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A Utility-Based Scheduling Approach for Multiple Services in Coordinated Multi-Point Networks

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Abstract—**Coordinated Multi-Point (CoMP) joint transmission is considered as a key technique to mitigate inter-cell interference (ICI) and improve the cell-edge performance in 3GPP LTE-Advanced. In this paper, a utility-based coordinated transmit scheduling method is proposed to support joint transmission in CoMP systems. The objective is to improve the cell-edge performance in downlink packet-based CoMP networks with mixed real-time voice over IP (VoIP) and best-effort (BE) traffic patterns. Via simulation results we show that compared to the traditional scheduling schemes with neither CoMP joint transmission nor diverse quality of service (QoS) provisioning, the proposed algorithm in this paper improves the cell-edge efficiency of BE users by greater than 45%, while better satisfying the QoS requirements for VoIP users with significant decrease in call outage by greater than 98%.**

Keywords - Coordinated multi-point joint transmission; QoS; scheduling and resource allocation, multiple traffic patterns

I. INTRODUCTION

Coordinated Multi-Point (CoMP) joint transmission, also known as network coordination, is proposed as a promising technique to satisfy the system requirements regarding coverage, cell-edge user throughput and system efficiency [1]. In CoMP systems, multiple coordinated cells are connected via a high-speed backbone. By using joint transmission scheme in the downlink of CoMP systems, the inter-cell interference (ICI) can be significantly mitigated by applying the signals transmitted from other cells to assist the transmission instead of acting as interference.

Clearly, radio resource management (RRM) cooperation among multiple cells plays a key role for controlling ICI, and in turn improving the system performance in CoMP networks. Currently, RRM schemes for CoMP systems are mainly studied for increasing cell-edge throughput and achieving the balance between efficiency and fairness, assuming all the users in the network have the same traffic modes [2]-[4]. In [2] and [3], algorithms utilizing coordinated scheduling and power control are proposed for controlling ICI. In [4], a utility-based algorithm for multi-cell coordinated resource allocation is proposed, and is proved to be more efficient in improving the cell-edge average throughput and user fairness, compared to traditional single-cell transmission. Note that all these schemes treat the users equally without considering multiple traffic types in the CoMP networks.

However, beyond efficiency and robustness to ICI, present and next-generation wireless networks are challenged to meet the diverse QoS imposed by various services [5]. The research on mixed-traffic scenarios is receiving more attention due to its significance in practical deployment of the Evolved UTRAN (E-UTRAN). Currently, research focuses mainly on single-cell mixed-traffic scenarios [5]-[7]. In [5], a unified approach based on utility functions to QoS-guaranteed scheduling is proposed for time-division multiplexing (TDM) in downlink. In [6] a mixed best-effort (BE) and voice over IP (VoIP) traffic is studied, and a dynamic packet scheduling architecture is proposed to differentiate scheduling of different traffic classes. The result in [6] shows that with VoIP prioritizing keeps the VoIP UEs satisfied at the cost of decreased system spectral efficiency. In [7], a utility-based optimization is proposed, and is shown to be able to satisfy the delay requirement of real-time (RT) traffic while balancing the fairness and efficiency. The main limitation of [5]-[7] is that RRM is designed for the single cell scenario and no joint transmission is undertaken.

In this paper, we propose a joint packet scheduling and power control algorithm on flat fading channel for CoMP networks with mixed BE and VoIP services. We focus on the downlink of a CoMP cluster, consisting of three base station sectors (BSSs) with fixed maximum transmit power. The objective is to maximize the sum of all the users' utilities, which present the users' satisfaction levels based on different traffic. Binary power control (i.e., in any time slot, the cell either transmits with full power or does not transmit) is also used. The results show that the optimization problem amounts to a user-group selection problem, i.e. choosing the best user group for each time slot. Via the simulation results, we show that through diverse utility functions the proposed algorithm well satisfies users of different traffic types regarding QoS requirements. By taking advantage of the joint transmission scheme, the presented algorithm is also proved to significantly improve the cell-edge BE users' efficiency, while suppressing the call outage probability (i.e. the interruption probability of VoIP calls due to excessive packet delay) for VoIP service.

The rest of this paper is organized as follows. In section II, we provide the system model considered in this paper. In section III, the constrained optimization objective is formulated, and a radio resource allocation algorithm for utility-based joint scheduling and power allocation is proposed. Simulation results are presented in section IV, and conclusions are presented in section V.

This work has been supported by The Swedish Agency for Innovation Systems (VINNOVA). The work has been performed in the framework of the Sino-Swedish program on 'IMT Advanced and beyond'.

II. SYSTEM MODEL

We focus on the downlink of a static CoMP cluster consisting of three neighboring BSSs. A central unit (CU) is used to determine user schedule and power control for all BSSs in the cluster; see Fig.1. According to the long term channel gain, users are divided into two classes, namely cell-center users (CCUs) and cell-edge users (CEUs). Joint transmission can only be applied to CEUs. In this paper, we focus only on CEUs. The BSSs are assumed to have one directional transmit antenna each with the same fixed maximum transmission power P, and share the same cell-edge bandwidth B. The CEUs are further divided into two categories based on the services they require, i.e. BE users and VoIP users, denoted as $\mathrm{CEU}_{\mathrm{BE}}$ and $\mathrm{CEU}_{\mathrm{V}}$ respectively in Fig.1. Each CEU is equipped with one receive antenna and can receive signals from a subset of the BSSs of the CoMP cluster.

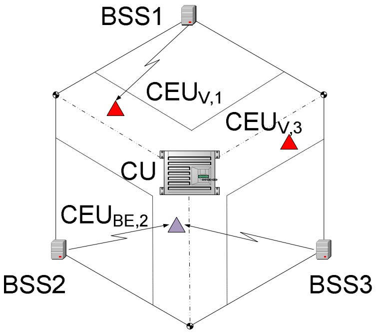

Figure 1. System model for downlink joint transmission in one CoMP cluster

The CoMP cluster is supposed to have a set $\mathcal{M}$ of CEUs and a set $\mathcal{N}$ of BSSs. In each time slot, the CU allocates users for each BSS n based on the channel state information (CSI) of each CEU m. A user schedule index $x_{nm}(t)$ is defined as

$$x_{nm}(t)=\begin{cases}1, \text{ if BSS } n \text{ transmits to CEU } m \text{ at time slot } t;\\ 0, \text{ otherwise.}\end{cases} \qquad (1)$$

Hence, the user schedule matrix can be denoted as $\mathbf{X}(t)=[x_{nm}(t)]$ with size $N\times M$, where N and M are the cardinality of $\mathcal{N}$ and $\mathcal{M}$, respectively. Assume that each BSS can transmit to no more than one user in a time slot, and thus we have $\sum_{m=1}^{M} x_{nm}(t)\le 1;\ \forall n\in\mathcal{N}$.

Let $P_n(t)$ denote the transmit power of BSS n at time slot t. Based on the binary power control assumption, each BSS either transmits with maximum power, i.e., P, or does not transmit. Let $G_{nm}(t)$ denote the channel gain between BSS n and CEU m at time slot t, consisting of path-loss, shadow fading, and small-scale fading. Then with the power of the additive white Gaussian noise (AWGN) N_0, the signal to interference and noise ratio (SINR) of the CEU m at time t based on non-coherent reception becomes

$$\gamma_m(t)=\frac{\sum_{n=1}^{N} G_{nm}(t)Px_{nm}(t)}{\sum_{j=1}^{N} G_{jm}(t)\left(\sum_{i\in\mathcal{M},i\neq m} Px_{ji}(t)\right)+N_0}. \qquad (2)$$

Hence, the achievable data rate of CEU m using Shannon theorem is

$$R_m(t)=B\log_2\left(1+\beta\gamma_m(t)\right), \qquad (3)$$

where β is related to the target bit error rate (BER), and given by [8] as $\beta=-1.5/\ln(5BER)$.

We consider two traffic types in our system, i.e. BE and VoIP. The sets of BE and VoIP users are denoted as $\mathcal{M}_1$ and $\mathcal{M}_2$, respectively, with $\mathcal{M}_1\cup\mathcal{M}_2=\mathcal{M}$ and $\mathcal{M}_1\cap\mathcal{M}_2=\varnothing$. Based on the different service requirements for each type of user, two different utility functions are defined to represent their satisfaction.

For a BE user, the satisfaction is assumed to depend on its average throughput. Hence, the utility function of BE user m is defined as a monotonically increasing function of the average throughput $\bar{R}_m(t)$ at time t

$$U_m(t)=U_{BE,m}\left(\bar{R}_m(t)\right);\ \forall m\in\mathcal{M}_1, \qquad (4)$$

where $\bar{R}_m(t)$ is estimated using an exponential filter as [9]

$$\bar{R}_m(t)=(1-\rho_{BE})\bar{R}_m(t-1)+\rho_{BE}R_m(t). \qquad (5)$$

The satisfaction of a VoIP user is assumed to depend on its service delay. Hence, the utility function for a VoIP user is defined as a monotonically decreasing function of its average queuing delay, which is given by

$$U_m(t)=U_{V,m}\left(\bar{d}_m(t)\right);\ \forall m\in\mathcal{M}_2, \qquad (6)$$

where $\bar{d}_m(t)$ is its average queuing delay at time t. We estimate $\bar{d}_m(t)$ through the approach proposed in [10]. Define $Q_m(t)$ as the queue size in bits at the end of time slot t, and $\alpha_m(t)$ as the instantaneous arriving bits at the end of slot t. With departure rate $R_m(t)$, the queue size is calculated by

$$Q_m(t)=Q_m(t-1)-\min\left\{R_m(t)T_s,Q_m(t-1)\right\}+\alpha_m(t-1), \qquad (7)$$

where T_s is the slot duration. Assuming that $Q_m(t)$ is ergodic, then with Little's Law the average delay can be estimated by $\bar{d}_m(t)=\bar{Q}_m(t)/\bar{\alpha}_m$, where $\bar{\alpha}_m$ denotes the time averaging arrival bits per slot, and $\bar{Q}_m(t)$ is the average queue size at time slot t. Similar to $\bar{R}_m(t)$ in (5), the average queue size is estimated by

$$\bar{Q}_m(t)=(1-\rho_V)\bar{Q}_m(t-1)+\rho_V Q_m(t). \qquad (8)$$

This in turn leads to the estimate of the average delay via

$$\bar{d}_m(t)=(1-\rho_V)\bar{d}_m(t-1)+\rho_V\bar{\alpha}_m^{-1}Q_m(t). \qquad (9)$$

Substitute (8) into (9), and the estimate of the average delay is ultimately expressed by

$$\begin{aligned}\bar{d}_m(t)=(1-\rho_V)\bar{d}_m(t-1)+\rho_V\bar{\alpha}_m^{-1}\big[Q_m(t-1)\\ -\min\left\{R_m(t)T_s,Q_m(t-1)\right\}+\alpha_m(t-1)\big].\end{aligned} \qquad (10)$$

III. UTILITY-BASED JOINT SCHEDULING AND POWER CONTROL

In this section, the maximum sum utility optimization problem is first formulated, and then a utility-based joint scheduling and power control algorithm is proposed for radio resource allocation.

A. Problem Formulation

Our objective is to maximize the system sum utility, so the objective function is formulated as

$$U(t)=\sum\nolimits_{m_1\in\mathcal{M}_1}U_{BE,m_1}\left(\bar{R}_{m_1}(t)\right)+\sum\nolimits_{m_2\in\mathcal{M}_2}U_{V,m_2}\left(\bar{d}_{m_2}(t)\right). \quad (11)$$

Note that $\bar{R}_{m_1}(t-1)$ and $\bar{d}_{m_2}(t-1)$ are known at time slot *t*. Hence, using Taylor expansion, to maximize (11) at time slot *t* is equivalent to maximize

$$\begin{aligned}\Pi(t)=&\sum\nolimits_{m_1\in\mathcal{M}_1}U'_{BE,m_1}\left(\bar{R}_{m_1}(t-1)\right)\bar{R}_{m_1}(t)\\&+\sum\nolimits_{m_2\in\mathcal{M}_2}U'_{V,m_2}\left(\bar{d}_{m_2}(t-1)\right)\bar{d}_{m_2}(t).\end{aligned} \quad (12)$$

Substitute (5) and (10) into (12), and let the CU control the service bit rate so that $R_{m_2}(t)T_s\le Q_{m_2}(t-1)$. Then with $Q_{m_2}(t-1)$ and $\alpha_{m_2}(t-1)$ known at slot t, we have $\Pi(t)$ as a function only of $R_m(t)$.

$$\begin{aligned}\Pi(t)=&\sum\nolimits_{m_1\in\mathcal{M}_1}\rho_{BE}U'_{BE,m_1}\left(\bar{R}_{m_1}(t-1)\right)R_{m_1}(t)\\&-\sum\nolimits_{m_2\in\mathcal{M}_2}\rho_V\bar{\alpha}_{m_2}^{-1}T_sU'_{V,m_2}\left(\bar{d}_{m_2}(t-1)\right)R_{m_2}(t).\end{aligned} \quad (13)$$

Note that the marginal utility functions $U'_{BE,m_1}(\cdot)$ and $U'_{V,m_2}(\cdot)$ are related to the scheduling weights or priorities, and thus play a key role in scheduling. Since $R_m(t)$ is related to $\mathbf{X}(t)$, $\Pi(t)$ turns out to be a function of $\mathbf{X}(t)$. Using $\Pi(\mathbf{X}(t))$ to represent $\Pi(t)$, (13) becomes

$$\Pi(\mathbf{X}(t))=\sum\nolimits_{m_1\in\mathcal{M}_1}\pi_{m_1}R_{m_1}(\mathbf{X}(t))+\sum\nolimits_{m_2\in\mathcal{M}_2}\pi_{m_2}R_{m_2}(\mathbf{X}(t)), \quad (14)$$

where π_{m_1} and π_{m_2} are fixed at time *t*, with

$$\begin{cases}\pi_{m_1}=U'_{BE,m_1}\left(\bar{R}_{m_1}(t-1)\right)\rho_{BE},\\ \pi_{m_2}=-U'_{V,m_2}\left(\bar{d}_{m_2}(t-1)\right)\rho_V\bar{\alpha}_{m_2}^{-1}T_s.\end{cases} \quad (15)$$

Ultimately, the optimization problem is mathematically formulated as

$$\begin{aligned}&\max_{\mathbf{X}(t)}\Pi(\mathbf{X}(t))\\&\text{s.t. 1) } R_{m_2}(\mathbf{X}(t))T_s\le Q_{m_2}(t-1),\forall m_2\in\mathcal{M}_2\\&\quad\ \ \text{2) }\sum\nolimits_{m=1}^{M}x_{nm}(t)\le 1,\forall n\in\mathcal{N}.\end{aligned} \quad (16)$$

That is, the optimization problem (16) becomes finding $\mathbf{X}^*(t)$ that maximizes $\Pi(\mathbf{X}(t))$ in (14) under the constraints 1) the instantaneous departure data size for VoIP users can be no more than the attainable waiting queue size, and 2) a BSS transmits to at most one CEU.

B. Algorithm Description

To solve the optimization problem in (16), a joint scheduling and power control algorithm is proposed in this section for the CoMP system.

We define the set of all feasible user schedules in each time slot as $\mathbb{X}(t)$. Assume *N* = 3, and CSI for all channels is perfectly known. Exploiting binary power control, then we have $(M+1)^3$ candidates in $\mathbb{X}(t)$ each time slot. In general, the complexity increases as the number of users per BSS increases. For a system with *M* users and *N* BSSs in the cluster, the complexity of the proposed joint scheduling and power control algorithm is $O\left((M+1)^N\right)$.

The algorithm starts with an empty user set, and assigns each BSS with the same maximum transmit power *P*. Then in each time slot, the algorithm does the exhaustive search of all the feasible user schedules in the set $\mathbb{X}(t)$ for the optimal user group $\mathbf{X}^*(t)$ that gives the largest $\Pi(\mathbf{X}(t))$. At the end of each time slot *t*, $\bar{R}_m(t)$, $\bar{d}_m(t)$, and $\bar{Q}_m(t)$ are updated based on $\mathbf{X}^*(t)$. The algorithm is outlined in Table I.

TABLE I. UTILITY-BASED JOINT SCHEDULING AND POWER CONTROL ALGORITHM

```
Initialization $P_n = P,\ \forall n\in\mathcal{N};\ \bar{R}_{m_1}(0)=0,\ \forall m_1\in\mathcal{M}_1;$
    $\bar{d}_{m_2}(0)=0,\ \bar{Q}_{m_2}(0)=0,\ \forall m_2\in\mathcal{M}_2$ at time slot $t=0$
In each time slot $t$
    For each schedule $\mathbf{X}(t)$ in $\mathbb{X}(t)$
        Compute $\Pi(\mathbf{X}(t))$ using (12)
    End
    $\mathbf{X}^*(t)=\arg\max_{\mathbf{X}(t)\in\mathbb{X}(t)}\Pi(\mathbf{X}(t))$
    For each user $m_1\in\mathcal{M}_1$
        Update $\bar{R}_{m_1}(t)$ using (5)
    End
    For each user $m_2\in\mathcal{M}_2$
        Update $\bar{d}_{m_2}(t),\ \bar{Q}_{m_2}(t)$ using (10), (8)
    End
    Advance $t$
End
```

IV. SIMULATION RESULTS

We focus on the downlink of flat fading channel in a cellular system, with carrier frequency of 2GHz. Assume path loss with $L(d)=128.1+37.6\log_{10}d$ in dB [4], where d is the distance in km, and log-normal shadowing with zero-mean and 10 dB standard deviation. A cluster of three BSSs is taken into account. The cell radius is set to 500m. A number of users are uniformly allocated in the cell-edge area of the CoMP cluster, where the long term channel gain is under the threshold -100 dB. 1000 independent trials are evaluated by Monte-Carlo simulation under various numbers of cell-edge users per cluster.

We randomly drop the two different types of users in the CoMP network, i.e., BE users and VoIP users, with the probability of 50% for each. The target BER for data transmission is prescribed as 10^{-5}. We then assume the full-buffer traffic model for BE users with the utility function defined as

$$U_{BE,m_1}\left(\bar{R}_{m_1}(t)\right)=\ln\left(\bar{R}_{m_1}(t)\right). \tag{17}$$

For the VoIP users we consider a VoIP traffic model with packet inter-arrival time of 5ms, and packet size of 10 bytes. Regarding QoS requirements, we set the maximum queuing delay to be 15ms. VoIP calls for users experiencing packet delays greater than the maximum delay result in call outage, and these users are redropped at another allocation. Hence, the utility function is defined as

$$U_{V,m_2}\left(\bar{d}_{m_2}(t)\right)=-\frac{\log_{10}\delta_{m_2}}{2\breve{d}_{m_2}}\left(\bar{d}_{m_2}^2(t)-\breve{d}_{m_2}^2\right), 0<\delta_{m_2}<1, \tag{18}$$

where $\breve{d}_{m_2}$ is the maximum allowable queuing delay for VoIP users; $\delta_{m_2}=0.1$ is a constant, chosen to balance the priorities of different types of users [11].

Recall (13), the best-effort users with lower average throughput can get higher priority in the scheduling if $U_{BE,m_1}(\cdot)$ is chosen as in (17). Similarly, with $U_{V,m_2}(\cdot)$ defined as in (18), the VoIP users will gain higher priorities if they experience larger delays. In fact, the marginal utility function of (18) turns out to be the largest-weighted-average-delay-first (LWADF) scheduling [5], i.e., users in the queue experiencing the largest average delay have the highest priorities and should be served first in each round of scheduling. Besides, ρ_{BE} and ρ_V also play an important role in balancing priorities of the two types of users in scheduling, and are prescribed as $\rho_{BE}=0.01$ and $\rho_V=0.05$ respectively.

The average sum utility is evaluated as the assessment of the proposed utility-based joint scheduling and power control algorithm, named C-UBPC. Meanwhile, as a special case of the proposed utility-based joint scheduling and power control algorithm, another algorithm with the power of all BSSs in the cluster always turned on, named C-UB, is also considered and assessed. Jain's Fairness Index (JFI) [4] of utilities is investigated as a fairness measure of user satisfaction based on users' average utility

$$\mathrm{FI}=\left(\sum_{m=1}^{M}\bar{U}_m\right)^2\Big/\left(M\sum_{m=1}^{M}\bar{U}_m^2\right). \tag{19}$$

Furthermore, we also show the resulting average call outage ratio for the VoIP traffic, and the average user throughput for the BE users, respectively. As comparison, three other algorithms are considered:

1) Coordinated proportional-fair scheduling without power control (C-PF): The algorithm is aimed to maximize the proportional throughput-fair index [5] with joint transmission, but the differentiations of diverse traffic models are not considered.

2) Utility-based scheduling without joint transmission or power control (NC-UB): Similar to the proposed C-UB algorithm, but no joint transmission is supported.

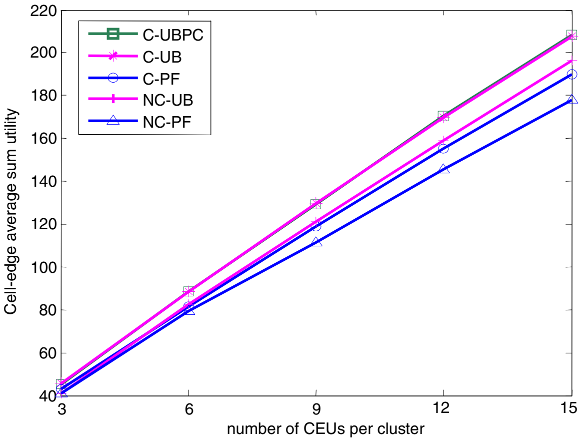

Figure 2. Average sum utility vs. number of CEUs per cluster

3) Proportional-fair scheduling without joint transmission or power control (NC-PF): Similar to *1)* but no joint transmission is supported either.

Fig.2 shows the cell-edge average sum-utility of the algorithms considered in this paper with respect to the number of cell-edge users per cluster. It can be seen that with joint transmission the proposed C-UBPC and C-UB algorithms achieve the highest aggregate utility. Additionally, even without joint transmission, the NC-UB algorithm still achieves slightly better performance than C-PF algorithm by exploiting different utility functions. The C-UBPC algorithm with binary power control achieves similar performance as the C-UB algorithm. However, there is a power saving in the C-UBPC algorithm based on the simulation results, with the average number of BSS turned on as 1.96-2.46; while in the C-UB algorithm, the number of BSS turned on is always 3. The NC-PF algorithm yields the lowest utility given neither joint transmission nor utility differentiations.

To further improve our understanding of joint transmission and utility-based scheduling in this paper, in Fig.3, Fig.4, we plot the average throughput for BE users, and the average VoIP call outage ratio, respectively. We can see that as the traffic gets heavier, for all the algorithms the average BE throughput decreases, and VoIP call outage increases within the prescribed QoS call outage, respectively. Nonetheless, under all the traffic conditions, by taking advantage of good diverse QoS provisioning through exploiting utility functions, the utility-based algorithms achieve relatively better performance than the proportional fair algorithms, i.e., the C-PF and NC-PF algorithms.

As seen from Fig.3 and Fig.4, compared with the NC-UB algorithm with no joint transmission supported, the proposed C-UBPC and C-UB algorithms achieve higher average BE throughput, and meanwhile, improve the VoIP service with much lower average call outage. From Fig.3, we can see that with binary power control, the C-UBPC algorithm has slightly better performance in terms of the average BE throughput while achieving a better power saving, compared to the C-UB algorithm without power control.

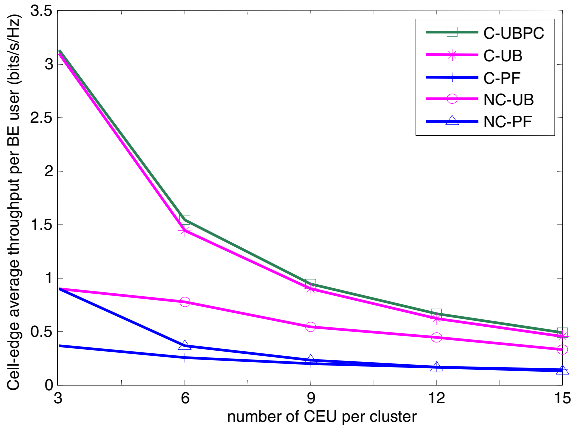

Figure 3. Average throughput per BE user vs. number of CEUs per cluster

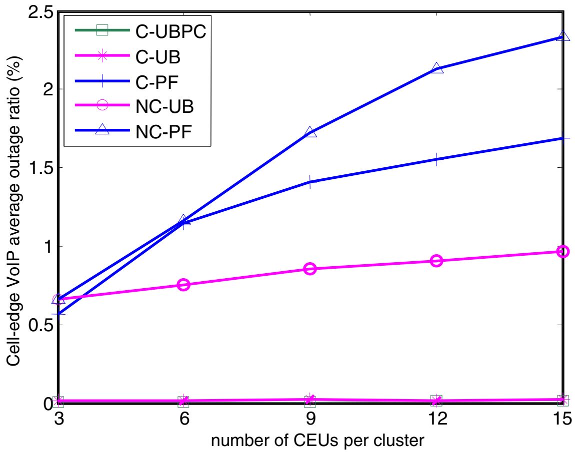

Figure 4. Average VoIP outage ratio vs. number of CEUs per cluster

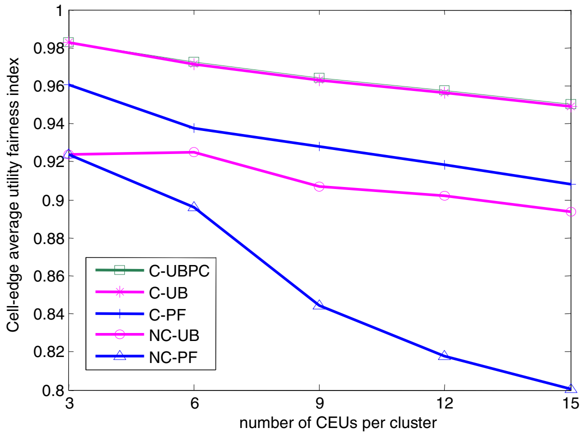

Figure 5. Utility JFI vs. number of CEUs per cluster

The utility JFIs of the five algorithms are plotted in Fig.5. It shows that with diverse utility functions and joint transmission, the proposed C-UBPC and C-UB algorithms achieve the best user utility fairness. By utilizing joint transmission, the C-PF algorithm also achieves higher utility fairness by contrast to the NC-UB and NC-PF algorithms.

V. CONCLUSIONS

In this paper, we consider the downlink of a CoMP cluster with three neighboring BSSs. A utility-based joint scheduling and power control algorithm is proposed in order to maximize the cell-edge sum utility of the CoMP system with mixed VoIP and best-effort traffic. First, we mathematically formulate the objective function with respect to the average throughput and queuing delay for joint transmission and power control. Then a resource allocation algorithm is developed to jointly assign a group of users in the cluster. The simulation results demonstrate that the proposed algorithm provides a significant improvement in terms of system sum utility and user fairness. The results also show that the algorithm increases the average throughput of best effort user by greater than 45% and decreases the average call outage of VoIP user by greater than 98%, compared to traditional scheduling schemes without joint transmission and diverse QoS provisioning.

The results in this paper focus on flat fading channel in a single cluster, but we do not consider the complexity introduced by joint scheduling. In future work, joint scheduling and power control problems in multi-subchannel systems with multi-cluster interference will be addressed, as well as less complex algorithms.

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