LETTER *Special Section on Information and Communication Technologies for Next-generation Mobile Multimedia Life*

Dynamic Channel Adaptation for IP Based Split Spectrum Femto/Macro Cellular Systems

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SUMMARY In femto/macro cellular networks, the stability and fairness problems caused by the unplanned and random characteristic of femtocells must be solved. By applying queueing theory in IP based femto/macro cellular networks, we found the stability condition, and described two kinds of cell section policies of users. As a main contribution, we provided the adaptive channel distribution algorithm which minimizes the average packet sojourn time at transmitting systems and keeps the whole systems stable and fair among cells. Through experiments in various environments, we analyzed the influence of channel reuse factor, cell selection policies, and the number of femtocells on system performance.

key words: *femto/macro cellular networks, queueing stability, cell selection policies, channel distribution algorithm*

1. Introduction

Femto/macro cellular networks have been considered one of the most promising architecture which can improve the cell capacity especially in indoor or densely populated areas. However, the femtocell is installed by individual users, thus its randomness of the deployment which not allows pre-cellplanning has a risk factor of making the system unstable.

There have been various works dealing with radio resource management of femto/macro cellular networks. [1] aims to enhance system stability by reducing the number of mobility events for the coverage adaption. [2] and [3] set the hybrid regions of coverage according to interference level. However they do not consider queueing stability or fairness. In addition, the hierarchical structure of femto/macro cellular networks gives challenging issues about control signaling and management problems caused by random deployment characteristic of femtocells.

In this paper, we propose the channel distribution algorithm for femto/macro cellular systems which aims for keeping the whole systems stable. At transmitting systems while maintaining fairness among cells, our algorithm minimizes the packet sojourn time. By reflecting the intensity of traffic in real time, the algorithm can find the optimum amount of channels for both femtocells and macrocell to satisfy the delay QoS of users. For applying the algorithm, we analyze how the cell selection policies and reuse factor decision have an influence on the system performance.

Our organization is as follows: we find the condition of stable services through the queueing model for the femto/macro cellular networks in Sect. 2, and describe cell selection polices of MSs in Sect. 3. Our channel distribution algorithm is provided in Sect. 4. We analyze the performance changes of proposed algorithm in varied system environments, and seek an efficient cell plan in Sect. 5. Finally, Sect. 6 makes conclusions.

2. System Structure

We consider the wireless cellular system consisted of a single macrocell and m femtocells in Fig. 1. Femtocells are located in macrocell area. The femto base stations (fBS) use distinct channels from macro base station (mBS) to avoid interference. The total number of whole system channels is N, where femtocells use n channels with frequency reuse factor K. Mobile stations (MS) are randomly deployed in macrocell area.

We apply $M/M/1$ queueing model of [4] to this system as Fig. 1. The average packet arrival rates at a macrocell and femtocell i are each λ_M and λ_i, which are measured at each cell. Likewise the average packet service rates at the macrocell and femtocell i for one channel, μ_M and μ_i, are also measured. This information is forwarded to the radio

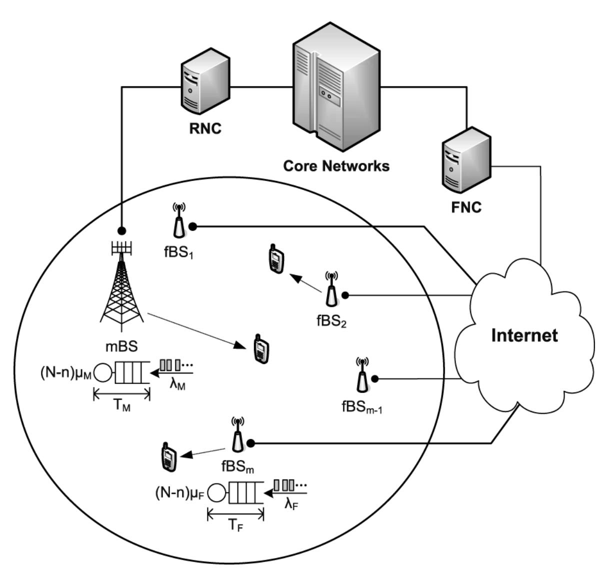

Fig. 1 Macro/femto cellular network structure and queueing model for the IP based macro/femto cellular networks. Average packet sojourn times, T_M and T_F, are controlled by adjusting the number of channels assigned to femtocells, n, considering system environments (λ_M, λ_F, μ_M, μ_F).

Manuscript received June 18, 2010.
Manuscript revised October 30, 2010.
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DOI: 10.1587/transcom.E94.B.694

network controller (RNC), and the mean values of λ_i and μ_i for all femtocells, $\lambda_F = E[\lambda_i]$ and $\mu_F = E[\mu_i]$, are obtained. The total packet arrival rates on whole systems are $\lambda = \lambda_M + \sum_{i=1}^{m} \lambda_i$, and the average packet service rates for channels occupied by a macrocell and femtocells are each $(N-n)\mu_M$ and $(n/K)\mu_F$. Consequently we can derive the average packet sojourn times, T_M and T_F, of packets in the transmitting system at a macrocell and femtocells.

$$T_M = \{(N-n)\mu_M - \lambda_M\}^{-1} \tag{1}$$

$$T_F = \{(n/K)\mu_F - \lambda_F\}^{-1} \tag{2}$$

For the system stability, the packet arrival rates at each cell should be smaller than the packet service rates. Thus $\lambda_M < (N-n)\mu_M$ and $\lambda_F < (n/K)\mu_F$, which determine the effective range of n.

$$K\lambda_F/\mu_F < n < N - \lambda_M/\mu_M \tag{3}$$

As n approaches to $N-\lambda_M/\mu_M$, T_M infinitely increases, and as n nears $K\lambda_F/\mu_F$, T_F infinitely increases. Therefore by selecting n in range (3), we can guarantee the system stability.

3. Cell Selection Policies

MSs fundamentally decide the serving cells among a macrocell and femtocells based on signal to interference ratio(SINR). In [5], for MS j connected to fBS i with MQAM modulation, if $M \geq 4$ and $0 \leq SINR_{i,j} \leq 30\,\text{dB}$, the BER is bounded by

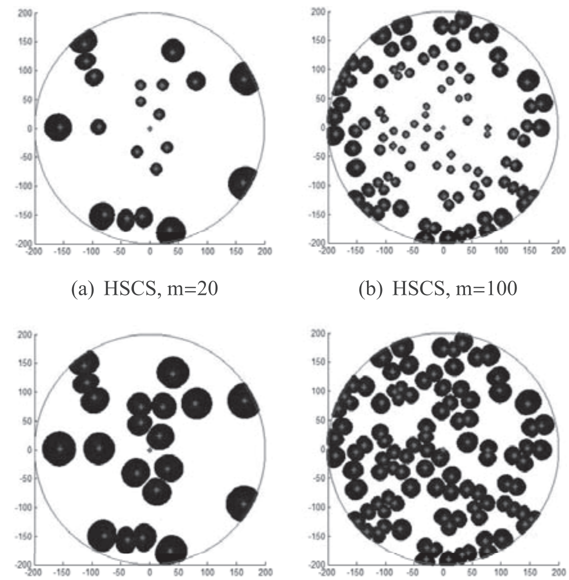
$$BER \leq 0.2e^{-1.5SINR_{i,j}/(M-1)}. \tag{4}$$

For a given BER on a packet transmission link, the maximum number of bits in a symbol for one channel, $q_{i,j} = \log_2 M$, is obtained.

$$q_{i,j} = \log_2\left(1 + SINR_{i,j}/\Gamma\right), \tag{5}$$

where $\Gamma = -\ln(5BER)/1.5$. We assume that the 64QAM is maximally available. Hence the maximum value of $q_{i,j}$ is 6. If $SINR_{i,j} \geq 63\Gamma = SINR_{MAX}$, it is possible to serve with the maximum symbol bits. Similarly we suppose that wherever MSs are located in macrocell area, mBS can serve with QPSK. That is, the minimum number of symbol bits is 2, and higher SINR than $3\Gamma = SINR_{MIN}$ is guaranteed from mBS.

We consider two kinds of cell selection policies of MSs, Highest SINR Cell Selection (HSCS) and Femtocell Preference Selection (FCPS). HSCS policy connects MS to the cell having the largest SINR among a macrocell and all femtocells. However if any femtocell provides higher SINR than $SINR_{MAX}$, MS selects that even though a macrocell has the largest SINR. In FCPS policy, if there are nearby femtocells guaranteeing $SINR_{MIN}$, MS is preferentially connected to the femtocell which provide the largest SINR among them. If not, MS selects a macrocell. Two cell selection policies of MSs can be written as follows.



(a) HSCS, m=20 (b) HSCS, m=100

(c) FCPS, m=20 (d) FCPS, m=100

Fig. 2 The areas where MSs select femtocells for two cell selection policies and the number of femtocells in a macrocell. (where $K = 1$)

• Highest SINR Cell Selection(HSCS) Policy

find fBS $\hat{i}$ which has the highest SINR for MS j
if $SINR_{\hat{i},j} \geq SINR_{mBS,j}$ **or** $SINR_{\hat{i},j} \geq SINR_{MAX}$
  connect MS j to fBS $\hat{i}$
else
  connect MS j to mBS

• Femtocell Preference Selection(FCPS) Policy

find fBS $\hat{i}$ which has the highest SINR for MS j
if $SINR_{\hat{i},j} \geq SINR_{MIN}$
  connect MS j to fBS $\hat{i}$
else
  connect MS j to mBS

where $SINR_{mBS,j}$ denotes SINR between MS j and mBS.

In Fig. 2, as more femtocells are installed or concentrated, the service area of a single femtocell generally shrinks owing to the increase of interferences. However, while the femtocells of HSCS policy which located close to mBS serve smaller area than ones at macrocell edge, the femtocells of FCPS policy have mostly uniform cell coverages in whole macrocell area. Therefore HSCS policy can take advantage of higher SINR from mBS at the center of a macrocell, on the other hand, FCPS policy has benefits to maximize channel reuse effects among femtocells. Based on these cell selection policies, in next session, we propose channel distribution algorithm to minimize T_M and T_F of (1) and (2). It allocates channel resources to reduce packet delays with considering system loads at a macrocell and femtocells.

4. Channel Distribution Algorithm

In the packet based queueing system, the packet sojourn time in the system determines the service delay for MSs. Moreover the large packet sojourn time in M/M/1 queueing system causes the increase of packet drop probabilities in the real system with limited buffer size. Therefore the efficient control of the packet sojourn time is necessary to reduce the service delay and improve stability. By deciding the number of channels assigned to the femtocells, the packet sojourn time control in each cell is feasible as shown in Fig. 1. We basically aim to guarantee the fairness among MSs in a macrocell and femtocells. Especially we consider min-max fair strategy for the average packet sojourn time at each cell, which minimizes the packet sojourn time at the cell serving with the maximum average packet sojourn time. It provides the fair services by improving the quality of services for underprivileged MSs.

The fairness optimization problem to minimize the maximum packet sojourn time is formulated as follows.

$$\min_{n} \{\max (T_M, \alpha T_F)\}, \tag{6}$$

where n is in the range (3). Fixed value α is the weighting factor in order to provide differentiated services to MSs in femtocells, which satisfies $\alpha \geq 1$.

Theorem 1: The solution of the min-max fairness optimization problem for T_M and αT_F is equivalent to that of equation $T_M = \alpha T_F$.

Proof: T_M is the strictly increasing function with respect to n in range (3), and αT_F decreases strictly. As n approaches to $K\lambda_F/\mu_F$, T_M converges and αT_F infinitely increases. In contrary, as n approaches to $N - \lambda_M/\mu_M$, T_M infinitely increases and αT_F converges. Therefore in range (3), T_M and αT_F should meet at one point $\hat{n}$. It is obvious that $T_M \geq \alpha T_F$ when $n \geq \hat{n}$, and $T_M < \alpha T_F$ when $n < \hat{n}$.

If $T_M \geq \alpha T_F$, T_M has the minimum value when $n = \hat{n}$. Moreover if $T_M \leq \alpha T_F$, αT_F reaches to the minimum value when $n = \hat{n}$. Consequently for all cases, the minimum value of larger one between T_M and αT_F is obtained when $n = \hat{n}$. That is, the min-max fairness optimization problem for T_M and αT_F is equivalent to the problem searching for the solution of equation $T_M = \alpha T_F$. □

From Theorem 1, the optimization problem (6) is simplified to equation $T_M = \alpha T_F$. Therefore the following equation is formed.

$$(N - n)\mu_M - \lambda_M = \frac{1}{\alpha}\{(n/K)\mu_F - \lambda_F\} \tag{7}$$

By numerical procedures, the optimal number of channels assigned to femtocells, n^*, is obtained, where we round up the theoretical result because the number of channels is integer value and channels can be used more efficiently in femtocells due to the channel reuse policy.

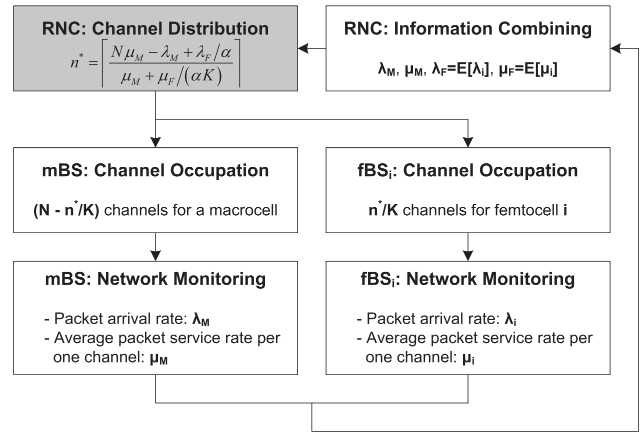


Fig. 3 Proposed channel distribution algorithm.

$$n^* = \left\lceil \frac{N\mu_M - \lambda_M + \lambda_F/\alpha}{\mu_M + \mu_F/(\alpha K)} \right\rceil \tag{8}$$

In this strategy, as μ_M, λ_F, K, or α increase, more channels are allocated to femtocells. On the contrary, if μ_F or λ_M is high, femtocells receive less channels, where λ_M has a larger value when there are less femtocells on a macrocell. The diagram in Fig. 3 represents the overall operation of proposed channel distribution algorithm.

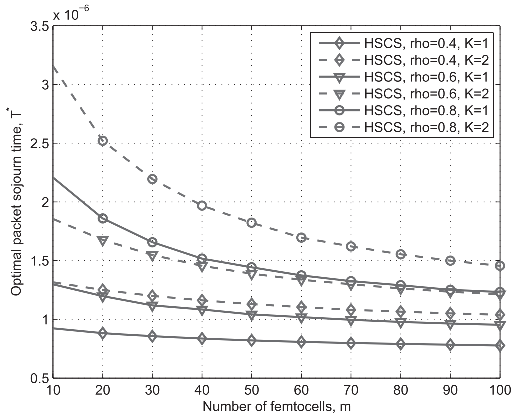
From (1), (2), and (8), we drive the optimal average packet sojourn time, $T^* = T^*_M = \alpha T^*_F$.

$$T^* = \frac{\alpha K \mu_M + \mu_F}{N\mu_M\mu_F - K\lambda_F\mu_M - \lambda_M\mu_F} \tag{9}$$

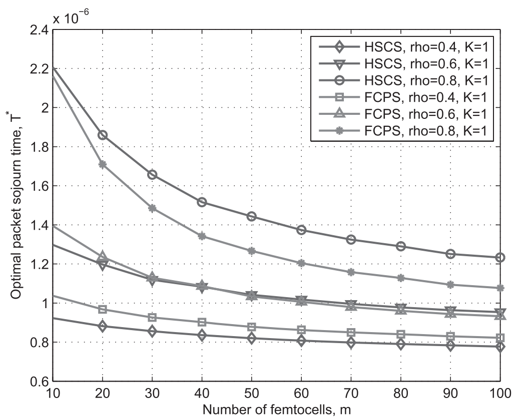
Note that when α is large, T^*_M grows, and T^*_F relatively becomes small. Moreover if μ_M or μ_F increase, or λ_M or λ_F is reduced, then T^* naturally decreases.

AS the more femtocells are installed like Figs. 2(b) and (d), T^* decreases owing to the decline of λ_M and λ_F since the coverage of each femtocell shrinks by the growth of number of installed femtocells. On the other hand, the shrunken femtocell coverage plays a role of suppressing the decrease of T^* by disturbing to let more users reuse channels. Within this context, the value of reuse factor K has a major effect on system performance because it controls interferences among femtocells. While the increase of K reduces interferences, it causes the decrease of available channels per one cell. When we assume that interferences among femtocells are in inverse proportion to K as in [6], the increase of K proportionally raises SINR in femtocells. In that case, from (5), symbol bits go on increasing with a log scale, and μ_F also increases in the same manner. Consequently, in (9), if K grows, μ_F increases only with a log scale, and it brings about the rise of T^*. That is, when $K = 1$, T^* can reach the smallest value.

In addition, according to the cell selection policies of MSs, HSCS and FCPS, the coverage and SINR of femtocells change as Fig. 2, and it impacts on T^*. Therefore we need to definitely analyze the effect that the cell selection policies have on system performance with respect to the number of femtocells and the amount of traffics.



(a) Different channel reuse factors for femtocells, K.



(b) Different cell selection policies, HSCS and FCPS.

Fig. 4 Optimal packet sojourn time, T^*, in various channel reuse factors and cell selection policies. ($\alpha = 1$)

5. Experimental Results

We fixed 200 m as a macrocell radius, and MSs generating the regular amount of traffic are uniformly distributed. The transmission power of mBS is 45 dBm, and fBS power is 20 dBm. We only considered path loss gain for a channel model. An adaptive modulation scheme of (5) is applied, and the 64QAM is maximally available. The target BER is 0.001 and the total number of system channel is 1024. We experimented proposed algorithm as increasing the number of femtocells for different ρ, K, and cell selection policies(HSCS and FCPS), where $\rho = \lambda/(\mu_M N)$ is the traffic intensity when there is no femtocell.

Figure 4 shows that as more femtocells are installed in a macrocell, the optimal packet sojourn time sharply decreases because more MSs reuses channels and are offered high SINR from fBSs. When few femtocells are distributed, the gap of T^* among different ρ is big. By contrast, as more femtocells are added, the gap is remarkably smaller.

Basically, MSs in femtocells of HSCS policy undergo larger interferences from other fBSs than ones of FCPS policy, hence HSCS policy has more effects of increasing K than FCPS policy. For this reason, in Fig. 4(a), we compared the cases of different K only applying HSCS policy. As described in Sect. 4, we can confirm that T^* has smaller values when $K = 1$ for all environments.

In Fig. 4(b), in small ρ cases, HSCS policy provides shorter T^* while in large ρ cases FCPS policy serves with smaller T^*. While HSCS puts emphasis on high SINR of mBSs, FCPS maximizes the advantages of channel reuse. When the amount of traffic is small, radio resources are enough. Therefore it is possible to optimize system performance by only using high SINR of HSCS policy. However in the heavy traffic environments, radio resources are insufficient. Hence FCPS that many MSs reuse channels is more advantageous to reduce the packet sojourn time of whole systems than HSCS which makes MSs served by mBS with high SINR monopolize resources.

6. Conclusion

In this paper, we found the stability condition of IP based femto/macro cellular systems, and described cell section policies of MSs. Based on these elements, we provided the adaptive channel distribution algorithm which minimizes the average packet sojourn time keeping the whole systems stable and fair. In experimental results, we analyzed the operation of the proposed strategy in different system environments. As future works, we will analyze the results yielded by various optimization strategies like a total throughput maximization, and develop our scheme in dynamic mobile user environments.

Acknowledgments

This research was supported by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency) (NIPA-2010-(C1090-1011-0006)).

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