

Macrocell batch resource allocation for a co-channel macrocell/femtocell network

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Abstract This research work proposes an interference mitigation strategy that adjusts the maximum transmit power of femtocell base stations so as to reduce the aggregate cross-tier interference received by nearby macrocell users. Most of the existing research works considered resource allocation and interference avoidance separately but in this work, both are investigated together. A resource block allocation strategy which ensures that each user served by the macrocell or femtocell base station receives a fair share of the resource blocks available in the serving cell is discussed in this work. In the case of femtocell, a non-linear optimization model is developed to maximize the total cell throughput. The optimisation process comprises of two parts, channel allocation and power allocation, which are treated separately. Simulation results show that the proposed scheme can increase considerably the average macrocell throughput in an interference-prone multilayer wireless network as the case of macro-femto cellular networks.

Key words Femtocell, macrocell, interference, co-channel

1. Introduction

In conventional cellular networks, network operators manage base stations under the control of trained technical staff. However, the next generation of cellular networks will comprise of some base stations that will be managed by users. One type of a user-managed base station is the femtocell. A femtocell is a small size, low power home base station that works in the licensed frequency band and backhauls data through a dedicated broadband gateway (DSL/Ethernet etc) to the cellular operator network. The femtocell brings various benefits to both consumers and operators, such as enlarged indoor coverage, enhanced system capacity, improved quality of service (QoS), and reduced capital and operation expenses.

However, the success of co-existence of femto and macrocell would depend on automatic co-ordination of radio resource distribution between macrocell and femtocell base stations. This is because femtocells are deployed without prior network planning which could cause large interference and possibly result in the depreciation of the overall performance of the macrocell network.

The rest of this paper is organised as follows: Section 2 contains related works. Our proposed batch resource allocation scheme for macrocell base stations, and optimisation model for femtocell base stations are presented in details in Section 3. Simulation results are discussed in Section 4 while conclusions are summarised in Section 5.

2. Related works

Various interference mitigation schemes using femtocell base station power level setting have been investigated. The basic method of transmit power setting is the fixed power setting scheme, which is the current practice in various femtocell base stations [1]. This method has the advantage of simplicity and ease of implementation since the transmit power is preconfigured. However, the non-adaptive nature of this scheme is a disadvantage, since it is difficult for it (femtocell base station) to adapt to changes in the RF conditions of surrounding macrocells and this could lead to large interference. In order to mitigate interference, Li and Sousa [2] used an optimization method to periodically update the pilot power configuration of femtocell base stations based on the RF condition of the network. In [3], Claussen et al developed an algorithm for the self-configuration of transmit power level of femtocell base stations based on the measured received signal level from the macrocell base station. Li et al in [4] used downlink power control to address the co-channel interference in a network of macrocell femtocell overlay. In [5], Ashraf et al discussed how to update the femtocell's pilot transmit power which serves to balance the user load amongst co-located femtocells as well as minimize the coverage hole and pilot transmit power. The authors in [6] proposed both open-loop and closed-loop power control strategies that adjust the maximum transmit power of femtocell users in order to suppress the cross-tier interference at a macrocell base station.

All these techniques, however, have not adequately catered for the interference caused to nearby macrocell users. This is majorly because the femtocell base station does not usually have information about the future network resource utilisation plan of the macrocell, which makes it difficult to achieve effective interference coordination at the femtocell base station.

In this paper, we model a time and frequency domain scheduler to proportionally allocate network resources to macrocell users in batch in such a way that the femtocell base station becomes aware of future resource usage of nearby macrocell users. We also develop an optimization model for throughput maximization at the femtocell.

3. Proposal of batch resource allocation

3.1 MACROCELL

Fig. 1(a) and Fig. 1(b) are two ways in which a macrocell user may be scheduled on the time-frequency space. The shaded blocks in both figures represent a macrocell user's resource schedule. Considering Fig. 1(a), a nearby femtocell base station sees the resource allocation of the macrocell user to be random both in the frequency and time space. In this random scheduling scheme, it is difficult to achieve effective interference coordination at the femtocell. On the contrary, Fig. 1(b) comprises of consecutive shaded blocks along the time axis which shows that the user's schedule follows an organised fashion in the time direction. In this case, a femtocell base station can predict accurately, the resource blocks that will be used by a nearby macrocell user at a given time and hence mitigate interference on such resource blocks.

This paper follows the resource allocation pattern of Fig. 1(b). Our network scenario is based on the LTE standard and we specifically consider a two-tier orthogonal frequency division multiple access (OFDMA) cellular network based on IEEE 802.16e assumptions. The downlink scenario is considered where the system bandwidth, W , comprises of a set of resource blocks denoted as $\mathcal{N}$. The macro cell base station network has a layout of one ring, i.e 7 cells with each cell comprising of 3 sectors as illustrated in Fig. 2. The macro-

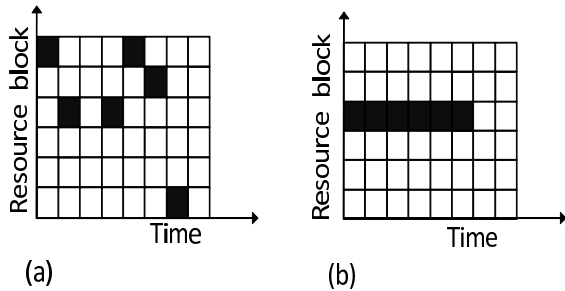


Figure 1 macrocell resource allocation

cell users are classified into two categories, cell edge users and cell centre users respectively. We define two throughput targets namely, cell edge throughput target, $\bar{R}_{\text{target,e}}$, and cell centre user throughput target, $\bar{R}_{\text{target,c}}$.

Assuming that the set of macrocell users in the macrocell base station is denoted as $\mathcal{M}$, then in each transmission time interval, the set of users to be scheduled on unallocated resource blocks is selected according to the following algorithm:

(1) initialize parameters:

$$\mathcal{U} = \emptyset, \quad (1)$$

$$\mathcal{V} = \emptyset, \quad (2)$$

$$\mathcal{B}_m = \emptyset, \quad \forall m \in \mathcal{U}, \quad (3)$$

$$K_m = 0, \quad \forall m \in \mathcal{U}, \quad (4)$$

$\mathcal{U}$ is a set of macrocell users, m , selected from set $\mathcal{M}$, who have lower proportional throughputs. Set $\mathcal{V}$ is the set of users, m , that have been allocated a resource block index in the current allocation round. $\mathcal{B}_m$ is the set of resource block indices allocated to user m and, K_m is the achievable data rate on one resource unit of the allocation of user m .

(2) resource block allocation of all users in set $\mathcal{U}$ is:

$$\mathcal{B} = \bigcup_{m \in \mathcal{U}} \mathcal{B}_m. \quad (5)$$

(3) calculate the proportional throughput of user m as,

$$\bar{R}_{\text{prop}}^{(m)} = \frac{\bar{R}^{(m)}}{\bar{R}_{\text{target}}}, \quad \forall m \in \mathcal{M}, \quad (6)$$

where $\bar{R}_{\text{target}}$ denotes $\bar{R}_{\text{target,e}}$ or $\bar{R}_{\text{target,c}}$ and, $\bar{R}^{(m)}$ is the long term data rate of user m .

(4) from set $\mathcal{M}$, select a set $\mathcal{U}$ comprising of users m' having lower values of proportional throughput, where, $|\mathcal{U}|$ is constant and,

$$\mathcal{U} \subset \mathcal{M}. \quad (7)$$

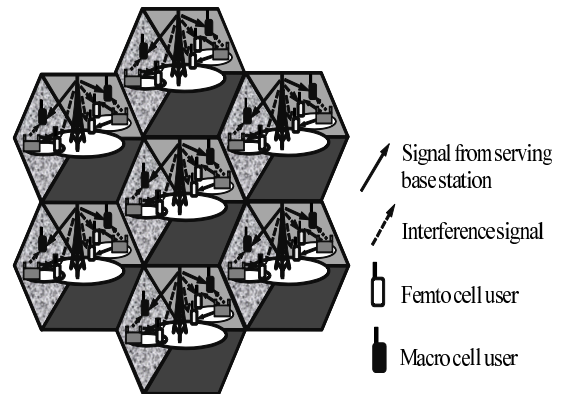


Figure 2 Network layout

(5) from set $\mathcal{U}$, pick a user m^* , that has the least proportional throughput,

$$m^* = \arg \min_{m \in \mathcal{U}} \{\bar{R}_{\text{prop}}^{(m)}\}. \quad (8)$$

(6) for each of the selected user m' in set $\mathcal{U}$, arrange the resource block index, n , in descending order based on the magnitude of the SINR of each resource block. For the selected user m^* pick the resource block n^* which has the highest SINR and allocate it to user m^* ,

$$n^* = \arg \max_{n \in \mathcal{N}} \{\text{SINR}_{m^*,n}\}, \quad (9)$$

such that, n^* is a resource block index in $\mathcal{N}$ that is not currently in use.

(7) add n^* to the set of resource blocks of user m^* ,

$$\mathcal{B}_{m^*} \leftarrow \mathcal{B}_{m^*} \cup \{n^*\}. \quad (10)$$

(8) calculate $T_{\text{schedule}}^{(m^*)}$, which is the number of timeslots the selected user will be scheduled on the selected resource block,

$$T_{\text{schedule}}^{(m^*)} = \min(X_{\max}, X_{\min} + \max(0, \lfloor A \cdot X_{\max} \rfloor)) \quad (11)$$

where

$$A = \frac{\bar{R}_{\text{prop}}^{(\text{avg})} - \bar{R}_{\text{prop}}^{(m^*)}}{\bar{R}_{\text{prop}}^{(\text{avg})} - \bar{R}_{\text{prop}}^{(\min)}}, \quad (12)$$

$$\bar{R}_{\text{prop}}^{(\text{avg})} = \frac{\sum_{m=1}^{|\mathcal{M}|} \bar{R}_{\text{prop}}^{(m)}}{|\mathcal{M}|}. \quad (13)$$

$X_{\min}$ denotes the minimum number of transmission time intervals that any user who has been selected for transmission can use, while, $X_{\max}$ is the maximum the user can use. $\bar{R}_{\text{prop}}^{(\text{avg})}$ is the average proportional throughput of all users, while, $\bar{R}_{\text{prop}}^{(\min)}$ represents the minimum value of proportional throughput reasonably selected to be lower than the average proportional throughput.

(9) remove user m^* from set $\mathcal{U}$ and add the user to another set $\mathcal{V}$,

(10) update the capacity of user m^* ,

$$r = \frac{T-1}{T}, \quad (14)$$

$$h = T_{\text{schedule}}^{(m^*)} - 1, \quad (15)$$

$$K_{m^*,n^*} = W \cdot \ln \left(1 + \frac{p_{m^*,n^*} \cdot g_{\text{mac},m^*}}{I_{m^*,n^*} + N_0} \right), \quad (16)$$

$$D = \frac{K_{m^*,n^*}}{T}, \quad (17)$$

$$R^{(m^*)} \leftarrow D \cdot \left[\frac{1-r^h}{1-r} + r^h \cdot \left(1 + r \cdot \frac{R^{(m^*)}}{D} \right) \right]. \quad (18)$$

K_{m^*,n^*} is the data rate that a user m^* can achieve on resource block of index n^* while p_{m^*,n^*} is the transmission

power loaded on resource block of index n^* allocated to user m^* . g_{mac,m^*} denotes the channel gain between user m^* and the macrocell base station while N_0 denotes the channel noise. The interference on resource block n^* which has been allocated to user f^* is denoted as I_{m^*,n^*} . Interested readers could refer to the appendix for more explanation on Equation (18).

(11) if $\mathcal{U} = \emptyset$, then,

$$\mathcal{U} = \mathcal{V}, \quad (19)$$

$$\mathcal{V} = \emptyset. \quad (20)$$

(12) if there are unused resource blocks and the maximum base station power has not been exceeded, go back to (2), otherwise, end.

3.2 FEMTOCELL

3.2.1 FEMTOCELL SPECTRUM USAGE

Usually, the interference received by the macrocell user from a femtocell base station is small, if the macrocell user is far away from the femtocell base station, since femtocell base stations usually transmit at a lower power compared to macrocell base stations. If however, the macrocell user is close to a femtocell base station, the level of interference received from this femtocell base station is high. In this section we present a way by which femtocell base stations control their transmit power to reduce the interference they cause to nearby macrocell users. We use a power control method similar to discussions in [6], but contrary to the uplink procedure considered in [6], we assume a downlink transmission for our consideration. Firstly, the femtocell base station classifies the resource blocks into 3 groups, that is,

(1) Resource blocks that are not to be used at all

(2) Resource blocks that are to be used at a controlled power and

(3) Resource blocks that are to be used at full power

3.2.2 FEMTOCELL OPTIMIZATION MODEL

The objective is to maximize the total cell throughput of femtocell base station and at the same time, limit interference caused to the macrocell users. In order to achieve this, we introduce a power control variable, J_n , which restricts the maximum allowed co-channel interference any femtocell base station can cause to a macrocell user that is currently being scheduled on resource block n . Each macrocell base station sets the value of J_n for each resource block it allocates to macrocell user, m , and its value depends on the density of femtocell base stations at a certain radius from m . Assuming $p_{f,n}$ denotes the power a femtocell base station loads on resource block n to serve femtocell user f , $g_{\text{fem},f}$ denotes the channel gain between femto user f and the femtocell base station and $I_{f,n}$ is the interference on resource block n which has been allocated to user f , then, the data rate on resource

block n is,

$$K_{f,n} = W \cdot \ln \left(1 + \frac{p_{f,n} \cdot g_{\text{fem},f}}{I_{f,n} + N_0} \right). \quad (21)$$

$\mathcal{N}$ is the set of femtocell resource blocks, $\mathcal{F}$ is the set of femtocell users, while W denotes the bandwidth of each resource block, the optimization problem can be described as:

$$\text{maximize} \sum_{f=1}^{|\mathcal{F}|} \sum_{n=1}^{|\mathcal{N}|} W \cdot \ln \left(1 + \frac{p_{f,n} \cdot g_{\text{fem},f}}{I_{f,n} + N_0} \right), \quad (22)$$

$$\sum_{f=1}^{|\mathcal{F}|} \sum_{n=1}^{|\mathcal{N}|} p_{f,n} \leq P_T, \quad (23)$$

$$\sum_{f=1}^{|\mathcal{F}|} \rho_{f,n} \leq 1 \quad \forall n, \quad (24)$$

$$\rho_{f,n} \in \{0, 1\}, \quad \forall f, n, \quad (25)$$

$$J_n \cdot \rho_{f,n} \geq p_{f,n}, \quad (26)$$

$$p_{f,n} \geq 0. \quad (27)$$

J_n is set by the macrocell base station if the macrocell user currently being scheduled on resource block n is close to a femtocell base station(s), otherwise, it (J_n) is fixed at a sufficiently large value. P_T is the maximum transmittable power available at the femtocell base station. $\rho_{f,n}$ is an allocation variable. $\rho_{f,n} = 1$ indicates that resource block n is allocated to user f , while $\rho_{f,n} = 0$ means otherwise. Equation (22) is the objective function. Equation (23) is the total base station power constraint, while Equation (24) is the exclusive resource block allocation condition which indicates that a resource block can be allocated to only one user f in the current time slot. Equation (26) restricts the maximum value of power that can be loaded on resource block n , while Equation (27) indicates that power is non-negative.

The problem described is a mixed integer non-linear programming problem. Optimisation variables p and ρ are coupled both on each resource block and also on each femtocell user. Equation (22) must be maximised subject to constraints in Equation (23), (24), (25), (26) and (27). The problem described is NP-hard and is very difficult to solve. We therefore present a suboptimal solution for the problem.

3.2.3 FEMTOCELL SUBOPTIMAL ALGORITHM

Our femtocell suboptimal algorithm consists of two parts namely:

- (1) Channel allocation
- (2) Power allocation

Channel Allocation: If some macrocell users are close to a femtocell base station, the femtocell base station measures its channel gain towards the macrocell users by listening to their uplink transmission. If any of the measured channel gains is above a given threshold, the resource blocks allocated to that particular macrocell user are orthogonalized

and are not used at all by the femtocell base station. If however the measured channel gain falls below the threshold, the femtocell base station uses the resource blocks allocated to the macrocell user. Resource blocks are allocated to femtocell users according to the procedure in Table 1.

Table 1 Resource block allocation algorithm (femto users)

initialize :

$$\mathcal{C}_f = \emptyset, \quad \forall f \in \mathcal{F}, \quad (28)$$

$$K_{f,n} = 0, \quad \forall f \in \mathcal{F}, \forall n \in \mathcal{S}, \quad (29)$$

$$p_{f,n} = \text{constant}, \quad \forall f \in \mathcal{F}, \forall n \in \mathcal{S}, \quad (30)$$

$$\bar{R}^{(f)}(t) = \frac{(T-1) \cdot \bar{R}(t-1)}{T}, \quad \forall f \in \mathcal{F}, \quad (31)$$

do

$$\mathcal{C} = \bigcup_{f \in \mathcal{F}} \mathcal{C}_f, \quad (32)$$

$$f^* = \arg \min_{f \in \mathcal{F}} \{ \bar{R}^{(f)}(t) \}, \quad (33)$$

$$n^* = \arg \max_{n \in \mathcal{S} \setminus \mathcal{C}} \{ \text{SINR}_{f^*,n} \}, \quad (34)$$

$$\mathcal{C}_{f^*} \leftarrow \mathcal{C}_{f^*} \cup \{n^*\}, \quad (35)$$

$$K_{f^*,n^*} = W \cdot \ln \left(1 + \frac{p_{f^*,n^*} \cdot g_{\text{fem},f^*}}{I_{f^*,n^*} + N_0} \right), \quad (36)$$

$$\bar{R}^{(f^*)}(t) \leftarrow \bar{R}^{(f^*)}(t) + \frac{K_{f^*,n^*}}{T}. \quad (37)$$

while($\mathcal{S} \setminus \mathcal{C} \neq \emptyset$)

In the algorithm described in Table 1, the set of resource blocks allocated to femto user f is denoted as $\mathcal{C}_f$ while $\mathcal{S}$ denotes the set of resource blocks that can be used by the femtocell without causing severe interference to nearby macrocell users. The power loaded on resource block n for user f , $p_{f,n}$, is temporarily made constant. Selecting a constant value for $p_{f,n}$ in the channel allocation stage does not have any negative impact on the performance of our algorithm since optimal values of $p_{f,n}$ will eventually be used during the power allocation stage.

Power Allocation: Since $\mathcal{C}_f$ which represents the set of resource blocks allocated to each femtocell user f is known after the channel allocation procedure, the problem therefore reduces to the maximization of total capacity where $p_{f,n}$ is the optimisation variable.

$$\text{maximize} \sum_{f=1}^{|\mathcal{F}|} \sum_{n \in \mathcal{C}_f} W \cdot \ln \left(1 + \frac{p_{f,n} \cdot g_{\text{fem},f}}{I_{f,n} + N_0} \right), \quad (38)$$

subject to:

$$p_{f,n} \geq 0, \quad (39)$$

$$\sum_{f=1}^{|\mathcal{F}|} \sum_{n \in \mathcal{C}_f} p_{f,n} \leq P_T, \quad (40)$$

$$J_n \cdot \rho_{f,n} \geq p_{f,n}. \quad (41)$$

The femtocell solves this problem by each user f . Using lagrange technique, the problem can be solved efficiently.

$$\begin{aligned} L(p, \lambda, \mu, \alpha) = & \sum_{f=1}^{|\mathcal{F}|} \sum_{n \in \mathcal{C}_f} W \cdot \ln \left(1 + \frac{p_{f,n} \cdot g_{\text{fem},f}}{I_{f,n} + N_0} \right) \\ & + \sum_{f=1}^{|\mathcal{F}|} \sum_{n \in \mathcal{C}_f} \lambda_{f,n} \cdot p_{f,n} + \mu \left(P_T - \sum_{f=1}^{|\mathcal{F}|} \sum_{n \in \mathcal{C}_f} p_{f,n} \right) \\ & + \sum_{f=1}^{|\mathcal{F}|} \sum_{n \in \mathcal{C}_f} \alpha_{f,n} \cdot (J_n \cdot \rho_{f,n} - p_{f,n}), \end{aligned} \quad (42)$$

$$p_{f,n} = \left[\frac{W}{\mu + \alpha_{f,n} - \lambda_{f,n}} - \frac{I_{f,n} + N_0}{g_{\text{fem},f}} \right]^+, \quad (43)$$

where

$$[x]^+ = \max(0, x). \quad (44)$$

Here, λ, μ, α are lagrange multipliers. Equation (43) is a water-filling type of power allocation which takes the per resource block SINR constraint into consideration. Note that it is possible that a resource block could be allocated to a femtocell user f but gets no power due to (relatively) poor channel gain or high interference.

4. Simulation results

System level simulations were performed to demonstrate the effectiveness our proposed macrocell batch resource allocation scheme. As at the time of this writing, simulations have only been performed for macrocell batch resource allocation while simulation of femtocell optimization is the content of future work. In our simulations, we deployed a hexagonal cell macrocell base station to serve 30 macro users. In order to avoid edge effect, 6 more macrocell base stations were deployed around the macrocell base station to serve as sources of interference but data was taken only from the macrocell base station located at the centre. We then deployed 10 femtocell base stations in the coverage area of the macrocell base station one at a time and observed the impact of thier deployment on the throughput of existing macrocell users. The femtocell base stations each serve one femtocell user. We implemented the proposed femtocell coordination scheme to limit the interference the femtocell base stations caused to the public users and the results of this investigation are illustrated in Figs. 3 and 4. Fig. 3 compares the total macrocell users throughput achieved when

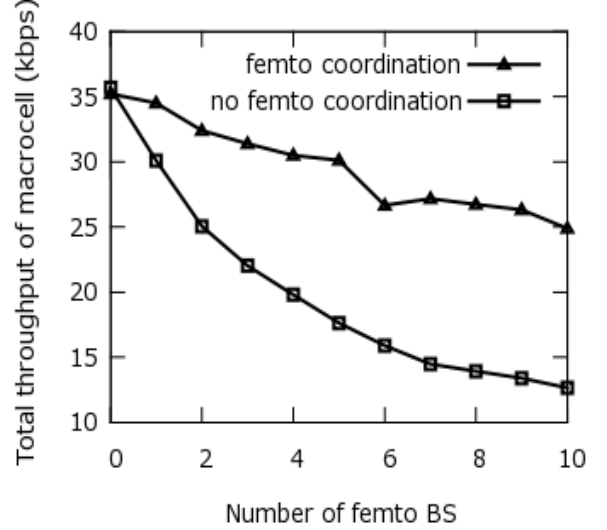


Figure 3 Total throughput of macrocell users.

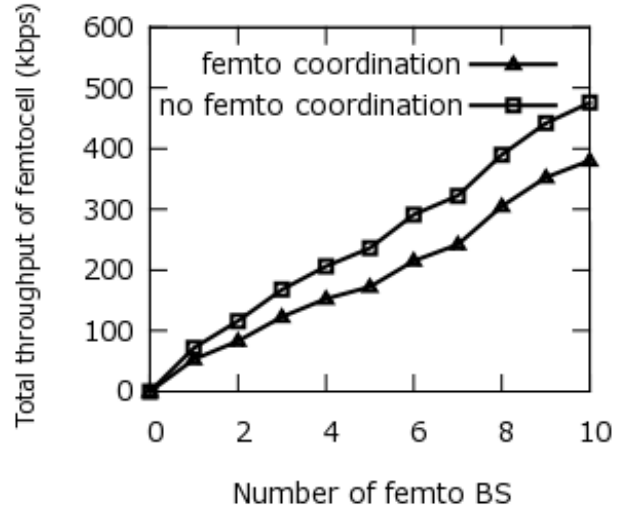


Figure 4 Total throughput of femtocells users in the network.

our scheme was implemented and when it was not used (i.e no femtocell coordination). It can be observed from the figure that when our proposed scheme was implemented, there was a significant improvement in the total macrocell users' throughput as the density of the deployed femtocells increased.

Fig. 4, however, shows a decrease in the total femtocell users throughput when our scheme was implemented, but this is justifiable since the total throughput of the femtocell significantly exceeds that of the macrocell even after interference coordination.

5. Conclusions

In this paper, we discussed a batch resource allocation strategy for a co-channel macrocell femtocell overlay in which a macrocell base station allocates resources to macrocell users in batch in the time domain. Femtocell base stations

coordinate interference based on the knowledge of future resources that will be used by nearby macrocell users and maximize the overall cell throughput. Simulation results show that our proposed scheme yielded a significant improvement in the macrocell total cell throughput. Most of the existing research works have treated resource allocation and interference avoidance separately but this work considers the two together which makes our approach to give a more realistic representation of the interference limited relationship between femtocell and macrocell base stations.

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Appendix

Fig. A.1 is an illustration of an LTE resource frame in which resource units "a," "b," "c," "d," "e," and "f" are allocated in batch to a user. Assuming T denotes time window, $\bar{R}$ denotes long term throughput while K denotes the instantaneous data rate on one resource unit, then, the moving average throughput is given as:

$$\bar{R} \leftarrow \left(\frac{T-1}{T} \cdot \bar{R} \right) + \left(\frac{1}{T} \cdot K \right). \quad (\text{A.1})$$

assuming

$$D = \frac{1}{T} \cdot K, \quad (\text{A.2})$$

$$r = \frac{T-1}{T}, \quad (\text{A.3})$$

if $\bar{R}$ is updated after each resource unit allocation, then,

(1) update of $\bar{R}$ for "a" allocation is,

$$\bar{R} \leftarrow \bar{R} \cdot r + D \quad (\text{A.4})$$

(2) update of $\bar{R}$ for "b" allocation is,

$$\bar{R} \leftarrow (\bar{R} \cdot r + D) \cdot r + D$$

$$\bar{R} \leftarrow D \left[1 + r \cdot \left(\frac{1}{D} (r \cdot \bar{R} + D) \right) \right] \quad (\text{A.5})$$

(3) update of $\bar{R}$ for "c" allocation is,

$$\bar{R} \leftarrow D \left[1 + r \cdot \left(\frac{1}{D} (r \cdot \bar{R} + D) \right) \right] \cdot r + D$$

$$\bar{R} \leftarrow D \left[1 + r + r^2 \cdot \left(\frac{1}{D} (r \cdot \bar{R} + D) \right) \right] \quad (\text{A.6})$$

(4) update of $\bar{R}$ for "d" allocation is,

$$\bar{R} \leftarrow D \left[1 + r + r^2 \cdot \left(\frac{1}{D} (r \cdot \bar{R} + D) \right) \right] \cdot r + D$$

$$\bar{R} \leftarrow D \left[1 + r + r^2 + r^3 \cdot \left(\frac{1}{D} (r \cdot \bar{R} + D) \right) \right] \quad (\text{A.7})$$

Hence, the general expression for the moving average throughput can be written as:

$$\bar{R} \leftarrow D \left[\frac{1 - r^{(n-1)}}{1 - r} + r^{(n-1)} \left(\frac{1}{D} (r \cdot \bar{R} + D) \right) \right] \quad (\text{A.8})$$

where n denotes the number of resource units allocated.

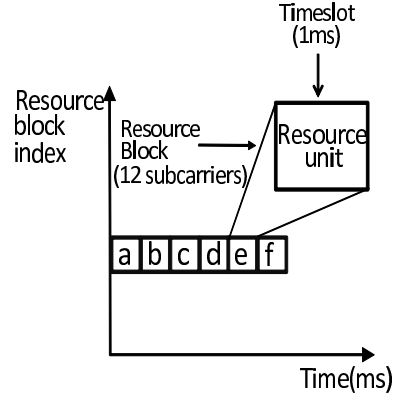


Figure A.1 LTE resource unit.