complicated conflicts among different SON functions based on the analysis of RSRP curves.

### Mapping of Conventional Cellular Network Trade-offs to SON Function Conflicts

As explained above, theoretical trade-offs in communication networks can be used as a guide for the identification of potential conflicts in future cellular networks. If the optimization or configuration of future cellular networks is done in a self-organized manner, these trade-offs directly result in SON function conflicts. One of these trade-offs is between the energy and spectral efficiency, and this maps directly to coverage and capacity optimization (CCO) and EE SON functions conflict. To analyze the underlying interplay of CCO and EE SON functions conflict we can consider a simplified scenario of a single link transmission over an additive white Gaussian noise (AWGN) channel with bandwidth $W$. In order to achieve a rate $R$ with transmit power $P$, the noise power spectral density $N_0$, and EE represented by $E_J$ (in terms of bits per Joule), we can show that the relationship between EE and spectral efficiency $R/W$ is given by [11]

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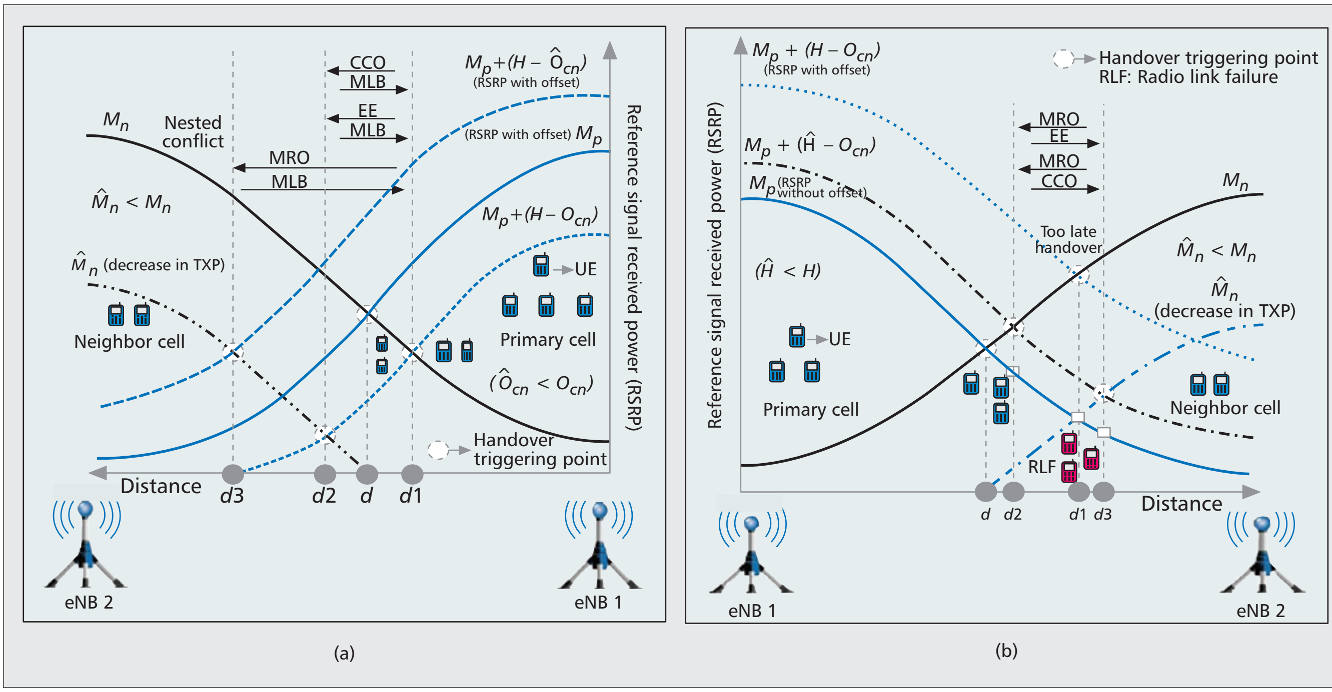


**Figure 1.** a) RSRP plot for illustration of conflict between MRO, EE, and CCO SON functions in multi-cell environments; b) RSRP plot for illustration of conflict between MLB, CCO, EE, and MRO SON functions in multi-cell environments.

$$E_J = \frac{1}{N_0}\left(\frac{R/W}{2^{R/W} - 1}\right). \quad (1)$$

It is evident from Eq. 1 that increasing the spectral efficiency decreases the EE, since the denominator increases exponentially. Although this equation shows a fundamental limit on the trade-off between two desirable objectives, this gives a solid reason to believe that EE and CCO functions in SON may suffer from a conflict and require a framework to manage this conflict. More specifically, EE may try to reduce the evolved Node B (eNB) transmission power (TXP) or try to activate the sleep mode at eNB for energy saving, while CCO may try to increase TXP for better coverage and capacity. Hence, both EE and CCO may try to set different values for TXP, which consequently causes an output parameter conflict.

## Case Study of Mobility Load Balancing, EE, and CCO Function Conflicts

The conflict among mobility load balancing (MLB), CCO, and EE functions is modeled with the help of an RSRP plot in multi-cell environments, as shown in Fig. 1a. More specifically, the X-axis and Y-axis represent the distance and RSRP, respectively. User equipments (UEs) move between eNB1 and eNB2. The MLB function monitors the load of cells periodically and adjusts the handover region by biasing the handover parameter, that is, cell specific offset of the neighbor cell ($O_{cn}$) when the traffic load is unbalanced. The handover triggering condition (A3) defined by 3GPP [13–15] as "neighbor becomes offset better than primary cell" is mathematically described as follows:

$$M_n > M_p + (H - O_{cn}), \quad (2)$$

where $H$ is the hysteresis parameter for handover and $M_n$, $M_p$ represent the RSRP without offset of primary and neighbor cells, respectively. The frequency specific offsets are set to zero in Eq. 2.

If the primary cell is heavily loaded and its neighboring cell is lightly loaded, the MLB function of the primary cell increases $O_{cn}$ to make the handover triggering earlier at $d_1$ instead of its original handover triggering point at $d$ in order to steer traffic toward the neighboring cell as shown in Fig. 1a. In practical scenarios $O_{cn}$ can have values between –6 dB and 6 dB [8]. However, CCO or EE function of the neighboring cell may decide to decrease the antenna TXP, due to its light load condition. This will shift the RSRP curve of the neighboring cell to the case $\hat{M}_n$ indicated on the graph for the reduced TXP. As a result, the new handover triggering point delays to position $d_2$ instead of earlier triggering position $d_1$ and consequently causes a conflict with the objective of the MLB function. Moreover, the weak received signal strength at the handover triggering position $d_2$ may cause a call drop or radio link failure (RLF) and consequently triggers the mobility robustness optimization (MRO) function. In order to avoid handover problems, the MRO function should decrease the cell-specific offset of the neighbor cell to $\hat{O}_{cn}$ ($\hat{O}_{cn} < O_{cn}$), which shifts the handover triggering position to $d_3$ as shown in Fig. 1a. However, the primary cell is still heavily loaded, and the corresponding MLB function of the primary cell would increase the cell specific offset of the neighbor cell to $O_{cn}$, while MRO may try to decrease $O_{cn}$ again due to the handover problems. This situation will trigger a conflict between MRO and MLB functions, which will ultimately generate oscillations of network parameter configuration. It must be mentioned here that the MRO and MLB functions conflict is triggered by MLB and CCO or MLB and EE functions conflict.

### Case Study of MRO, EE and CCO Function Conflicts

This conflict between MRO, EE, and CCO SON functions is modeled with the help of the RSRP plot in multi-cell environments as shown in Fig. 1b. The MRO function monitors handover problems, including too late handover, ping pong and so on. In connected mode handover, decisions are made at eNBs by using UEs' measurement reports. The eNBs configure triggering points for UE measurement reports in such a way that these reports are sent when certain conditions are fulfilled. For example, Eq. 2 describes a specific handover triggering condition (A3). If frequency-specific offsets are zero, the handover triggering point is calculated by setting hysteresis parameter $H$ and cell-specific offset for neighbor cell $O_{cn}$. Hysterisis parameter $H$ can have 21 values between 0 and 10 dB with a step size of 0.5 dB [13, 14]. If the hysteresis parameter is set to a large value, the handover triggering point is configured such that it causes too late handover at position $d_1$, as shown in Fig. 1b. Too late handover can cause RLF due to weak RSRP at position $d_1$. In case of RLF, the MRO function decreases the handover hysteresis to $\hat{H}$ ($\hat{H} < H$) in order to shift the handover triggering point to some earlier position $d_2$ as shown in Fig. 1b. However, if EE or CCO function in the neighboring cell decreases its transmission power due to light load conditions, the RSRP curve of the neighboring cell shifts to case $\hat{M}_n$, thus further delaying the handover triggering point to position $d_3$ as shown in Fig. 1b. As a result, the MRO function objective is in conflict with EE or CCO function.

## Hybrid Classification of Self-Organizing Network Function Conflicts

In this section, we provide a comprehensive taxonomy and classification of conflicts among SON functions. We first present a hard classification of different kinds of conflicts that may be generated in Long Term Evolution/Advanced (LTE/LTE-Advanced) SONs. Then we present soft classification of conflicts among SO functions. Finally, we present nested conflicts in this section.

### Hard Classification of SON Function Conflicts

Most recently, in [10], Lateef *et al*., presented a hard classification framework for SON function conflicts based on five major categories: parameter conflicts, network topology mutation conflicts, KPI conflicts, logical dependency conflict, and measurement conflict.

**Parameter Conflicts:** These can be further classified into output and input parameter conflicts. Output parameter conflicts may occur when two or more SON functions try to modify the same network configuration parameter. Input parameter conflicts may arise when a SON function is triggered by an input parameter with a value that is dependent on some other network parameters.

**Network Topology Mutation Conflict:** This may occur due to a change in network conditions caused by the addition or removal of a relay, eNB or Home eNB (HeNB).

**Key Performance Indicator Conflict:** This may arise when different SON function actions try to alter the same KPI of a cell while adjusting different network configuration parameters.

**Measurement Conflict:** This could happen if a SON function is either triggered or computes new parameter configuration values based on outdated measurements.

**Logical Dependency Conflict:** This might take place if there is a logical dependency among the objectives of SON functions.

The interested reader may refer to [10] for further details on this hard classification of conflicts.

### Soft Classification of SON Function Conflicts

We analyze here the potential interference that may exist among different kinds of conflicts defined in the above subsection.

***Some of the SON Function Conflicts Associated with the Output Parameter Conflict Category May Also Be Classified in Measurement and Logical Dependency Conflict Categories:*** More specifically, if an outdated measurement activates a SON function that computes contradictory configuration settings for network parameters, compared to other SON functions, this kind of conflict belongs to both the output parameter and measurement conflict categories. Moreover, if some of the conflicting SON functions not only compute contradictory configuration settings for network parameters compared to other SON functions, but also have logical dependency between their objectives, these kinds of conflicts belong to both the output parameter and logical dependency conflict categories. A representative example of specific SON functions conflict association with output parameter, measurement, and logical dependency conflicts is presented below.

**CCO and Inter-Cell Interference Coordination Functions Conflict:** Figure 2 depicts the effect that this conflict can have on the cell boundaries, as well as the message exchanges at the architecture level through the Itf-S and X2 interfaces. Intercell interference coordination (ICIC) functionalities are typically implemented distributively, while CCO functions typically use a centralized architecture located in the operation, administration, and management (OAM) domain. For centralized implementation of CCO function, signaling and KPIs are exchanged with eNBs over the Itf-S interface. On the other hand, the UE reports on measurements related to RSRP, reference signal received quality (RSRQ), and channel quality indicator (CQI), and X2 signaling in

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If there are two PCI functions executing with intersecting impact area and time, then the PCI configurations gathered by the first PCI function could be modified by the second PCI function while the first PCI function is allocating physical cell identity to the target cell. Hence, the new physical cell identity by the first PCI function might be erroneous due to outdated input neighboring configurations.

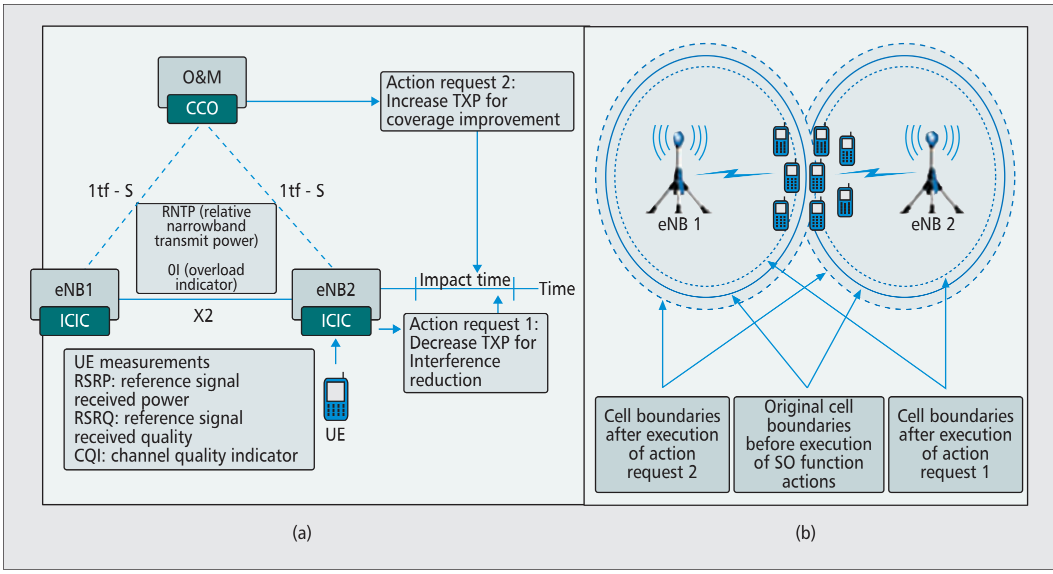


**Figure 2.** Conflict between CCO and ICIC SON functions: a) 3GPP architecture model for CCO and ICIC SON functions conflict; b) impact of CCO and ICIC SON functions conflict on cell boundaries.

terms of relative narrowband transmit power (RNTP) and overload indicator (OI) supports a dynamic ICIC coordination among cells. However, outdated measurement reports of CQI or RSRQ may cause false triggering of ICIC function. As a result, the ICIC function may try to decrease TXP for interference reduction, while the CCO function may try to increase TXP for coverage improvement, which can cause not only output parameter configuration conflict but also measurement conflict.

In another case, the CCO function may try to modify the antenna remote electrical tilt (RET) for coverage improvement, while the ICIC function may try to change TXP for interference reduction. In this scenario, both CCO and ICIC functions configure different network parameters with different objectives. This may negatively affect the performance gains made by each function, as both of them affect the same coverage area and have an implicit relationship between their objectives. As a result, CCO and ICIC functions trigger a logical dependency conflict.

***SON Function Conflicts Associated with Logical Dependency Conflict Category May Also Be Classified in Measurement Conflict Category:*** More specifically, if an outdated measurement value triggers a SON function conflict and there is also a logical dependency between the objectives of these conflicting SON functions, this type of conflict belongs to both measurement and logical dependency conflict categories. A representative example of specific SON functions conflict association with both logical dependency and measurement conflicts is presented below.

**Mobility Robustness Optimization and CCO Functions Conflict:** CCO function can modify RET in order to optimize coverage and capacity, which will have impact on the cell size. Meanwhile, if a mobility robustness optimization (MRO) function is triggered based on measurements collected in the time before the change in cell size is reflected in measurements, the MRO function could be using outdated measurements for calculating new handover settings. As a result, MRO and CCO functions may degrade the performance improvement achieved by each other and cause a measurement conflict.

In another scenario, an MRO function can adjust the cell individual offset (CIO) and hysteresis parameter in order to calculate the optimum handover triggering point. However, the CCO function in the neighboring cells can modify the RET in order to improve coverage and capacity, which will change coverage overlap between these cells and hence the hysteresis region. As a result, the handover triggering point calculated by the MRO may become non-optimum due to the inter-relationship between the objectives of MRO and CCO functions. This kind of conflict is a logical dependency conflict.

***SO Function Conflicts Associated with Input Parameter Conflict Category May Also Be Classified in the Measurement Conflict Category:*** More specifically, if an outdated measurement value on one hand triggers a SON function conflict, and on the other hand this measurement serves as input parameter to the conflicting SON functions, this type of conflict belongs to both measurement and input parameter conflict categories. A representative example of specific SON functions conflict association with both input parameter and measurement conflicts is presented below.

**Conflict between Two Physical Cell Identity Functions:** In order to allocate physical cell identity (PCI) to the target cell, PCI configurations of neighboring cells are gathered as an input to PCI function. However, if there are two PCI functions executing with intersecting impact area and time, the PCI configurations gathered by the first PCI function could be modified by the second PCI function while the first PCI function is allocating a PCI to the target cell. Hence, the new PCI by the first PCI function might be erroneous due to outdated input neighboring configurations. In this example, PCI configurations of neighboring cells are acting as both measurement and the value input to the PCI function. Therefore, this kind of conflict is associated with both input parameter and measurement conflict categories.

***SON Function Conflicts Associated with Network Topology Mutation Conflict Category May Also Be Classified in Measurement Conflict Category:*** More specifically, if an outdated measurement value triggers a SON function conflict, and these conflicting SON functions are also affected by the addition or removal of network nodes, this type of conflict belongs to both measurement and network topology mutation conflict categories. Similarly, SON function conflicts associated with the KPI conflict category may also be linked with the measurement conflict category. More specifically, if an outdated measurement value triggers a SON functions conflict, and these conflicting SON functions also affect the same KPI of a cell, this type of conflict belongs to both the measurement and network topology mutation conflict categories.

Table 1 provides a comprehensive list of soft classification of SON function conflicts soft classifications.

### Chain Reaction among SON Function Conflicts or Nested Conflicts

Some SON function conflicts may occur as a reaction to other SON function conflicts. For example, it is evident from Fig. 1a that MRO and MLB functions conflict is initiated as a chain reaction of MLB and CCO or MLB and EE function conflicts. We refer to chain reactions among SON functions as nested conflicts, as shown in Fig. 1a.

Nested conflicts of SON functions can change the priorities of SON conflict resolution because some low-priority conflicts can trigger crucial SON function conflicts. For example, an MLB and EE function conflict is considered low priority because it does not affect the end user quality of service. However, an MLB and EE conflict can trigger an MRO and MLB conflict as a nested conflict, which can have severe impact not only on the end user quality of service due to handover problems, such as call drop and RLF, but also on the efficiency of network resource utilization due to ping pong and too late handover problems. Therefore, we can conclude that less important nested SON function conflicts may also deteriorate the end user quality of service and efficiency of radio resource utilization. Moreover, nested conflicts are more challenging for root cause evaluation of the problem due to chain reaction among multiple SON function conflicts.

## Hybrid Self-Coordination Framework

Given the changing and complex nature of SON function conflicts, hybrid self-coordination with diverse coordination techniques is essential for conflict resolution among SON functions. We refer to our framework for self-coordination solution as hybrid if it makes use of more than one distinct self-coordination mechanism. In this section, we propose such a hybrid self-coordination mechanism for conflict resolution between MRO and EE SON functions. This self-coordination mechanism paves the way for possible evolution of SON conflict resolution.

### Centralized and Distributed Approach for Conflict Resolution among SON Functions

A hybrid self-coordination mechanism based on centralized architecture for conflict resolution among MRO and EE functions is presented in Fig. 3a. More specifically, for conflict-free operation of MRO and EE functions, both eNB1 and eNB2 communicate with each other over an X2 interface in order to check whether there is any conflicting MRO or EE function active. The rationale behind the proposal of scanning for conflicting SON functions is to reschedule or delay the execution of the current MRO or EE function until the effects of the previously executing MRO or EE function become visible in the measurement. In this way, measurement conflict between MRO and EE functions can be avoided. However, despite the above self-coordination between eNB1 and eNB2, there is still a possibility of conflict between MRO and EE functions due to the logical dependency between these function objectives. In this situation, the root cause evaluation procedure is executed at both eNB1 and eNB2 in order to resolve a logical dependency conflict between MRO and EE functions. The eNBs exchange up-to-date coverage measurement with each other in order to measure the accuracy of the handover triggering point. Moreover, eNB1 and eNB2 exchange root cause evaluation results with an operation and maintenance (O&M) server via an Itf-S interface. Finally, if the handover problem is caused by EE function actions, the O&M server takes corrective measures. More specifically, the O&M server conveys new antenna TXP/RET and handover triggering point settings to eNB1 and eNB2 in order to resolve the conflict between MRO and EE functions.

It must be mentioned here that the above self-coordination mechanism is hybrid in nature because on one hand it makes use of information exchange between eNB1 and eNB2 in order to avoid measurement conflict between MRO and EE functions, and on the other hand it utilizes a root cause evaluation procedure in order to resolve the logical dependency conflict between MRO and EE functions. The hybrid self-coordination mechanism shown in Fig. 3 can be generalized to other SON function conflicts associated with measurement and logical dependency conflict categories, listed in Table 1. More specifically, the information exchange between neighboring eNBs about the currently executing SON function can avoid possible measurement conflicts among SON functions, and root cause evaluation of network performance degradation problems at eNBs can resolve logical dependency conflicts between SON functions.

A hybrid self-coordination mechanism based

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on distributed architecture for conflict resolution among MRO and EE functions is presented in Fig. 3b. In a distributed self-coordination solution, corrective measures for conflict resolution regarding new handover triggering point and antenna TXP are decided at eNB1 and eNB2 instead of at the O&M server.

## Performance Evaluation

We now evaluate the proposed hybrid self-coordination algorithm between MRO and EE SON functions. The network topology we used for performance evaluation consists of seven macrocellular base stations with uniformly distributed users as shown in Fig. 4a. We present a graph-theory-based approach for modeling the network under consideration as shown in Fig. 4b. In an LTE-Advanced SON, we let β be a set of macro base stations and τ be a set of users. The macro base stations and users constitute the vertices of a graph, representing our network. The edges of the graph represent the connectivity opportunities among the vertices.

Our objective is not only to minimize the power consumption of the network but also to reduce handover failures. We formulate the hybrid self-coordination algorithm between MRO and EE SON functions as an integer lin-

| Sr. no. | SON function conflict scenario | Output parameter conflict | Logical dependency conflict | KPI conflict | Measurement conflict | NTM conflict | Input parameter conflict |
|---|---|---|---|---|---|---|---|
| 1 | CCO and EE | ✓ | ✓ | X | ✓ | X | X |
| 2 | MLB and EE | X | ✓ | X | ✓ | X | X |
| 3 | New eNB/HeNB/relay and EE | X | X | X | ✓ | ✓ | X |
| 4 | COC and COC | ✓ | ✓ | X | ✓ | X | X |
| 5 | Two PCI instances | X | X | X | ✓ | X | ✓ |
| 6 | MRO and MLB | ✓ | X | X | ✓ | X | X |
| 7 | CCO (RET and TXP) | X | X | ✓ | ✓ | X | X |
| 8 | New eNB/HeNB/relay and MLB | X | X | X | ✓ | ✓ | X |
| 9 | CCO and ICIC | ✓ | ✓ | X | ✓ | X | X |
| 10 | MRO and COC | X | ✓ | X | ✓ | X | X |
| 11 | COC (RET and TXP) | X | X | | ✓ | X | X |
| 12 | MRO and CCO | X | ✓ | X | ✓ | X | X |
| 13 | MLB and COC | X | ✓ | X | ✓ | X | X |
| 14 | New eNB/HeNB/relay and CCO | X | X | X | ✓ | ✓ | X |
| 15 | MRO and PCI | X | ✓ | X | X | X | X |
| 16 | MLB and PCI | X | ✓ | X | X | X | X |
| 17 | MLB and CCO | X | ✓ | X | ✓ | X | X |
| 18 | New eNB/HeNB/relay and MRO | X | X | X | ✓ | ✓ | X |
| 19 | CCO and PCI | X | ✓ | X | ✓ | X | X |
| 20 | COC and PCI | X | ✓ | X | ✓ | X | X |
| 21 | New eNB/HeNB/relay and ANR | X | X | X | ✓ | ✓ | X |
| 22 | New eNB/HeNB/relay and ICIC | X | X | X | ✓ | ✓ | X |
| 23 | MRO & EE | X | ✓ | X | ✓ | X | X |

**Table 1.** Soft classification of SON function conflicts.

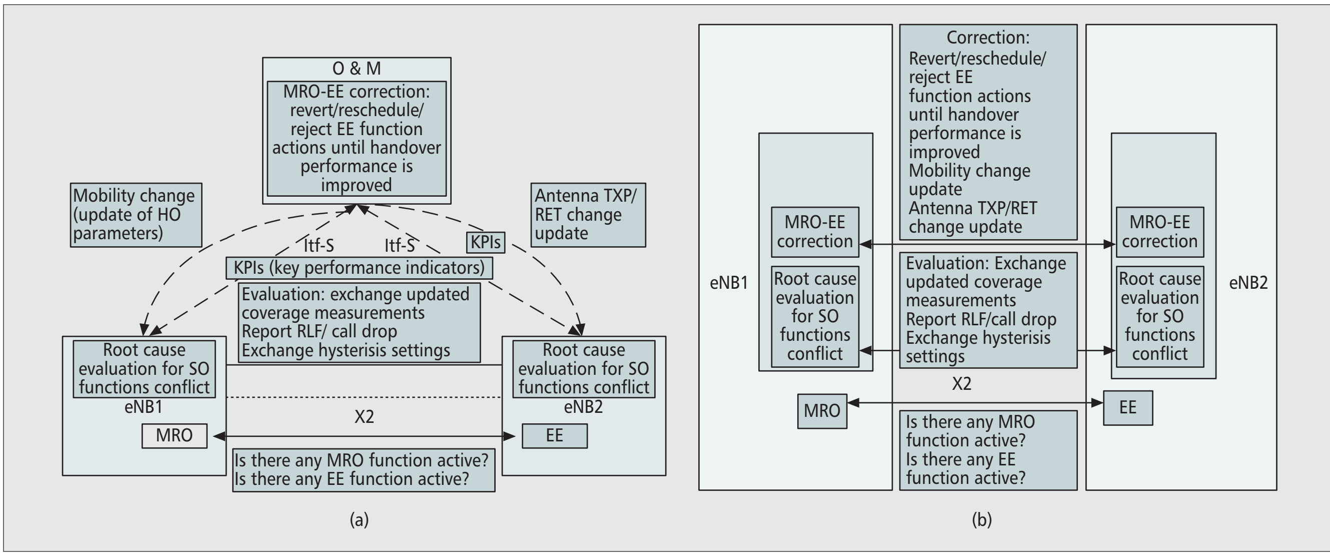


**Figure 3.** Hybrid self-coordination between MRO and EE functions: a) centralized architecture; b) distributed architecture.

ear programming (ILP) problem. Formally, it can be written as

$$\min \sum_{b\in\beta}\left[ y_{ee_b}\left(\sum_{t\in\tau} y_{eeopt_b}\, p(b,t)x(b,t)\right) + y_{mro_b} H_b \right], \tag{3}$$

where $y_{ee_b}, y_{mro_b} \in \{0,1\}$ are binary variables expressing, whether MRO and EE functions are active or inactive, respectively; $y_{eeopt_b}$ is a real variable that can have values between 0 and 1 in order to optimize transmit power $p(b, t)$ between base station $b$ and user $t$; $x(b, t)$ represents the data transfer between base station $b$ and user $t$; and $H_b$ represents the hysteresis function of base station $b$. The binary variables $y_{ee_b}$ and $y_{mro_b}$ are utilized to control the execution of conflicting EE and MRO functions in order to avoid measurement conflicts. Moreover, we apply a lower bound on real variables $y_{eeopt_b}$ such that EE function maintains sufficient coverage overlap with neighboring cells in order to avoid logical dependency conflict between EE and MRO functions. The objective function is linear and can be solved optimally using the state-of-the-art IBM CPLEX Optimizer. Figure 5a depicts a comparison of handover failure ratio for our proposed hybrid self-coordination between MRO and EE with uncoordinated MRO and EE SON functions. From the plot, it can be seen that the handover failure rate of hybrid self-coordinated MRO and EE SON functions is significantly lower than uncoordinated MRO and EE SON functions.

A comparison of power consumption for hybrid self-coordination between MRO and EE with uncoordinated MRO and EE SON functions is shown in Fig. 5b. Figure 5b shows that the transmit power consumption of the hybrid self-coordination solution is slightly higher than the uncoordinated solution. The rationale behind this fact is that the hybrid self-coordination solution provides better coverage than an uncoordinated solution in order to avoid severe effects on the end user quality of service, such as handover failures.

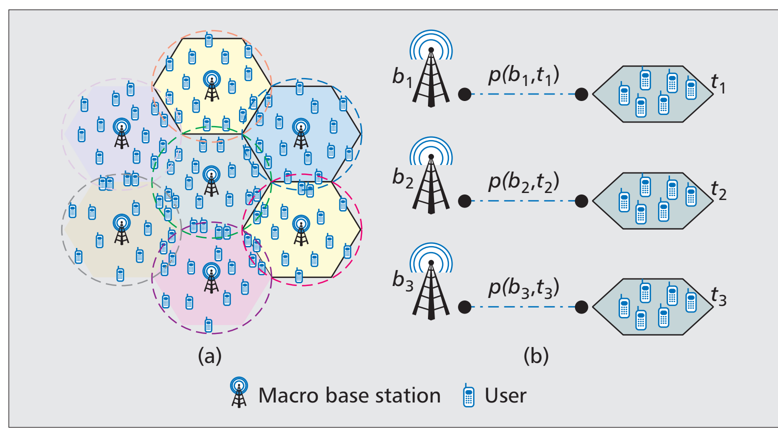


**Figure 4.** An illustration of a macrocellular network topology: a) an overview of a seven-cell macrocellular network; b) a graph-based representation of a macrocellular network.

## Conclusion and Future Work

While self-organizing networking has attracted significant attention from industry, the most challenging issue in implementing SON in reality is the identification of the best possible self-coordination mechanisms among conflicting SON functions in order to guarantee stable and desired network operation. For in-depth modeling and rectification of conflicting SON functions, we have presented a hybrid classification of SON function conflicts, which classifies these conflicts on the basis of soft and hard classification, and paves the way for designing appropriate self-coordination solutions. More specifically, for comprehensive investigation of SON function conflicts, we have presented a case study of mobility load balancing, mobility robustness optimization, coverage and capacity optimization (CCO), and EE SON function conflicts using reference signal received power plots in multicell environments and 3GPP architecture details. In this direction, we have also proposed an analytical mapping of conventional cellular networks' spectral efficiency and energy efficiency

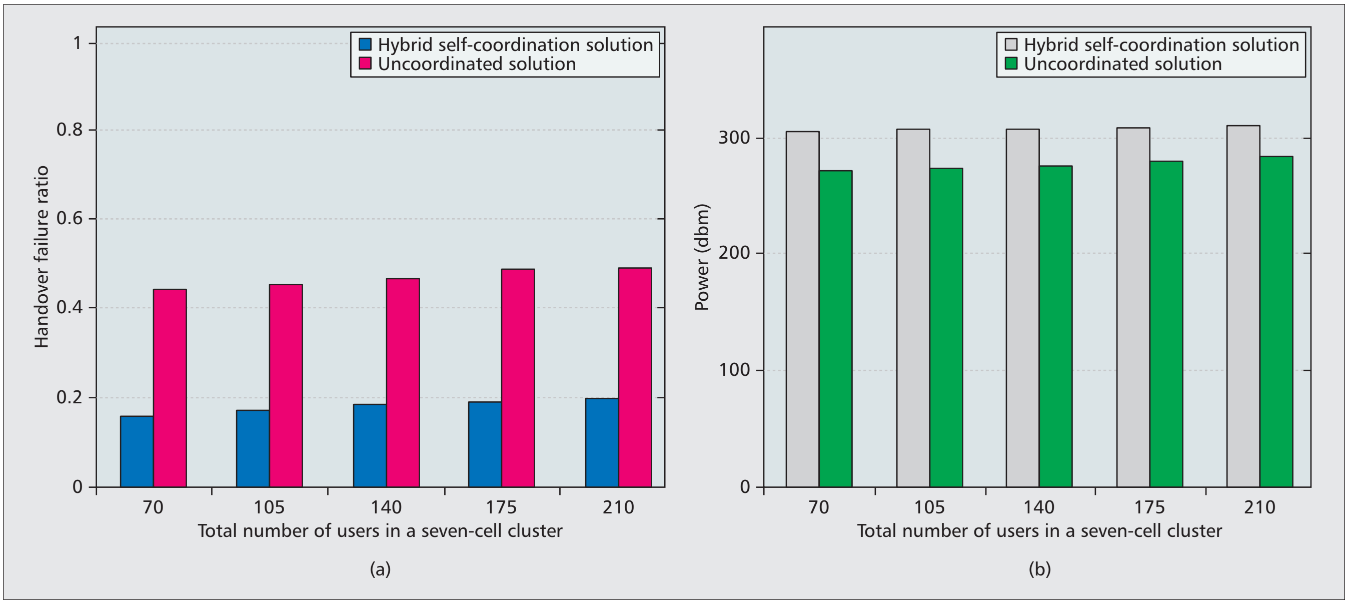


**Figure 5.** The performance evaluation of hybrid self-coordination between MRO and EE: a) the performance analysis of handover failure ratio; b) the performance evaluation of transmission power consumption.

performance metrics trade-off to SON CCO and EE SON functions conflict. We have proposed that SON function conflicts associated with output parameter, input parameter, network topology mutation, logical dependency, and key performance indicator conflict categories can also be classified into the measurement conflict category. Moreover, we have identified the case of SON function conflicts triggering more conflicts. More specifically, we have shown that a low-priority conflict between MLB and CCO functions triggers a crucial conflict between MRO and MLB functions. For possible evolution of the self-coordination paradigm, we have proposed both centralized and distributed hybrid self-coordination mechanisms between MRO and EE functions. We have presented the performance evaluation of the hybrid self-coordination solution using a graph-theory-based approach. The performance evaluation shows that the handover failure ratio of the proposed hybrid self-coordination between MRO and EE functions is significantly lower than the uncoordinated execution of MRO and EE functions. We have recommended that scanning for possible conflicting SON functions using information exchange among neighboring eNBs over X2 interface can avoid measurement conflicts. Moreover, the proposed hybrid self-coordination mechanism can be generalized to other SON function conflicts associated with measurement and logical dependency conflict categories. Root cause evaluation of nested conflicts that arise due to a chain reaction among multiple SON function conflicts is still an open area of research. The hybrid classification of SON function conflicts and self-coordination mechanisms presented in this article will assist further research on designing conflict-free SON solutions, which will eventually expedite the incorporation of SON in next generation wireless communications systems.

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## Biographies

Hafiz Yasar Lateef [M] is currently a research scientist in the College of Engineering at Qatar University. He has participated in several international projects in collaboration with Texas A&M University, Politecnico Di Torino, Italy, CTTC Spain, and CCSR, University of Surrey. His research interests encompass green cellular networks, self-organizing networks, smart grid, big data analytics, smart cities, and the Internet of Everything. He has authored numerous peer-reviewed international journal and conference papers, and has delivered several tutorials in many international conferences. From 2007 to 2014, he held various roles at the University of Leeds, Texas A&M Qatar, Telecoms Experts Services Ltd. UK, U.E.T Lahore and Qatar Mobility Innovations Center.

Ali Imran is an assistant professor in telecommunications at the University of Oklahoma. He is currently leading a multinational $1.045 million research project on self-organizing cellular networks, QSON (www.qson.org). His research interests include self-organizing networks, radio resource management, and big data analytics. He has authored over 40 peer reviewed articles and has presented a number of tutorials at international forums such as IEEE ICC, IEEE WCNC, and European Wireless on these topics. He is an Associate Fellow of Higher Education Academy (AFHEA), UK and a Member of the Advisory Board to the Special Technical Community on Big Data of the IEEE Computer Society.

Lorenza Giupponi [SM] received her telecommunications engineering degree at the University of Rome "La Sapienza" in July 2002 and her Ph.D. at the Department of Signal Theory and Communications (TSC) of the Technical University of Catalonia (UPC) in 2007. She joined the Radio Communications Group of UPC in 2003 with a grant from the Spanish Ministry of Education. During 2006 and 2007 she was an assistant professor at UPC. In September 2007 she joined the CTTC. Currently she is a senior researcher in the Communication Networks Division, Mobile Networks Department, and she acts as director of institutional relations as a member of CTTC Executive Committee.

Muhammad Ali Imran [SM] is currently a reader (associate professor) in the Institute for Communication Systems (ICS, formerly known as CCSR) at the University of Surrey, United Kingdom. He has led a number of multimillion international research projects encompassing the areas of energy efficiency, fundamental performance limits, sensor networks, and self-organizing cellular networks. He is also leading the new physical layer work area for the 5G Innovation Centre at Surrey. He has a global collaborative research network spanning both academia and key industrial players in the field of wireless communications. He has supervised 20 successful Ph.D. graduates and published over 200 peer-reviewed research papers including more than 20 IEEE transactions papers. He has delivered several keynotes, plenary talks, invited lectures, and tutorials in many international conferences and seminars. He has been a Guest Editor for special issues in *IEEE Communications Magazine*, *IEEE Wireless Communications*, *IET Communications*, and *IEEE Access*. He is an Associate Editor for *IEEE Communications Letters* and *IET Communications Journal*. He was awarded IEEE ComSoc's Fred Ellersick Award 2014 and FEPS Learning and Teaching Award 2014 and twice nominated for Tony Jean's Inspirational Teaching Award. He was a shortlisted finalist for the Wharton-QS Stars Awards 2014 for innovative teaching and the VC's Learning and Teaching Award from the University of Surrey. He is a Senior Fellow of the Higher Education Academy (SFHEA), United Kingdom.

Mischa Dohler [F] is a full professor in Wireless Communications at King's College London, head of the Centre for Telecommunications Research, a co-founder and member of the Board of Directors of the smart city pioneer Worldsensing, a Distinguished Lecturer of the IEEE, and Editor-in-Chief of *Transactions on Emerging Telecommunications Technologies*. He is a frequent keynote, panel, and tutorial speaker. He has pioneered several research fields, contributed to numerous wireless broadband, IoT/M2M, and cyber security standards, holds a dozen patents, has organized and chaired numerous conferences, has more than 200 publications, and has authored several books. He has a citation h-index of 38. He acts as a policy, technology and entrepreneurship adviser, examples being Richard Branson's Carbon War Room, House of Lords United Kingdom, U.K. Ministry BIS, EPSRC ICT Strategy Advisory Team, European Commission, ISO Smart City working group, and various startups. He is also an entrepreneur, angel investor, and passionate pianist, and fluent in six languages. He has talked at TEDx and received coverage by national and international TV and radio, and his contributions have been featured on BBC News and in the *Wall Street Journal*.