Downlink Transmission Optimization Framework

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***Abstract*—This paper presents an optimization framework for downlink transmission parameters of mobile cellular systems. A typical network optimization approach is to divide the network into disjoint clusters of base-stations (BS). Optimization is then performed within each cluster for important parameters such as transmit power, precoder, etc. This approach is widely adopted in academic research and industrial standard bodies, e.g. 3GPP LTE-Advanced. While reducing the optimization complexity, this strategy suffers from a performance limit due to interference from the nodes outside cluster. We thus propose a framework to overcome this limit by allowing clusters to exchange their parameters and optimization information via low-rate and non-zero delay backhauls. System-level simulations for LTE downlink transmit power optimization show that the proposed optimization model, while having the low-complexity of cluster-based approach, could nearly achieve the performance of network-wise optimization. Therefore, this model is particularly suitable for optimization of 4G and beyond-4G cellular networks.**

Keywords: Downlink optimization, radio resource management, LTE-A, 4G, HetNet.

I. INTRODUCTION

Heterogeneous network architecture (Hetnet) is expected to play an important role for capacity enhancement of the forth-generation (4G) mobile networks, such as long-term evolution advanced (LTE-A) networks [1]. In HetNet, low power nodes, e.g. pico nodes (PN), are deployed in the coverage areas of macro nodes (MN) for offloading or coverage extension. To facilitate an efficient offloading, the coverage of pico nodes is extended by including a cell selection bias or range extension (RE) towards pico nodes when the system finds a serving cell for user equipments (UE).

With large values of RE, the downlink (DL) signal of pico UEs may be severely interfered by macro nodes. In 3GPP (Third-Generation Partnership Programme), a technique called enhanced inter-cell interference coordination (eICIC) is proposed [2] as a measure to mitigate the interference between macro and pico nodes. The eICIC scheme is fundamentally a time-division multiplexing (TDM) transmission, where the interferers (in this case macro nodes) do not transmit data in some data sub-frames to reduce interference to UEs served by pico nodes.

In a broader context, instead of reducing transmit power of macro nodes only, the transmit power of macro and pico nodes in the network should be jointly optimized. In a more general setting, the other parameters of access nodes such as precoders, elevation angle of transmit antennas, etc., could also be jointly optimized. However, a joint optimization of these parameters is very difficult. Theoretically the DL transmit power and

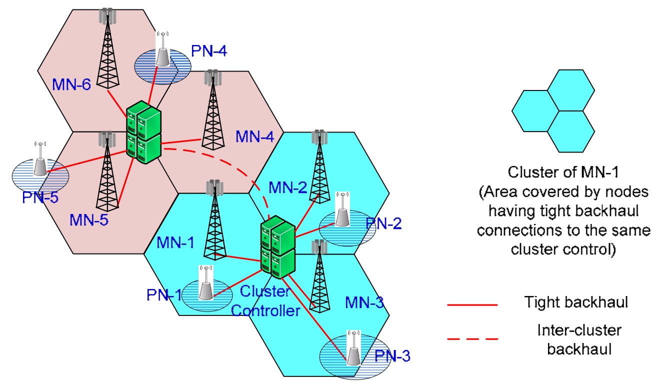

Figure 1: Example of heterogeneous networks with macro and pico nodes and clusters of nodes.

precoder optimization problem is non-convex [3]. Solutions for this problem require highly complex optimization tools. The problem is more difficult if the DL transmit power levels are discrete as specified in LTE standard [4], and given the dynamic nature of UE selection and throughput requirements.

To reduce the complexity of the network-wise optimization, the network could be divided into disjoint clusters of nodes. Then parameter optimization can be performed for nodes within a cluster [5][6]. This approach is widely used in academic research and industry. In Figure 1, an example of clusters is given. The 'blue' cluster has 6 nodes linked to a central controller by high-speed and low-delay links. This approach helps to reduce the complexity to a manageable level, but at the same time suffers from a performance limit [5]. The solution is only optimal for nodes in the cluster. At the same time, the impacts from nodes outside cluster are uncontrolled and these impacts deteriorate the gain of in-cluster optimization.

There are some solutions for mitigating the inter-cluster interference such as scheduling [8], beamforming [9], and dynamic clustering [10][11]. With scheduling approach in [8], the scheduling information needs to be frequently exchange among cluster with low delay; these requirements may not be always fulfilled in practice. According to the beamforming method in [9], the inte- cluster channel information is required to calculate precoder for UEs at the cluster boundary. This in facts requires more stringent transmission constraints for cluster-edge UEs to facilitate inter-cluster channel estimation and feedback, as well as user scheduling information to avoid interference. By dynamic clustering [10][11], the clusters are

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formulated to maximize the network throughput. However, with limitation of backhaul support, it is not always possible to arbitrarily setup clusters.

Contributions: In this paper, we present a framework to optimize cellular networks with fixed clusters of network nodes. Each cluster performs their own optimization algorithm, while the impacts from/to outside-cluster nodes are taken into account. Clusters communicate with each other via feed-forward and feedback links. The benefits of our proposed optimization model are verified by LTE HetNet system-level simulations for downlink power optimization.

- A very significant gain can be achieved, while the complexity is kept the same as that of the conventional cluster-based optimization.
- The resource allocation fairness between macro and pico layers is greatly improved, compared to the eICIC technique.
- Remarkable energy saving can be obtained.

The rest of the paper is organized as follows. Section II introduces the system model. Section III discusses our proposed framework in detail, and simulation results are presented Section IV. Finally, concluding remarks are given in Section V.

II. System Model

Consider a generic downlink channel of wireless networks. The radio access network (RAN) consists of N nodes, each serves 1 user for simplicity. We assume that the RAN employs single-carrier transmission. Extension to multi-carrier OFDM-based transmission is possible with some modifications.

The whole network is divided into multiple disjoint clusters. Let us consider a user k ($k = 1, \dots, N$). Let Ω be the set consisting the indices of nodes, including node k. We call these nodes in-cluster nodes. The other nodes, having indices in another set Φ, are called out-cluster nodes.

The transmit-receive signal model of user k ($k = 1, \dots, N$) is given below.

$$\boldsymbol{y}_k = \sqrt{\rho_k}\boldsymbol{H}_{k,k}\boldsymbol{P}_k\boldsymbol{x}_k + \sum_{n\in\Omega, n\neq k} \sqrt{\rho_n}\boldsymbol{H}_{n,k}\boldsymbol{P}_n\boldsymbol{x}_n + \sum_{n\in\Phi} \sqrt{\rho_n}\boldsymbol{H}_{n,k}\boldsymbol{P}_n\boldsymbol{x}_n + \boldsymbol{n}_k, \quad (1)$$

where

- $\boldsymbol{y}_k$ and $\boldsymbol{x}_k$ are received and transmitted vectors of user k,
- $\boldsymbol{H}_{n,k}$ is the channel matrix from node n to user k,
- $\boldsymbol{P}_k$ is the precoding matric for user k,
- ρ_n is the transmit power for user n,
- $\boldsymbol{n}_k$ is the noise vector at user k.

The above transmit-receive signal model simply breaks down the receive signal into three terms: the design signal, interference from the in-cluster nodes, and interference from out-cluster nodes. Note that we do not assume perfect cancellation of interference from nodes in the same cluster.

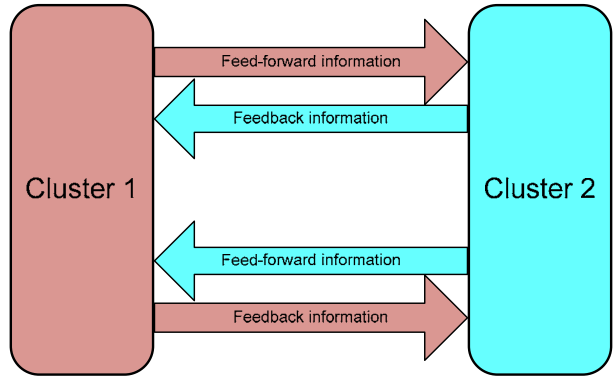

Figure 2: Inter-cluster information exchange model.

The conventional approach to optimize the network is to independently optimize the parameters of nodes in each clusters. This approach can dramatically reduce the optimization complexity, but it performance is fundamentally limited by the amount of interference from out-cluster nodes [5]. Heuristically, even the best coordination among in-cluster nodes may eliminate the interference from the in-cluster nodes to user k, the interference from out-cluster nodes may be uncontrollable and it could be significant to saturate the performance of any in-cluster optimization algorithms.

In the following, we introduce an inter-cluster model allowing a better collaboration among clusters.

III. Proposed Solution

The proposed inter-cluster information exchange model is given in Figure 2. In this model, clusters are inter-connected by non-zero delay backhauls. There are two kinds of information exchanged between two clusters described below.

- Feed-forward information: optimized parameters (e.g. transmit power, precoder index, etc.) are sent from one cluster controller to other cluster controllers.
- Feedback information: the utility information of other clusters is sent back to one cluster.

When a node changes transmit parameters, other nodes should know these new settings to track the interference to their UEs and hence for better data user selection/rate adaptation. Nevertheless, the information exchange may lead to a certain delay between the time the transmit parameters are optimized and the time the transmit parameters are actually used. So the performance gain by sharing transmit parameter information could be reduced due to the delay. Nevertheless, when the network is in a stable state for a certain period (for a fixed set of UEs and fixed UEs locations), the transmit parameter optimization could fluctuate less, and the impacts due to information sharing delay could be mitigated.

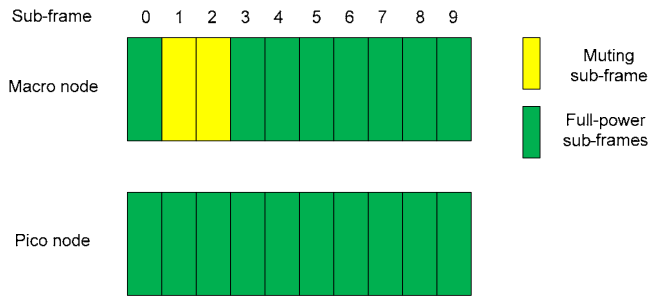

Figure 3: Example of transmit power setting at macro and pico BSs employed in eICIC technique.

In the feedback link, for example the feedback from Cluster 2 to Cluster 1, the nodes in Cluster 2 tell which nodes in Cluster 1 make significant impacts to their utility functions. The cross-cluster impacts could be quantified by interference power, throughput penalty and so on. When optimizing the parameters of nodes in Cluster 1, these impacts are taken into account. Therefore, the optimization within Cluster 1 virtually goes beyond the cluster boundary; it is possible to nearly achieve the performance of network-wise optimization.

Special case

We take a look at eICIC [4] as a special case of our model. Let us describe this scheme and then analyze how this scheme is fitted in the proposed model.

The eICIC technique is proposed for interference coordination between macro nodes (high transmit power) and pico nodes (or low transmit power nodes). Due to a strong interference from macro nodes to UEs of pico nodes, the coverage of pico nodes is quite limited if the UEs are served by BSs with strongest received signal. To increase the coverage of pico nodes, a bias known as range extension (RE) is added to the received signal from pico nodes. With large RE (6 dB or higher), the pico UEs at the cell edge actually have very low signal-to-interference plus noise (SINR) and thus have zero throughput.

In order to serve pico cell-edge UEs, the macro BSs may turn off their signal for some transmission time slots (or transmission time interval - TTI). In these muting sub-frames, the interference from interfering macro BSs is minimal, thus pico cell-edge UEs could have higher SINR.

An example illustrating the transmit power setting in eICIC technique is given in Figure 3. In every 10 sub-frames, macro nodes synchronously turn off transmission in sub-frames 1 and 2. Pico nodes are aware of this muting pattern. So pico UEs have no interference from macro BSs, and thus pico cell-edge can enjoy high data rate transmission in these muting sub-frames.

We can see how the eICIC scheme fit in our proposed model. The feed-forward information is transmit power information of macro and pico nodes, including the muting pattern of macro nodes. The feedback information in this case could be the request from BSs outside cluster to change the number muting sub-frames or muting patterns of macro/pico nodes inside cluster.

In the following, we present simulation results to highlight the advantages of the proposed model.

IV. SIMULATION RESULTS

We compare the performance of our proposed optimization framework with baseline system configuration, where no optimization is implemented, and eICIC technique. An LTE system-level simulator is employed. In the simulations, the network consists of 19 sites, the inter-site distance is 500 m. Each site has 3 sectors (cell). In each cell, 5 pico nodes are randomly deployed. We also assumed UEs are uniformly distributed in the whole network. UEs report channel quality information (CQI) every 10 msec. MMSE/IRC receivers are employed in UEs. The Typical Urban (TU) channel model with is used. Other simulation parameters are summarized in Appendix.

Simulation Settings

In the simulations, each cluster includes all macro (3) and pico BSs (15) within one site (intra-site cluster). The transmit powers of BSs in one cluster are jointly optimized. In this paper, our main focus is to show the advantage of the proposed optimization framework in Figure 2. Hence we omit the implementation detail of our specific power optimization algorithm for brevity.

We compare the performance of four schemes below.

1. Baseline: no interference coordination among nodes.
2. eICIC: Macro nodes have the same and synchronized muting pattern. Pico nodes transmit full power. The optimal number of blank sub-frames (3 and 5 sub-frames every 10 sub-frame period for 6 and 12 dB RE, respectively) is found by exhaustive simulations.
3. Conventional in-cluster optimization without information exchanges among clusters.
4. Proposed in-cluster optimization with inter-cluster information exchanges model.

In this study, the impacts of range extension on the performance of control channels are not been considered. In other words, we only investigate the throughput of data channels assuming perfect control channel information.

Since we employ a proportional fair scheduler, the average sum log throughput of UEs is used as the optimization parameter. We thus compare this metric as a performance indicator, together with cumulative distribution function (CDF) of UE throughput of the four schemes.

We performed simulations for random and clustered-UE distributions, random and planned deployments of pico nodes. Although the absolute numbers are different, we observe similar trends in these scenarios. Therefore, we only present the results for random UE and random pico scenario in the following.

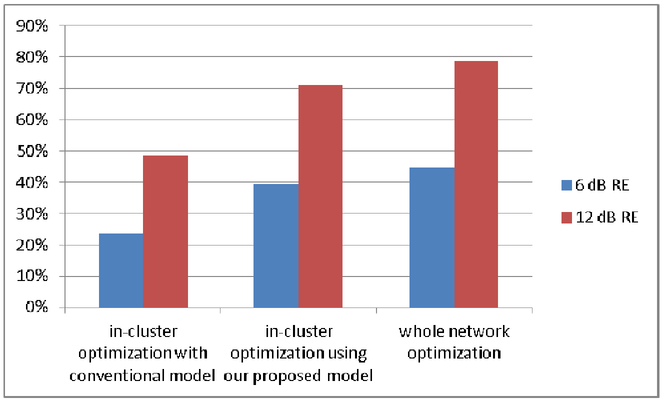

Figure 4: Performance gain over baseline of the proposed optimization framework in terms of average sum log throughput of UEs.

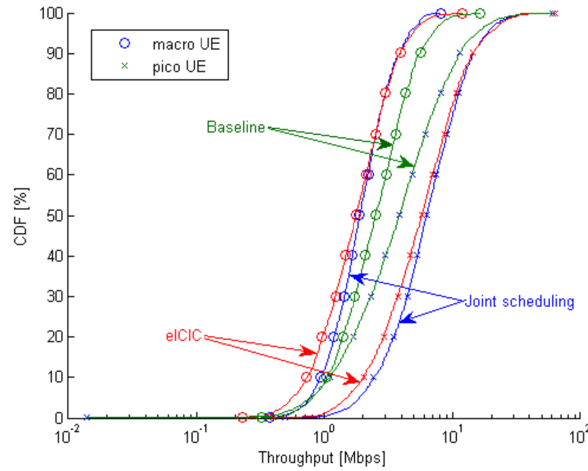

Figure 5: Resource allocation fairness between macro and pico nodes, 6 dB RE.

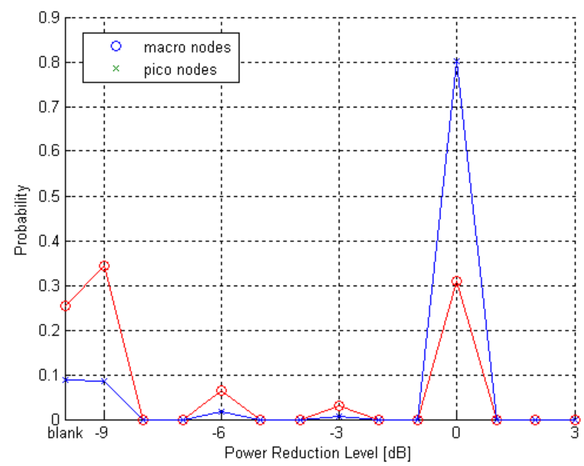

Figure 6: Transmit power of macro and pico nodes with joint scheduling, 6 dB RE.

A. Baseline Comparison

The performance gains of the proposed optimization framework and the conventional approach against baseline scheme are shown in Figure 4. For the conventional approach, two cluster sizes are considered, intra-site cluster only and whole-network. The best performance is expected with whole-network optimization. From the results, we can see that, while significantly outperforms the former, the proposed framework can capture most of the gain by optimizing the whole-network. For example, with 12 dB range extension, the whole-network optimization could provide 79% gain, and our proposed framework brings 71% gain, which is far beyond the 49% gain due to the conventional in-cluster optimization approach.

We also observe that with larger range extension, better gains can be obtained. The main reason is that with 12 dB RE, pico nodes serve 72% of UEs, which is significantly larger than 62% of UEs served by pico nodes with 6 dB RE. The average system resource per pico UEs is much larger than that for macro UEs. Therefore, with proper interference management between macro and pico layers, the network throughput will be improved extensively.

B. Macro-Pico Layer Resource Allocation Fairness

In eICIC technique, macro nodes stop transmissions in some data sub-frames to reduce interference to pico UEs. This will definitely lead to a lower throughput for macro UEs, while pico cell-edge UEs will have much better performance. It means that the improvement of pico throughput will compensate for the loss of macro UE throughput.

On the other hand, our optimization framework can flexibly assign the transmit power to macro and pico nodes to maximize the objective function, while considering the impacts to other clusters. Therefore, our approach can mitigate this issue as illustrated in Figure 5, where the throughput of macro and pico UEs, especially cell-edge UEs, is significantly improved compared to eICIC.

C. Energy Efficiency

Since energy efficiency has been becoming a key performance metric of cellular networks [7], we investigate the energy efficiency of the proposed framework, measured by the saving of transmit power for data channels in Figure 6. The probabilities of transmit power is plotted for JS with 6 dB RE. Compared to the baseline, the power saving is 61% and 18% for macro and pico nodes, respectively. Note that the best eICIC with 3 muting sub-frames saves only 30% transmit power of macro nodes.

V. CONCLUSIONS

In this paper, we presented an optimization framework in which the inter-cluster information exchanges are shown to be very beneficial. Different from the conventional approach, there are two kinds of information, feed-forward and feedback information, are exchanged among clusters. The exchanged information allows nodes to estimate of mutual impacts among clusters. While having low complexity, our approach could nearly achieve the performance of the highly-complex network-wise optimization. We show the results for transmit power optimization, but the same concept can be applied for other parameters, such as precoder, elevation angles, etc.

Another important aspect of our proposed model is that by taking into account the inter-cluster mutual impacts, the problem cluster formulation (determining which nodes to cooperate with which nodes) becomes less important, or even unnecessary [8] [10] [11]. Therefore, our framework is robust with respect to the potential network reconfiguration, where new macro and pico nodes could be deployed in an existing network. With manageable complexity, the proposed optimization framework is highly suitable for 4G and beyond networks, where a very dense deployment of access network nodes is anticipated.

APPENDIX

Simulation Parameters

Parameter	**Value**
Cellular layout	Hexagonal grid, 19 macro cell sites, 3 cells per site
Inter-site distance	500 m
Number of pico nodes	5 per cell (random deployment)
Pico-to-pico distance	Minimum 40 m
Carrier frequency	2 GHz
Bandwidth	10 MHz
Channel model	Typical Urban (TU)
Number of UE per cell	25
UE speed	3 km/h
BS transmit antennas	2 antennas (cross-polarized)
UE receive antennas	2 antennas
UE channel estimation	Ideal
UE receiver type	IRC
Traffic model	Full buffer
Scheduler	Proportional fair
Channel feedback info	PMI/CQI/RI
CQI feedback cycle	10 msec
Cluster size	Intra-site (3 macro & 15 pico nodes)
Max transmit power	Macro 46 dBm, pico 30 dBm

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