Traffic-aware Utility based QoS Provisioning in OFDMA Hybrid Smallcells

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***Abstract*—Smallcell technology is gaining significance as part of the next-generation cellular systems due to their performance benefits in terms of increased network capacity and improved indoor and local coverage. Hybrid access smallcells, which provide service to both indoor as well as neighboring users, adopt adhoc policies to guarantee performance benefits to indoor home users in the presence of external neighboring users. Such policies must be able to stabilize user queues as well as to provision performance benefits in terms of delay and throughput, especially for the indoor users. As a result, classification of user data in terms of traffic type and user type is required to effectively achieve the differentiated QoS performance.**

In this paper, a traffic-aware utility function is proposed, which takes into account for the user's priority index and traffic characteristics to efficiently provide differentiated QoS benefits to users served under an OFDMA hybrid smallcell. The problem of the traffic-aware utility based scheduling under power constraints is posed as an optimization objective and an optimal algorithm for the scheduling problem is presented. The results show that the proposed scheme achieves QoS performance benefits in terms of throughput and delay.

***Index Terms*—Smallcells, Hybrid access, QoS, Heterogeneous traffic, Utility.**

I. INTRODUCTION

THE tremendous advances in wireless technologies has led to the proliferation of Hi-Tech smartphones, tablet computers that consume large amount of multimedia and data traffic in addition to the traditional voice traffic in cellular networks. To satisfy the rapidly growing capacity needs, the existing cellular infrastructure that consists of a single macrocell layer is being overlaid with several layers of small base stations ranging from picocells, microcells, femtocells. These smallcells increase the network capacity through the spatial reuse of spectrum and in addition, improve the indoor cellular coverage. [2]. These are average to low powered devices connected to the operator's core network through a proprietary or public backhaul.

The application of smallcells to a targeted area such as enterprise, private buildings result in unique access control policies to handle different user types. Smallcells access control policies can be broadly classified as

- *Open access* policy: Smallcells can service all mobile users of the carrier within range.
- *Closed access* policy: Smallcells reserve exclusive access for pre-registered mobile users, also called Smallcell users (SUs).
- *Hybrid access* policy: Smallcells utilize adhoc schemes to achieve QoS guarantees for the SUs in the presence of unregistered external users (EUs).

Although, the open access policy offers the largest increase in the network capacity, it can degrade the QoS performance of SUs served under the smallcells. The QoS degradation is particularly large when the number of EUs increases or when the EUs are running bandwidth-hungry applications. The closed access approach is capable of providing better QoS performance for the SUs but the SU performance can also be significantly affected if there are nearby EUs that cause strong interference to the smallcell network. Therefore, a hybrid access scheme that can provide differentiable service to SUs and EUs is required to achieve the best of both worlds.

A. Related Work

Hybrid access schemes have been investigated before in the literature. The authors in [3] consider hybrid access in femtocells where they propose a fixed probability p for EUs to be able to connect to a femtocell based on the computation of the carrier to interference (C/I) ratio at the location of the EUs. In [12], the authors propose a hybrid access scheme for OFDMA smallcells where a limited amount of subchannels v is reserved for EU access. Although, the outage probability is shown to notably decrease for EUs in this scheme, increasing v can affect the throughput achieved by SUs. In addition, lower outage probability does not necessarily equal QoS performance of both SUs and EUs. Further work has been conducted under hybrid access approach, for eg., in [15], the authors propose an adaptive access control strategy based on the average cellular user density. It is shown that the ergodic rate for EUs is notably increased under low user-density case, whereas under the high user-density case, the rate gain for EUs is not significant.

Unfortunately, the above hybrid access schemes fail to consider the nature of the higher layer traffic in performing scheduling and access control for smallcells. One of the fundamental performance metric is network stability which

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guarantees the queue size to be bounded for all packet arrivals within the capacity region. Scheduling policies like Maximum Delay Scheduling can stabilize the queues for admissible arrival rates. At the same time, these policies can result in poor delay performance and unfair allocation for the SUs if the EU traffic is bursty.

The objective of the paper is to propose and evaluate an optimal scheduling scheme for QoS provisioning for hybrid smallcells. We summarize the main contributions of our work as follows:

- We define a specific system model for OFDMA based hybrid smallcell and review some existing cross-layered scheduling approaches.
- We propose a cross-layered traffic-aware utility function that provisions QoS for the users under smallcells.
- We present an optimal scheduling algorithm to perform scheduling using utility as the cost function.
- We provide results from simulations highlighting the performance gains obtained through our scheduling policy.

The rest of this paper is organized as follows. In Sec. II, the system model for the OFDMA based hybrid smallcells is presented and a brief review on some existing scheduling disciplines are discussed. In Sec. III, the utility function is first presented and the problem of constrained QoS scheduling using traffic-aware utility is posed as an optimization framework. An optimal scheduling algorithm for the optimization framework is provided. Sec. IV illustrates the performance gains of the proposed scheme through simulation results. Finally, the main conclusions are summarized in Sec. V.

II. SYSTEM MODEL

The time-varying, bursty and location-dependent nature of the wireless channel makes it challenging to achieve scheduling with QoS performance. Therefore, interaction across the layers can enable exchange of information in order to make scheduling decisions to provide effective QoS. Particularly, the exchange of system dynamics such as channel conditions, location, queue state, application layer requirements are crucial in achieving QoS satisfaction. Under such a setup, the time is slotted and the channel is assumed to be unvarying for the slot length. At the beginning of each slot, the scheduler obtains the channel gain from the lower layers through user feedback. Using this information, the data rates achievable and power required for the user in the time slot is determined. Based on these parameters, several scheduling algorithms perform resource scheduling to achieve the QoS objectives.

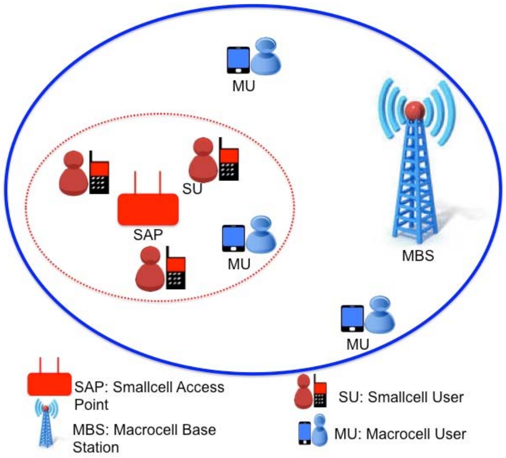

Fig. 1. Network topology of a hybrid smallcell overlaid in a macrocell coverage region

The downlink of an OFDMA hybrid smallcell network overlaid on a macrocell coverage area is considered as shown in Fig. 1 with a smallcell access point (SAP) serving $\mathcal{N}$ users $\{1, 2, ...N\}$. Out of this, $\mathcal{F}$ represents the set of all SUs $\{1, 2, ...F\}$ and $\mathcal{E}$ represents the set of all EUs $\{1, 2, ...E\}$, and therefore, $\mathcal{N} = \mathcal{F} \cup \mathcal{E}$. B represents the total system bandwidth consisting of K subcarriers. Hence the bandwidth of each subcarrier is represented as $\Delta B = \dfrac{B}{K}$. The time is slotted and each slot has a duration of T_s equivalent to the coherent time of the channel. $h_{n,k}$ represents the channel gain of user n transmitting on subcarrier k. $p_{n,k}$ represents the required power for user n to transmit on subcarrier k for a given bit error rate (BER). The noise power over a subcarrier is represented as σ^2. If the SNR gap is defined as $\beta = -1.5/\ln(5 * BER)$, then the transmission rate for user n on subcarrier k is given as

$$\mu_{n,k} = \Delta B \, log(1 + \beta \frac{|h_{n,k}|^2 p_{n,k}}{\sigma^2}). \tag{1}$$

Each user can be assigned several subcarriers with the constraint that the same subcarrier cannot be assigned to different users in the same slot. This is represented by the binary variable $s_{n,k}(t)$ indicating whether the subcarrier k is assigned to user n or not in slot t. Hence, the subcarrier assignment constraint is given as $\sum_{n=1}^{N} s_{n,k}(t) = 1$. Therefore, the data rate $\mu_n(t)$ assigned to user n in slot t is given by the equation

$$\mu_n(t) = \sum_{k=1}^{K} s_{n,k}(t) \mu_{n,k}(t). \tag{2}$$

The SAP has queues corresponding to each of the n users it serves. The arrival process $\Lambda_n(t)$ represents the number of packet arrivals at queue n in time t. Here, $\lambda_n \overset{\Delta}{=} E[\Lambda_n(t)]$ and the arrival rate vector is given as $\overrightarrow{\lambda} = (\lambda_1, \lambda_2, ...\lambda_N)$. $\overrightarrow{Q(t)} = (Q_1(t), Q_2(t), ...Q_N(t))$ represents the Queue Length vector. The Waiting Time of a packet in the queues is represented by the vector $\overrightarrow{W(t)} = (W_1(t), W_2(t), ...W_N(t))$. The queue evolves according to the Discrete Time Queueing Law as

$$Q_n(t+1) = max(Q_n(t) - \mu_n(t), 0) + \Lambda_n(t). \tag{3}$$

By Little's Law, the waiting time of user n in slot t is given by

$$W_n(t) = \frac{\overline{Q_n}(t)}{\lambda_n}. \tag{4}$$

Our objective is to stabilize the queues of all SUs and EUs when the arrivals are inside the capacity region. In addition, we want to additionally offer QoS performance for different SU traffic types in terms of throughput and delay. These objectives together present an interesting case of QoS provisioning. Scheduling policies such as proportionally fair (PF) scheduling, Modified Largest Weighted Delay First (M-LWDF) are not suitable in the presence of heterogeneous traffic since they do not provide bounded delay performance. The EXP rule proposed in [8] is shown to offer improved QoS performance in terms of throughput and delay over M-LWDF and PF scheduling schemes when there is a mixture of real-time and non-real-time users in the system. Another popular approach to QoS scheduling is the utility based approach. Scheduling rules based on maximizing utility, which represents the amount of satisfaction that can be obtained by scheduling a resource for a user, have been proposed in [10], [11], [6]. The utility functions here are defined as decreasing functions of the packet delay in the queue. In [10], [11], [5], although the scheduling rule is shown to achieve throughput optimality, the utility function does not provide strict bounds on delay. In addition, many of the above policies only consider subcarrier allocation without any power constraints. Since smallcells are limited by hardware on the total transmit power as well as by the interference they cause to the external network, power constraints become significant in our problem.

III. TRAFFIC-AWARE UTILITY BASED QOS PROVISIONING

The need for achieving diverse QoS requirements for heterogeneous traffic classes calls for an improved scheduling rule that can deal with the unique attributes of these traffic. Especially, under the hybrid smallcell setup, the delay performance for SUs must be bounded in the presence of EUs. The authors in [13], [14] show that if the message size of users exhibit heavy-tail characteristics with an index α, then the delay has an infinite mean and infinite variance for $\alpha < 1$ and $\alpha < 2$ respectively. The authors also propose a modified maximum weight-α scheduling policy that allocates channels for users based on queue size raised to the power α in order to guarantee bounded delay mean and variance.

In this paper, we propose a novel traffic aware utility based scheduling policy for hybrid smallcells in order to effectively provision QoS. The scheduler is fed with channel state information and traffic information in order to make scheduling decisions at every time slot T_s based on the computation of the utility function. The utility function associated with the allocation of subcarrier k to user n is defined as

$$U_{n,k}(t) = \gamma_n W_n^{\alpha}(t) \mu_{n,k}(t), \qquad (5)$$

where $\gamma_n = \dfrac{a_n}{\bar{r}_n}$. Here, a_n represents the *priority index* and can be tuned for SUs and EUs to achieve the required QoS for each user type. $\bar{r}_n$ represents the average data rate achieved for user n. α is the exponent of the average waiting time W_n for packets in queue n. This is the *traffic coefficient* that takes unique values for different traffic classes.

A. Intuition

The utility function defined in Equation 5 is aimed at achieving the heterogeneous objectives of QoS perceived by different user types. For the real-time users, the delay performance is critical and they have a strict deadline on the waiting time of the packet. For CBR user types, the throughput as well as delay performance are important. By using suitable values for the *traffic coefficient* α, different utility function shapes can be obtained for different users types. In addition, in order to provide fair allocation for SUs in the presence of bursty EU traffic, the parameter a_n can be set to a higher value for SUs. It can be observed that by setting the value of α to 1 for all traffic types, the utility function shows similarity to the M-LWDF rule. Therefore, for homogeneous best effort traffic classes, it can be easily established that the traffic-aware utility based scheduling is *throughput optimal.*

B. Power Constrained Utility based Scheduling

The subcarrier allocation with power constraints using the proposed utility function is performed based on the following optimization objective:

$$\max_{S} \qquad \sum_{n=1}^{N} \sum_{k=1}^{K} U_{n,k}(t)\, s_{n,k}, \qquad (6)$$

$$\text{subject to} \quad \sum_{n=1}^{N} s_{n,k} = 1 \;;\; S_i \neq S_j \;\forall i,j \in N \,\text{and}\, i \neq j \;;$$

$$s_{n,k} \in \{0,1\};$$

$$\sum_{n=1}^{N} p_{n,k}\, s_{n,k} \leq P_s \;; \quad \sum_{n=1}^{N} \sum_{n=1}^{N} p_{n,k}\, s_{n,k} \leq P_{tot}, \qquad (7)$$

where the optimization variable *S* is the subcarrier allocation matrix with order $N \times K$. $S_i = \{s_{i,1}, s_{i,2}, ..., s_{i,K}\}$ is the set of subcarriers allocated to node i, P_s is the maximum allowed subcarrier power and P_{tot} is the total transmission power available at the SAP.

C. Minimal Algorithm for Utility-based Subcarrier Assignment

The above optimization problem can be classified into the Multiple Choice Knapsack Problem (MCKP) with additional constraints on the maximum weight of each item. The MCKP is defined as a binary knapsack problem with additional disjoint multiple-choice constraints [9]. The constraints are such that the items are divided into multiple classes and only one item is to be selected from each of the classes. The MCKP has been shown to be NP-hard since the KP problem needs to be solved in the process, nevertheless, through dynamic programming it is shown to be solved in pseudo-polynomial time [4]. A minimal algorithm for solving MCKP is presented in [7]. First, the integrality constraint $s_{n,k} \in \{0,1\}$ is relaxed to $0 \leq s_{n,k} \leq 1$ to obtain the Linear Multiple-Choice Knapsack Problem (LMCKP). A simple partitioning algorithm is proposed for solving the LMCKP and obtaining a feasible solution. Using the initial solution, dynamic programming is used to solve MCKP. The partitioning algorithm can compute in $O(n)$ time, a small subset of items called as the core of classes, to be considered for the optimal value. New classes are then added to the core by need.

Applied to the utility-based subcarrier assignment problem, the classes correspond to the set of subcarriers $\mathcal{K}$. Each item corresponds to a node n to be assigned for a subcarrier k. In our problem, we have an additional constraint in the form of maximum per-subcarrier power. Only one node among N nodes is assigned for subcarrier k given that it satisfies the global and local power constraints. $U_{n,k}(t)$ is the profit while $p_{n,k}(t)$ is the weight. The output of the algorithm is the matrix S of dimension $N \times K$ with assignment indicators $s_{n,k}$. The algorithm is presented in Algorithm 1. The procedure partitionalgo() provides an LP-optimal solution for the relaxed LMCKP problem. reduceclass() uses upper-bound computation, dominance tests to prune nodes for each subcarrier while reduceset() checks and updates the $CurrentBestSolution$ if a state improves the lower-bound. The computational complexity of the one-dimensional MCKP is shown to be $O(n + P_{tot} \sum_{R_k \in C} num_k)$ where R_k is the reduced set of subcarriers. As a result, the algorithm solution has linear time for a small core and pseudo-polynomial time when the core is large. When the number of users is not considerably large, it can also be shown that performing adaptive modulation combined with subcarrier assignment does not increase the algorithm performance significantly. This is a reasonable assumption since smallcells, on an average, support few tens of users.

```
input : Profit matrix $U$ of dimension $N \times K$, Weight matrix $p$ of dimension $N \times K$
$\{a, b_k, s_{b_a,a}, s_{b'_a,a}\} \Leftarrow$ partitionalgo($U, p, P_{tot}$);
$a :=$ fractional subcarrier, $\{b_k\} :=$ LP Optimal soln., $s_{b_a,a}, s_{b'_a,a} :=$ fractional variables in $a$;
Calculate $\lambda = (U_{b'_a,a} - U_{b_a,a})/(p_{b'_a,a} - p_{b_a,a})$;
Calculate $\lambda_k^+ = \max_{n \in N, p_{n,k} > p_{b_k,k}} (U_{n,k} - U_{b_k,k})/(p_{n,k} - p_{b_k,k})$, $k = 1, ..., K$, $k \neq a$;
Calculate $\lambda_k^- = \min_{n \in N, p_{n,k} < p_{b_k,k}} (U_{b_k,k} - U_{n,k})/(p_{b_k,k} - p_{n,k})$, $k = 1, ..., K$, $k \neq a$;
Gradients $L^+ = \{\lambda_k^+\}$ and $L^- = \{\lambda_k^-\}$ for $k = 1, ..., K, k \neq a$;
sortascen($L^+$);
sortdescen($L^-$);
Current Best Solution $z := 0$; Initial Core $C := N_a$;
Current Set of States $Y_C :=$ reduceclass($N_a$);
Vectors in $Y_C$ represented by states $(\theta_k, \pi_k, \nu_k)$;
$\theta_k := \sum_{k \in C} p_{y_k,k} + \sum_{k \notin C} p_{b_k,k}$;
$\pi_k := \sum_{k \in C} U_{y_k,k} + \sum_{k \notin C} U_{b_k,k}$;
$\nu_k :=$ partial representation of vector $\vec{y_i}$;
repeat
    reduceset($Y_C$);
    if ($Y_C = \emptyset$) then break ;
    Choose $nextsubcarrier\, k$ from $L^+$
    $R_k :=$ reduceclass($k$) if $|R_k| > 1$ then
    addclass($Y_C, R_k$) ;
    repeat above steps for $L^-$
    reduceset($Y_C$);
    if ($Y_C = \emptyset$) then break ;
until forever;
Find optimal allocation S;
```

Algorithm 1: Minimal Algorithm for constrained utility-based subcarrier assignment

IV. PERFORMANCE EVALUATION

The performance of the constrained utility-based scheduling is evaluated where the utility function is modeled using OFDMA system parameters and queue models using MATLAB and the minimal algorithm routine is implemented in C. The traffic types modeled for our problem are as follows:

A. *Traffic Modeling*

The users served under SAP are grouped into three classes using three different queuing disciplines as in [1]. These classes are as follows:

- Constant Bit Rate (CBR) Users: These users have deterministic behaviors, and are modeled by a D/G/1 queuing system. The average waiting time is calculated as:

$$W_{CBR,n} = \frac{\lambda_{CBR,n} \sigma^2_{CBR,\overline{X_n}}}{2(1 - \lambda_{CBR,n} \overline{X_n})}, \qquad n \in N, \tag{8}$$

  where $\lambda_{CBR,n}$, $\sigma^2_{CBR,\overline{X_n}}$ and $\overline{X_n}$ are the mean arrival rate, the variance of the service time and the mean service time respectively and $\overline{X_n} = E[1/\mu_n]$ for OFDMA.
- Video-Streaming Users: These users are modeled using *Gamma Distribution* with shape parameter s and a G/G/1 queuing system where the average waiting time is

$$W_{Vid,n} = \frac{\lambda_{Vid,n}(\sigma^2_{Vid,\overline{X_n}} + s/\lambda_{Vid,n})}{2(1 - \lambda_{Vid,n} \overline{X_n})}, \quad n \in N. \tag{9}$$

- Best-Efffort (BE) Users: The BE users can be modeled using an M/G/1 queueing system where the average queue waiting time is expressed as:

$$W_{BE} = \frac{\lambda_{BE,n}(\sigma^2_{BE,\overline{X_n}} + \sigma^2_T)}{2(1 - \lambda_{BE,n} \overline{X_n})}, \qquad \forall\, m. \tag{10}$$

  where σ^2_T is the variance of the inter-arrival time and $\rho_{BE} = \overline{\lambda_{BE}/X_m}$ is the utilization.

B. *Simulation Setup*

We simulate a smallcell with an SAP serving N users. All users experience i.i.d Rayleigh fading and the required power corresponding to a given BER. The system parameters considered are shown in Table I. We have 5 users from each traffic class described in the previous section with a mix of SUs and EUs. The arrival rates of CBR users are randomly distributed with range $75 - 125$kbps. Video-Streaming users have arrival rates randomly distributed with range $175 - 200$kbps. The shape parameter for Video-Streaming user is 3.066.The BE users have randomly distributed arrival rates within range

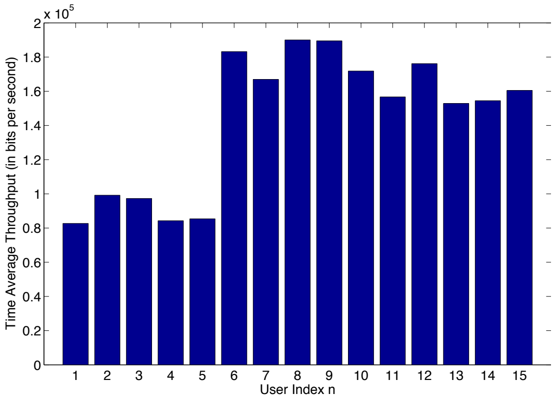

Fig. 2. Throughput performance under Traffic-aware Utility based Scheduling

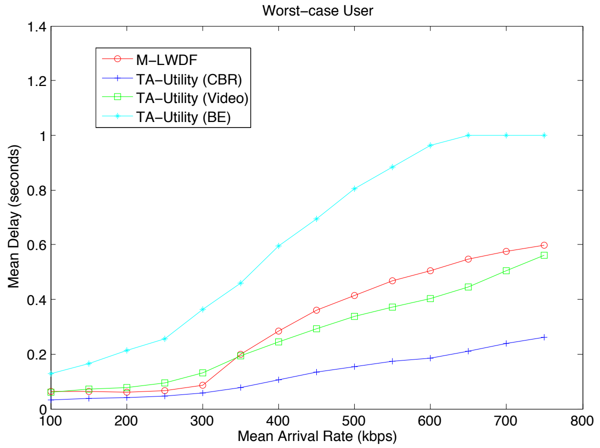

Fig. 3. Mean Delay performance of worst-case user

$150 - 180$kbps. The maximum delay allowed for CBR and Video users are fixed $80ms$, $150ms$ respectively. In each slot, the utility and power matrices, the global and local power constraints are computed and fed as input to the algorithm. The output of the algorithm is the subcarrier assignment matrix S. The entire simulation sequence is run for 1500ms. Initial results for the traffic-aware utility(TA-Utility) based scheme are presented in this section.

Fig. 2 shows the time average throughput achieved by the users. The fairness can be adjusted between the SUs and EUs in order to provide higher throughput for SUs. Fig. 3 presents the mean delay vs arrival rate performance of our solution compared with the M-LWDF scheme. It is clear that the TA-utility scheme achieves lower and bounded mean delay for delay-sensitive traffic types of CBR and $Video$ compared to the M-LWDF scheme for arrivals within the capacity region. The BE traffic experiences large delays compared to M-LWDF scheme but this is still acceptable due to BE's elastic nature.

V. CONCLUSIONS

In this paper, the problem of QoS provisioning in hybrid smallcells with SUs and EUs has been considered. The need for an improved scheduling to provide stability and QoS performance in the presence of heterogeneous traffic has been explained. A novel traffic-aware utility maximization approach under power constraints has been proposed and is posed as an optimization objective. In order to obtain the optimal solution, a minimal algorithm that results in a minimal core of allocation vectors is presented. In the end, the performance of the proposed scheme is illustrated. The proposed work can be considered as a framework in order to design efficient admission control algorithms in a hybrid smallcell network. Further proof of stability for the proposed scheme through network control techniques can establish the feasibility of the scheme for other traffic types.

TABLE I
SIMULATION PARAMETERS

System Bandwidth	1.92MHz
Number of Subcarriers	64
Subcarrier Bandwidth	30KHz
BER Required	10^{-3}
Max. SAP Tx. Power	$1W$
Max. subcarrier Tx. Power	$0.05W$
Total Number of Users	15
Slot Length	10ms

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