Detection and Protection of Macro-Users in Dominant Area of Co-channel CSG Cells

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Abstract— **Co-channel deployment of Closed Subscriber Group (CSG) home-cells or Home E-UTRAN NodeBs (HeNBs) will create coverage holes for macro connected user that is not part of the CSG. In this paper, we address the problem of detecting the macro-cell coverage hole and protecting the macro-users that are located inside such a coverage hole. To reduce the impact of HeNB interference on the macro-cell performance, the HeNBs can be partially muted on some subframes, leading to Time Domain (TDM) muting. With TDM muting, macro-users in the coverage hole can be protected by scheduling them only on the muted subframes that are free of HeNB interference. Different methods for coverage hole detection are considered, and their performance is evaluated under the downlink transmission of a Long Term Evolution (LTE) network. These methods are based on user measurements. Recommendations on the coverage hole detection will be provided based on the obtained results.**

I. Introduction

Heterogeneous network with mixed macro-cells and HeNBs has become a very important deployment scenario for future generation wireless communication systems. It allows the coordinated planning of the traditional macro-sites, but also adds the flexibility to boost the performance in hot-spot areas by installing either pico-nodes or HeNBs. The current paper only considers the uncoordinated deployment of CSG HeNBs.

The HeNBs are typically installed following the CSG mode [1]. Therefore, macro-users that are not configured as being part of the CSG at the HeNBs cannot be served by the HeNBs. In the remainder of this paper, the term HeNB refers to HeNBs configured with CSG access. In terms of carrier configuration, the HeNBs can potentially be configured to use a different (usually higher) carrier frequency than the one used for the macro-cells. Alternatively, both HeNBs and macro-cells could share the same carrier, leading to the so-called co-channel deployment. The latter scenario is considered in this paper. It allows more spectrum resources for each network layer, but creates challenges to the interference management between macro-cells and HeNBs. In the downlink transmission, macro-users close to HeNBs tend to receive heavy HeNB interference, leading to the well-known macro-cell coverage hole problem [2][3]. Meanwhile, the HeNB-users are less affected by the macro-eNB, due to the fact that they are close to their serving base station.

The study in this paper is carried out in the downlink transmission of a co-channel deployed heterogeneous network, with TDM muting in the HeNBs. TDM muting is an interference management method currently being standardized in 3GPP. It prevents the HeNBs from transmitting on certain subframes, and hence reduces the interference experienced on the macro layer on these subframes. One can refer to [4] for further information about TDM muting. Some restrictions could then be applied to the macro-cell packet scheduler, which prioritizes the macro-users suffering from heavy HeNB interference (within the macro-cell coverage hole) on muted subframes and vice versa. A method to identify these in-coverage hole users is needed as a pre-requisite.

This paper analyzes several methods for the coverage hole detection, based on available macro-user measurements. It is difficult to mathematically model the multi-user access and the dynamic interference conditions due to fast fading and TDM muting. Therefore, we rely on simulations for the evaluation of these different methods and obey the simulation guideline agreed in 3GPP. These detection methods are evaluated together with the restricted scheduling of macro-users, in which the in-coverage hole macro-users are scheduled only when HeNBs are muted. Recommendations on the coverage hole detection will be provided based on the obtained results. The analysis is carried out for two cases, the LTE legacy users and the LTE Rel-10 users. These two kinds of users have different capabilities in measuring and reporting the Channel State Information (CSI) to the base stations, and the different benefits of using restricted scheduling for these two user categories will also be shown.

The paper is organized as follows: Section II illustrates the coverage hole problem and introduces the concept of restricted scheduling; the different coverage hole detection methods are also discussed. Section III describes the simulation methodology and assumptions; In Section IV, the performance for the different coverage hole detection methods in combination with the restricted scheduling is analyzed. Finally, the main findings of the paper are concluded in Section V.

II. Coverage Hole: Detection and Protection Methods

The co-channel deployment of the CSG HeNBs creates heavy interference within their dominant area and can cause macro-cell coverage holes. Macro-users inside the coverage hole will suffer from extremely low Signal to Noise and Interference (SINR), which is mainly caused by the interference from the HeNB. Such users can hardly receive any reliable service unless special protection is applied against the HeNB interference. The SINR value at different locations within a heterogeneous network is illustrated in Fig. 1. A Single-input Single-output (SISO) antenna configuration is used when generating this figure. Both shadow fading and fast fading are neglected here. Other simulation assumptions are similar to those summarized in Section III. It can clearly be seen from Fig. 1 that macro-users near the CSG HeNBs are severely affected by HeNB interference, resulting in poor SINR, even lower than -30 dB.

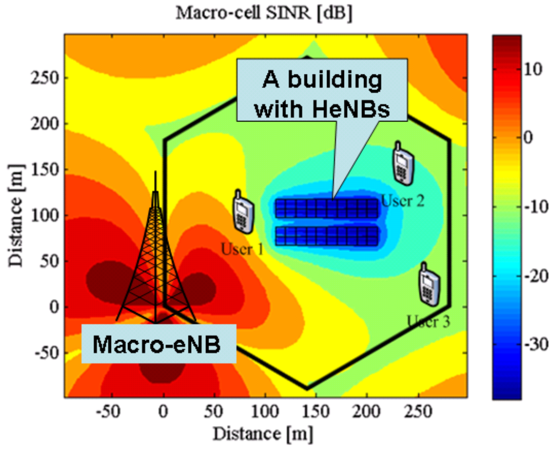

Fig. 1. Macro-cell SINR in a heterogeneous network with co-channel deployed CSG HeNBs.

Figure 2 depicts the macro-cell Radio Resource Management (RRM) framework in a heterogeneous scenario with TDM muting at HeNBs. As can be seen from this flowchart, the coverage hole detection and protection (via restricted scheduling) methods are needed at macro-cell. While the coverage hole detection can be performed according to long term user measurement, the restricted scheduling is performance in the time domain, for each Transmission Time Interval (TTI). Afterwards, Frequency Domain (FDM) packet scheduling is applied to distribute the spectrum among the users according to certain criteria, e.g., maximizing fairness or throughput. Link adaptation is then performed to select a proper modulation and coding rate for each user, and HARQ is used to guarantee reliable decoding. Finally, the physical layer processions are needed, and the signal is sent to the users.

The operations related to TDM muting are discussed in the following. Detailed information on traditional RRM operations in LTE systems can be found in [5].

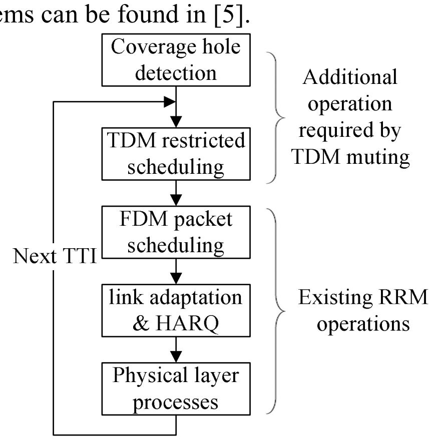

Fig. 2. Macro-cell RRM framework in a heterogeneous network with TDM muting at HeNBs.

A. *Detection of the in-coverage hole users*

The detection is based on the macro-user measurements. As specified in [6], the user could measure both Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) information and report these measurements back to the serving macro-base station. RSRP is the linear average over the power for the cell-specific reference signals from a certain base station. RSRQ indicates the received signal power for reference signals over the total received power (including co-channel serving and non-serving cells, thermal noise etc) [6]. In this study, the cell-specific reference signals are not explicitly modeled, and the power for the data signals is used for the RSRP and RSRQ measurements.

One method for the macro-cell coverage hole detection is based on the RSRP measurement. A macro-user will be considered as inside the coverage hole if the RSRP to the strongest non-allowed co-channel HeNB is higher than a certain threshold. According to [7], this detection method can be realized using event A4: "*neighbour becomes better than threshold*". Note that "*neighbour*" could potentially be any co-channel cells, so the macro-eNB should filter out the irrelevant ones and confirm the coverage hole detection only if the A4 event is triggered by RSRP to non-allowed HeNB. However, this method is inaccurate since the HeNB-RSRP does not provide the full picture of the interference. With the user being in situations with a correspondingly high RSRP to the serving macro cell, the user experienced SINR may be at an acceptable level. For example, in Fig. 1, both user1 and user2 have the same HeNB RSRP, but user1 has much better SINR than user2 and is less affected by HeNBs.

Another method for the coverage hole detection is based on macro-cell RSRQ measurement: a user will be considered as inside the coverage hole if the RSRQ is lower than a threshold. This is achievable using event A2: "*serving becomes worse than threshold*" [7]. RSRQ-based detection is also imperfect in the sense that some users suffering from low signal strength may be considered as inside the coverage hole. An example is shown in Fig. 1, that user3 is at the boundary of one cell and hence has low SINR. It may trigger event A2, but its performance cannot be improved by avoiding the co-channel HeNB interference. These two methods will be evaluated separately in the following, and the possibility to combine these two methods will also be analyzed.

B. *Protection of the in-coverage hole users*

The protection of the in-coverage hole users is realized via TDM muting at HeNBs and restricted scheduling in macro-cells. A macro-cell that is heavily affected by co-channel HeNBs will request HeNBs to apply TDM muting. Afterwards, it will restrict the macro-users inside the coverage hole being scheduled only when HeNBs are muted. The remaining macro-users are schedulable on all subframes, but with low priority on the muted subframes.

In order for macro-cell packet scheduler to best exploit the interference reduction with TDM muting, the users should preferably have CSI measurements for both muted and un-muted subframes. However, the LTE legacy users support only one measurement pattern and hence no separate CSI feedback. Furthermore, the interference measurement for the legacy users is averaged across several subframes, which cannot fully represent the instantaneous interference status. In this situation, using restricted scheduling avoids the risk of serving a user when the channel condition is poor, and increases the system spectral efficiency.

As regards the LTE Rel-10 users, they can be configured with two CSI measurements patterns, one for muted subframes and the other for un-muted ones [8]. However, the Radio Link Monitoring (RLM) for the in-coverage hole users should only be performed on muted subframes. This prevents the potential radio link failures at un-muted subframes and reduces the risk of hand-over or dropped calls. When in-coverage hole users are subject to restricted scheduling, they can be re-configured with only one measurement pattern (for the muted subframes) so that the uplink feedback overhead is reduced. Still, the in-coverage hole user has to perform channel measurement for un-muted subframes in a slower manner, such that when a user leaves the coverage hole, this can be detected.

III. Simulation Methodology and Assumptions

The performance of the different techniques is evaluated in a quasi-static downlink multi-cell system level simulator that follows the LTE specifications defined in [9], including detailed implementations of packet scheduling, Hybrid Automatic Repeat Request (HARQ) and link adaptation. The link to system mapping is based on the exponential effective metric model [10]. A 2x2 Multi-input Multi-output (MIMO) with rank adaptation [11] and Interference Rejection Combining (IRC) is used, which is able to cancel the strongest interference and can significantly increase the macro-user SINR in presence of co-channel HeNBs.

The macro-layer is modeled according to the macro-cell case #1 [12]. Among all the macro-cells, only the center one is simulated, and one dual-stripe building is randomly placed within the coverage of this center cell. The surrounding ones are used to generate time continuous interference across the full bandwidth. The dual-stripe building is modeled following the guideline in [13], which is a 6-floor building with 40 rooms per floor (separated into two stripes by a 10 m wide corridor). The size of each room is 10x10 m^2. There is 20% probability for each room to have an HeNB installed, and each HeNB is associated with an activity factor of 50%. Overall, 24 HeNBs are actively transmitting from the dual-stripe building. TDM muting with a muting ratio of 1/8 or 2/8 is applied at HeNBs, assuming zero HeNB interference on muted subframes.

The simulation process is conducted as a series of simulation runs (200 runs with 1 second duration per run) with a constant number of users per cell. During each run, the HeNBs are randomly activated in the dual-stripe building, with random locations inside each room. Macro-users are generated within the whole cell coverage area, with 8 users inside the dual-stripe building and 2 outside. Once generated, users keep their positions until the end of each simulation run. The simulation parameters are summarized in Table I.

In the considered co-channel heterogeneous network, the HeNB layer maintains reasonable performance as the impact of macro-interference is marginal. However, as Fig. 1 indicates, the macro-layer may suffer from coverage hole problem and hence poor performance. We thus devote our effort to study the macro-layer performance, and use the following performance indicators for the evaluation:

- Average cell throughput: the cell throughput averaged over all simulated cells from all simulation runs.
- Cell edge user throughput: the 5^{th} percentile worst user throughput from all simulated ones.

TABLE I: System simulation settings

Parameter	Setting / description
Test scenario	3GPP Macro-cell case #1 (19 sites with 500 m inter-site distance; 3 cells per site; reuse 1) with a co-channel deployed dual-stripe HeNB building
Bandwidth	10 MHz bandwidth at 2 GHz frequency
Sub-frame duration (TTI)	1 ms (11 data plus 3 control symbols)
MIMO configuration	2 by 2 with rank adaptation and IRC
Transmit power	Macro: 46 dBm; HeNB: 20 dBm
CSI feedback delay	6 ms
Interference average window for LTE legacy users	5 ms
FDM packet scheduler	Proportional fair
Modulation and coding schemes	QPSK (1/5 to 3/4), 16-QAM (2/5 to 5/6), 64-QAM (3/5 to 9/10)
HARQ modeling	Ideal chase combining with maximum 4 transmissions; 10% BLER target
Traffic type	Full buffer
User speed	3 kmph
Urban-dense femtocell modeling parameters [13]	
Number of rooms per row	10 (in total 40 rooms per floor)
Building model	1 building per cell; 6 floors per building
HeNB model	deployment ratio: 20%; activation ratio: 50%
Indoor user probability	80%
TDM muting	Muting ratio: 1/8 (unless otherwise specified); zero HeNB interference on muted subframes

IV. Performance

A. *Statistics of the different user measurements*

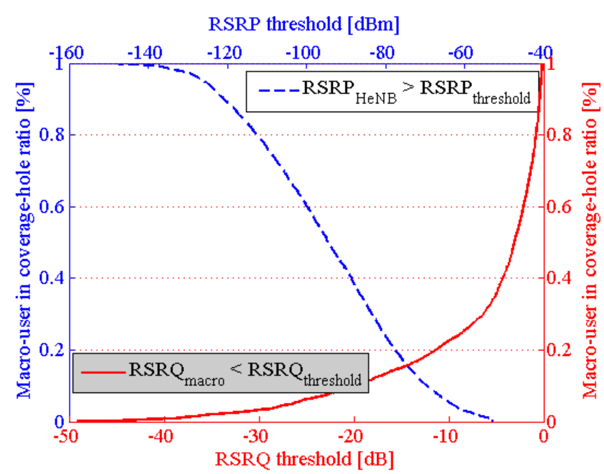

Fig. 3. Cumulative distribution of macro-user RSRP and RSRQ.

Figure 3 shows the distribution of the macro user RSRP and RSRQ statistics, with full HeNB interference (i.e., no muting of HeNBs). Different ratios of the in-coverage hole users can be obtained by properly setting the threshold values. Note that the same protection ratio can be achieved by both methods, but the users detected as inside the coverage hole might be different between the two methods, and different throughput performance is expected.

B. Performance with LTE legacy users

The average cell throughput and cell edge user throughput with restricted scheduling and different coverage hole detection methods are shown in Fig. 4 for the case of legacy users. The performance is evaluated with various ratios of in-coverage hole users. Different ratio can be obtained by tuning the threshold for the coverage hole detection. It does not represent the user geographical location.

As can be seen from Fig. 4, very low cell edge user throughput is experienced with un-restricted scheduling (in-coverage hole ratio of 0%). The reason is that the legacy users have similar CSI measurement for both muted and un-muted subframes (due to the time domain interference averaging). As a consequence, a user has equal probability of being scheduled on both kinds of subframes, with similar modulation and coding schemes. This increases the risk of reception errors on un-muted subframes and reduces the spectral efficiency on muted subframes.

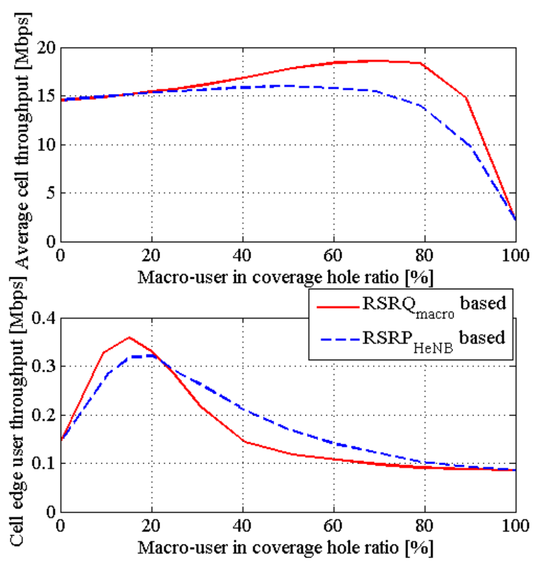

Fig. 4. Average cell throughput and cell edge user throughput with different coverage hole detection method and TDM restricted scheduling.

When increasing the restricted user ratio from 0 to around 15%, both average cell and cell edge user throughput see a gain. This is expected as the in-coverage hole users can now better exploit the muted subframes and leave the un-muted subframes to the users that are less affected by HeNB interference. However, a further increasing of this ratio reduces the cell edge user performance. This is due to the fact that too many users are squeezed onto the muted subframes, and hence the resource sharing is not fair between users inside and outside the coverage hole. When all users are considered as in the coverage hole, only 1/8 of the macro-cell resources will be utilized. This leads to very poor performance in both average cell throughput and cell edge user throughput.

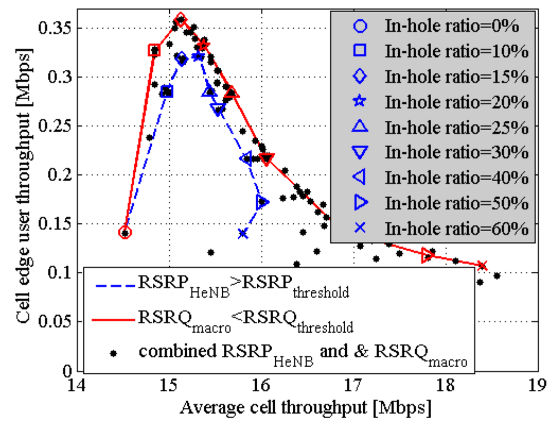

Fig. 5. Throughput performance with different coverage hole detection methods and various ratios of in-coverage hole users.

Figure 5 shows the average cell throughput versus the cell edge user throughput for the two detection methods and their combination, where the different points correspond to the different in-hole ratios. From this figure it is seen that for the same average-cell throughput, the cell edge user throughput is higher for RSRQ based approach than RSRP based. Also, for the same cell edge user throughput, the RSRQ based detection offers higher average cell throughput. It achieves the maximum cell edge throughput when 15% of the users are considered as in-coverage hole, which is 157% higher than the case without any restriction. Meanwhile, the average cell throughput is slightly improved by 4%. In the given scenario where HeNBs always exist, the detection method that combines both RSRP and RSRQ measurement offers no better performance than purely RSRQ based detection. Therefore, only RSRQ based detection will be used for the following studies.

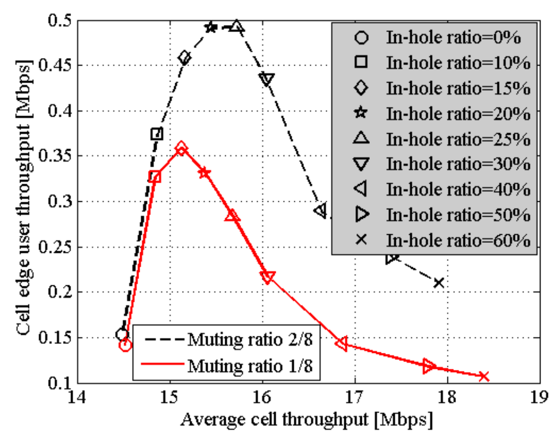

Fig. 6. Throughput performance with macro-RSRQ based coverage hole detection method and different HeNB muting ratios.

Performance with a higher TDM muting ratio of 2/8 is also evaluated and the results are summarized in Fig. 6. The performance with muting ratio 1/8 is plotted for reference. A higher muting ratio reduces the HeNBs throughput and causes the HeNBs to have less offloading capability of the macro-traffic. However, it offers more protection of the macro-users as the HeNB interference is reduced. As can be seen from Fig. 6, the cell edge user throughput now is maximized when 25% of the users are configured with restricted scheduling. With this configuration, the performance is better than muting ratio 1/8 with 15% restricted users by 37% in cell edge user throughput and 4% in average cell throughput.

C. Performance with LTE Rel-10 users

For the LTE Rel-10 users that are able to have separate CSI measurement for muted and un-muted subframes, a normal proportional fair scheduler can efficiently prioritize the in-coverage hole users when HeNBs are muted, and vice versa. From the perspective of downlink throughput, there is no need to apply any scheduling restrictions. However, considering the fact that the users inside the coverage hole are less likely to be scheduled on un-muted subframes, it is preferable to reduce uplink overhead by configuring the users near HeNBs to measure and report only on muted subframes. Consequently, these users should be subject to scheduling restrictions. Furthermore, coverage hole detection is needed even without restricted scheduling, as the in-coverage hole users should perform RLM only on muted subframes.

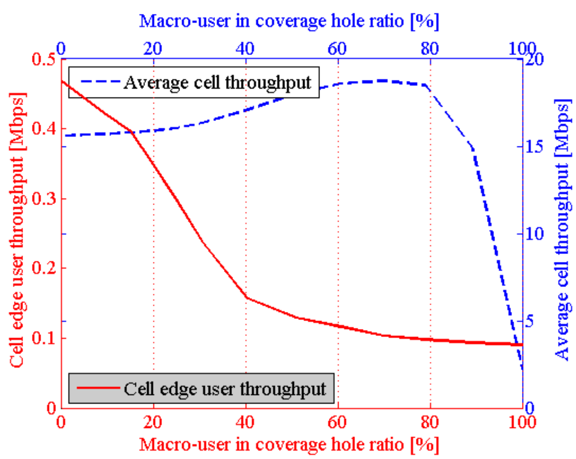

Fig. 7. Average cell throughput and cell edge user throughput for LTE Rel-10 users with macro-RSRQ based detection and restricted scheduling.

The downlink throughput with different ratios of users inside the coverage hole is plotted in Fig. 7 for both average cell throughput and cell edge user throughput, with a muting ratio of 1/8 at HeNBs. Increasing the ratio of restricted users helps to reduce the uplink overhead, but decreases the cell edge user throughput. Meanwhile, the average cell throughput slightly increases because the users with good channel quality are prioritized. The loss in cell edge user throughput is 16% when 15% of the users are considered as inside the coverage hole.

V. Conclusion

In this paper we have studied different methods to detect the macro-cell coverage hole in a heterogeneous network. The macro-RSRQ based coverage hole detection offers better performance than HeNB-RSRP based detection. However, although not shown in this paper, only macro-RSRQ based detection may cause unnecessary protection when no HeNB exists in a network. It is therefore recommended to assist the RSRQ-based detection with the HeNB-RSRP measurement. A fixed RSRP threshold will be used for the macro-users to identify the presence of HeNBs. Afterwards, the user will trigger coverage hole event if the macro-RSRQ is lower than the RSRQ threshold. The RSRQ threshold and the muting ratio should be jointly chosen such that macro-users with poor RSRQ are considered as inside the coverage hole, and the muting ratio matches the in-coverage hole user ratio.

Once the users inside the macro-cell coverage hole are identified, they can be protected by being scheduled only when HeNBs are muted. In a scenario where HeNBs have a muting ratio of 1/8 and all users are LTE legacy, time domain restricted scheduling offers a gain of 157% in cell edge user throughput and 4% in average cell throughput. Coverage hole detection is also necessary for users inside the coverage hole to perform radio link monitoring only on muted subframes.

Among others, future research should include cases where user measurement imperfections are included as well as validating the proposed methods for other environments. The finite buffer traffic model could also be applied, which allows to study the performance from aspects other than throughput, e.g. the blocking probability and waiting time.

Acknowledgment

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