Power Control Based on Kalman Filter for Uplink Transmission in Two-Tier Heterogeneous Networks

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Abstract. The problem of interference management and power control in two-tier heterogeneous network is investigated in this paper. Due to the time-varying characteristics of channels, the optimal transmit power changes with time. A hierarchical power control based on Kalman filter is proposed. Using Kalman filter, the current uplink transmit power under the influence of time varying channel gains due to the shadow fading effect is obtained by estimating the power of the last moment. This proposed method follows the slowly varying channel characteristics under the influence of the shadow fading effect in order to obtain an accurate power allocation. The proposed power control method is verified by computer simulations.

Keywords: Heterogeneous networks · Time-varying channel · Kalman filter · Power control

1 Introduction

Recently, the amount of traffic created in cellular systems increased rapidly. According to the estimation, most of the data traffic and the calls come from indoor scenarios [1]. The small cell/femtocell is a promising solution for the indoor scenario, which can increase the capacity and coverage [2]. However, due to the limit of licensed bands, co-channel deployment is inevitable for femtocells, which raises a critical issue on interference. Co-tier interference is generated between adjacent femtocells, besides, cross-tier interference between femtocells and microcells will greatly degrade the system performance [3]. Power control is a particularly critical issue for the auto-configuration of femtocells, especially in the cochannel deployment since it determines the interference and thus further affects coverage, handover, and drop-call-rate [4]. In uplink, the cross-tier interference from femtocell users (FUEs) has to be maintained in a reasonable range or below a certain threshold, in order to ensure the quality of transmissions in microcell [5].

There are many prior works on power control in heterogeneous networks. The authors in [6] propose a distributed power allocation scheme based on game theory which can adjust the signal to interference plus noise ratio (SINR) at femtocells so that the cross-tier interference from the co-channel femtocells can be reduced. In [7], the

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macrocell base station (MBS) first decides the power of macrocell users (MUEs) and the interference allowance according to the average uplink power budget. Then FUEs adjust their transmitting power below the interference allowance based on the broadcasted message from MBS. In [8], an interference estimation method based on Kalman is proposed to increase the handshaking success rate in IEEE 802.11. Given channel uncertainty, a robust hierarchical game is formulated and solved with distributed algorithms in [9].

On the basis of the above, we propose a new distributed uplink power control method for MUEs and FUEs based on Kalman filter. The shadow fading is considered and the maximum likelihood estimation is used to obtain the mean value of the shadow fading effect between users and their serving base stations. Then we use Kalman filter to estimate user's current powers. This method can reduce measurement errors when the MBS measures the channel gain due to the shadow fading effect.

The remainder of this paper is organized as follows. The system model is presented in Sect. 2. Section 3 gives the details of our proposed power control scheme based on Kalman filter. Section 4 analyses the simulation results. Section 5 concludes the works done in this paper.

2 System Model

It assumed that the system is consisted of a single central macrocell with a coverage radius R_{m}, and N_{f} co-channel femtocells with each providing a coverage radius R_{f}, as shown in Fig. 1. FUEs are located in a small region, which are served by femtocell APs. We assume one scheduled user in each wireless resource block for the macrocell, as well as for each femtocell. Let $i \in \{0, 1, \ldots, N\}$ be the index of the user who connected to its BS B_i, and let P_i denote its transmission power. Without loss of generality, the index 0 represent the MBS/MUE, the other indexes denote FBSs/FUEs. It assumed that the number of the active FUEs is K. The received SINR at B_i can be written as

$$\gamma_i = \frac{P_i \cdot g_{i,i}}{\sum_{j \neq i} P_j \cdot g_{i,j} + \sigma^2} \geq \Gamma_i \tag{1}$$

where Γ_i is the minimum target SINR of user i at B_i, σ^2 is the power of additive white Gaussian noise (AWGN) at B_i. The term $g_{i,i}$ and $g_{i,j}$ denote the channel gain between user i, user j and B_i, respectively. In this paper we just consider the large-scale path loss and shadow fading effect. The fast fading is ignored because power control can effectively compensate for the slowly variations of channel shadow fading. The term $g_{i,j}$ can be expressed as

$$g_{i,j} = r_{i,j}^{-\alpha_{i,j}} e^{k\xi_{i,j}} \tag{2}$$

where $r_{i,j}^{-\alpha_{i,j}}$ denotes the path loss between user j and B_i, $e^{k\xi_{i,j}}$ models the shadow fading effect, $\alpha_{i,j}$ is the path loss factor, $\xi_{i,j}$ is a Gaussian r.v., k equals $\ln 10/10$.

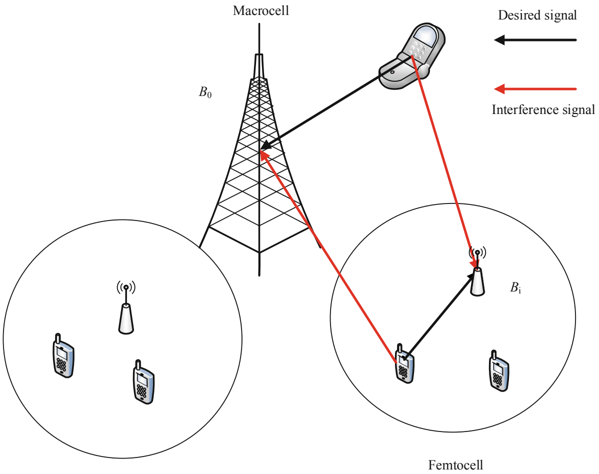

Fig. 1. A macrocell underlaid with co-channel femtocells

3 Proposed Algorithm

In this paper, the MUE is considered as a primary user. This means that the transmissions from macrocell users should reach the target SINR at the MBS's side by limiting the aggregate interference from active femtocells. FUEs adjust their power ensuring that the sum of their power is within the budget of aggregate interference power. User's signal will suffer from propagation loss including distance-dependence path loss and shadow fading effect. It is assumed that the base station can obtain the accurate path loss between its user and itself. B_0 estimates the mean of its serving user's channel gain due to the shadow fading effect by maximum likelihood estimators

$$\widehat{E}_{0,0} = e^{\hat{\mu}_{0,0} + \frac{\hat{\sigma}_{0,0}^2}{2}} \tag{3}$$

Here $\widehat{\mu}_{0,0}$ and $\widehat{\sigma}_{0,0}^2$ are given by

$$\widehat{\mu}_{0,0} = \frac{1}{N}\sum_{i=1}^{N} \ln x_{i,0} \tag{4}$$

and

$$\widehat{\sigma}_{0,0}^2 = \frac{1}{N}\sum_{i=1}^{N} \left(\ln x_{i,0} - \frac{1}{N}\sum_{i=1}^{N} \ln x_{i,0} \right)^2 \tag{5}$$

where $x_{i,0},\ i = 1,\ldots,N$, are the samples which can be obtain from the pilot information. Similarly, the maximum likelihood estimators of mean of the channel gain from the FUE to B_0 are

$$\widehat{E}_{0,j} = e^{\hat{\mu}_{0,j} + \frac{\hat{\sigma}_{0,j}^2}{2}},\ j = 1,\ldots,N \tag{6}$$

where $\widehat{\mu}_{0,j}$ and $\widehat{\sigma}_{0,j}^2$ can be derived as

$$\widehat{\mu}_{0,j} = \frac{1}{N}\sum_{i=1}^{N}\ln x_{i,j} \tag{7}$$

$$\widehat{\sigma}_{0,j}^2 = \frac{1}{N}\sum_{i=1}^{N}\left(\ln x_{s,j} - \frac{1}{N}\sum_{i=1}^{N}\ln x_{s,j}\right)^2 \tag{8}$$

3.1 MUE Power Allocation

The minimum target SINR should be guaranteed for the MUE, given its primary role in two-tier heterogeneous networks. B_0 first decides L_0 called the uplink power allocation reference. L_0 can be formulated as

$$L_0 = P_{\mathrm{max,m}}\widehat{E}_{0,0}r_{\mathrm{m}}^{-\alpha_{\mathrm{m}}} \tag{9}$$

where $P_{\mathrm{max,m}}$ is the maximum transmission power, $\widehat{E}_{0,0}$ is the estimated mean value of shadow fading effects, and $r_{\mathrm{m}}^{-\alpha_{\mathrm{m}}}$ is the channel gain from the MUE located on the cell edge to B_0. Then the transmitting power of MUE can be obtained for the first time with the power constraint $P_{\mathrm{max,m}}$ as follows

$$P_0 = \min\left(P_{\mathrm{max,m}}, \frac{L_0}{r_0^{-\alpha_{\mathrm{m}}}\cdot\widehat{E}_{0,0}}\right) \tag{10}$$

where $r_0^{-\alpha_{\mathrm{m}}}$ is the channel gain between the MUE and B_0. The minimum target SINR can be expressed as

$$(1+\delta)\Gamma_0 = \frac{L_0}{P_{\mathrm{AGGI}} + \sigma^2} \tag{11}$$

where σ^2 is AWGN and P_{AGGI} represents the interference allowance of the MUE in the uplink transmission. Let $1+\delta$ be the protection margin, which provides extra SINR to cushion the aggregate interference from all active FUEs. The interference allowance of the MUE can be determined as

$$P_{\mathrm{AGGI}} = \frac{L_0}{(1+\delta)\Gamma_0} - \sigma_n^2 \tag{12}$$

The uplink transmitting power of each FUE is allocated for the first time according to (12), which can be given under the maximum transmitting power constraint $P_{\max,\mathrm{f}}$ by

$$P_j = \min\left\{ P_{\max,\mathrm{f}}, \frac{P_{\mathrm{AGGI}}}{K \cdot r_j^{-\alpha_{\mathrm{f}}} \cdot \widehat{E}_{0,j}}, j = 0, 1, \ldots, K \right\} \tag{13}$$

where K represents all active FUEs, $r_j^{-\alpha_{\mathrm{f}}}$ is the path loss from the FUE to B_0, and $\widehat{E}_{0,j}$ is mean value of shadow fading effects between B_0 and FUEs.

Kalman filtering is a linear quadratic estimator for unknown variables according to the measurement values with the statistical noise or other inaccuracies. In our work, the base station uses a Kalman filter to reduce measurement errors when measuring the received power under the influence of time-varying channel gains due to the shadow fading effect.

The uplink power P_0 can be formulated as

$$P_0 \cdot e^{k\hat{\xi}_{0,0}} \cdot r_0^{-\alpha_{\mathrm{m}}} = L_0 \tag{14}$$

Take logarithm on both sides of (14), and then divide $k\widehat{\xi}_{0,0}$ into two parts $k\widehat{\mu}_{0,0}$ and $k^2\widehat{\sigma}_{0,0}^2\tau$, we can get

$$\ln\left(P_0 \cdot r_0^{-\alpha_{\mathrm{m}}}\right) + k\widehat{\mu}_{0,0} + k^2\widehat{\sigma}_{0,0}^2\tau = \ln L_0 \tag{15}$$

where $k\widehat{\xi}_{0,0}$ is a Gaussian r.v. with mean $k\widehat{\mu}_{0,0}$ and standard deviation $k\widehat{\sigma}_{0,0}$, τ is a Gaussian r.v. with zero mean and unit standard deviation, k is a constant equals to $\ln 10/10$.

Let $P_L = \ln\left(P_0 \cdot r_0^{-\alpha_{\mathrm{m}}}\right) + k\widehat{\mu}_{0,0}$, which is known as the process in Kalman filter and is to be estimated according to (7). The dynamics of P_L can be described as

$$P_L(t) = P_L(t-1) - W(t-1) \tag{16}$$

where $W(t-1)$ represents the fluctuation of P_L as the MUE start a new transmission and/or adjust its transmission. In the terminology of Kalman filtering, $W(t-1)$ is the “process noise”, which obeys the Gaussian r.v. with zero mean and variance $Q = k^2\widehat{\sigma}_{0,0}^2$. Let $Z(t)$ be the measured power P_L for slot t. Then

$$Z(t) = P_L(t) - V(t) \tag{17}$$

where $V(t)$ is called as measurement noise and is a Gaussian r.v. with zero mean and variance R. Based on Kalman filter theory, the update equations for P_L are [10]

$$\begin{cases} \widetilde{P}_L(t+1) = \widehat{P}_L(t) \\ \widetilde{P}(t+1) = \widehat{P}(t) + Q \\ K(t+1) = \frac{\widetilde{P}(t+1)}{\widetilde{P}(t+1)+R} \\ \widehat{P}_L(t+1) = \widetilde{P}_L(t+1) + K(t+1)\varepsilon(t+1) \\ \varepsilon(t+1) = Z(t+1) - \widetilde{P}_L(t+1) \\ \widehat{P}(t+1) = [1 - K(t+1)]\widetilde{P}(t+1) \end{cases} \tag{18}$$

where $\widehat{P}_L(t)$ and $\widehat{P}(t)$ are the updated filter estimate of P_L and error variance associated with the filter estimate $\widehat{P}_L(t)$ at time t, and $\widetilde{P}_L(t+1)$ is the predictive estimate of P_L at time $(t+1)$ given all the measurements through t, $\widetilde{P}(t+1)$ is the error covariance associated with the predictive estimate $\widetilde{P}_L(t+1)$, $K(t+1)$ is the Kalman gain, and Q and R are the variances for the process voice $W(t-1)$ and measurement noise $V(t)$, respectively. We need the initial conditions when using the Kalman filter for the first time. From the problem statement we can say

$$\widehat{P}_L(t_1) = \ln(L_0) \tag{19}$$

Otherwise, the previous updated filter estimate is input to the filter to obtain the current updated estimate. The uplink transmitting power of MUE can be obtained from the above filtering result under the power constraint $P_{\mathrm{max,m}}$ by

$$P_0(t+1) = \min\left(P_{\mathrm{max,m}}, \frac{\exp\left(\widehat{P}_L(t+1) - \frac{\ln 10}{10}\cdot\widehat{\mu}_{0,0}\right)}{r_0^{-\alpha_{\mathrm{m}}}}\right) \tag{20}$$

3.2 FUE Power Allocation

The uplink transmit power of FUE can be determined for the first time subject to the power constraint $P_{\mathrm{max,f}}$ according to (13). The interference allowance of the MUE can also be formulated as

$$P_{\mathrm{AGGI}} = \sum_{j=1}^{K} P_j \cdot r_j^{-\alpha_{\mathrm{f}}} \cdot e^{k\hat{\xi}_{0,j}} \tag{21}$$

where $r_j^{-\alpha_{\mathrm{f}}}$ is the path loss from the FUE to B_0, $k\hat{\xi}_{0,j}$ is a Gaussian r.v. with mean $k\widehat{\mu}_{0,j}$ and standard deviation $k\widehat{\sigma}_{0,j}$, and k is a constant equals to $\ln 10/10$. The uplink power P_j can be formulated as

$$P_j \cdot r_j^{-\alpha_{\mathrm{f}}} \cdot e^{k\hat{\xi}_{0,j}} = \frac{P_{\mathrm{AGGI}}}{K}, j = 0, 1, \ldots, K \tag{22}$$

Take logarithm on both sides of (22), and then divide $k\widehat{\xi}_{0,j}$ into two parts $k\widehat{\mu}_{0,j}$ and $k^2\widehat{\sigma}_{0,j}^2\tau$, we can get

$$\ln\left(P_j \cdot r_j^{-\alpha_{\mathrm{f}}}\right) + k\widehat{\mu}_{0,j} + k^2\widehat{\sigma}_{0,j}^2\tau = \ln\frac{P_{\mathrm{AGGI}}}{K} \tag{23}$$

where τ is a standard normal r.v.

Let $P_{\mathrm{f}} = \ln\left(P_j \cdot r_j^{-\alpha_{\mathrm{f}}}\right) + k\widehat{\mu}_{0,j}$ be the estimated process state by the Kalman filter. Using the similar analysis procedure of MUE in the above section, the uplink transmit power of each FUE subject to maximal power constraint $P_{\max,\mathrm{f}}$ can be determined

$$P'_j(t+1) = \min\left(P_{\max,\mathrm{f}}, \frac{\exp\left(\widehat{P}_{\mathrm{f}}(t+1) - \frac{\ln 10}{10}\cdot\widehat{\mu}_{0,j}\right)}{r_j^{-\alpha_{\mathrm{f}}}}\right) \tag{24}$$

4 Performance Evaluation

In this section, we evaluate the performance of our proposed power control scheme through Monte Carlo simulation. We consider a simulation scenario referring to [6]. The simulation scenario is shown in Fig. 2. The main system parameters are given in Table 1.

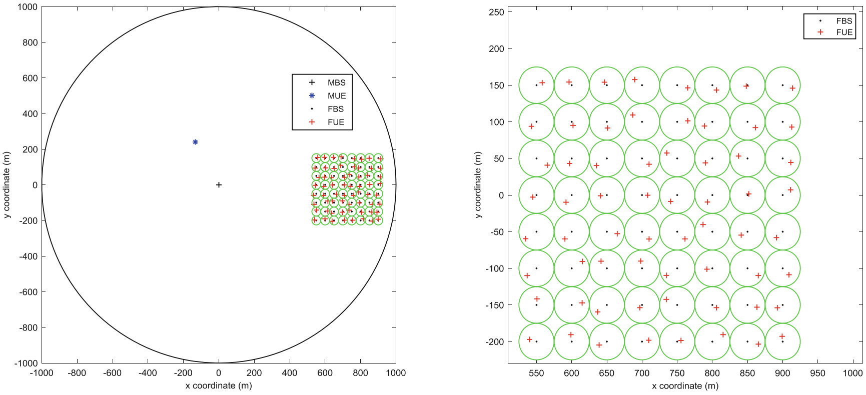

Fig. 2. Simulated two-tier heterogeneous network

Table 1. System parameters

Variable	Parameter	Value
R_m	Macrocell radius	1000 m
R_f	Femtocell radius	30 m
$P_{max,m}$	Max transmission power of MUE	30 dBm
$P_{max,f}$	Max transmission power per FUE	25 dBm
Γ_0	Max cellular SINR target	10
α_{m}, α_f	Path loss exponents	4, 4

Figure 3 shows the estimated power performance of MUE through Kalman filter. The true power of MUE means MUEs optimal transmit power which makes MUE reach its minimum target SINR, mitigating the shadow fading effect to a large extent. The MBS measures its received power transmitted by MUE at time t and determines the transmit power of MUE at time $(t + 1)$ without Kalman filter. We call this transmit power as the measured power of MUE. If the MBS determines the transmit power of MUE at time $(t + 1)$ with Kalman filter, we will call this power as the estimated power of MUE based on Kalman filter. Using Kalman filter we can effectively reduce the measurement errors.

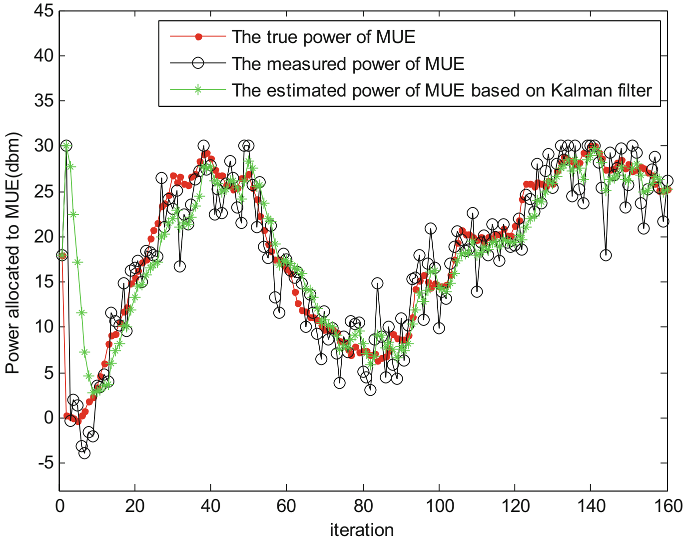

Fig. 3. Power allocated to MUE

Figure 4 compares the measured deviation and estimated deviation. As can be viewed from Fig. 4, the estimated deviation is smaller than the measured deviation.

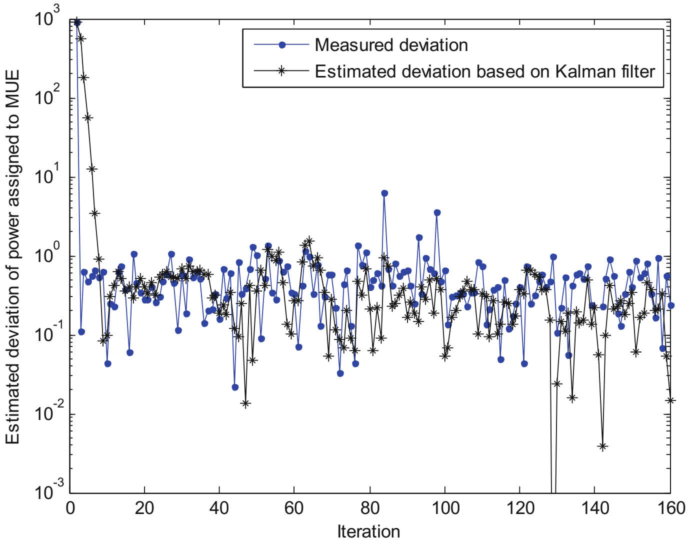

Fig. 4. Estimated deviation of power allocated to MUE

Figure 5 shows the estimated power performance of a certain FUE through Kalman filter. As can be viewed from Fig. 5, Kalman filter is able to follow the true power of FUE with an excellent accurately estimate. Using Kalman filter can effectively reduce the measurement errors.

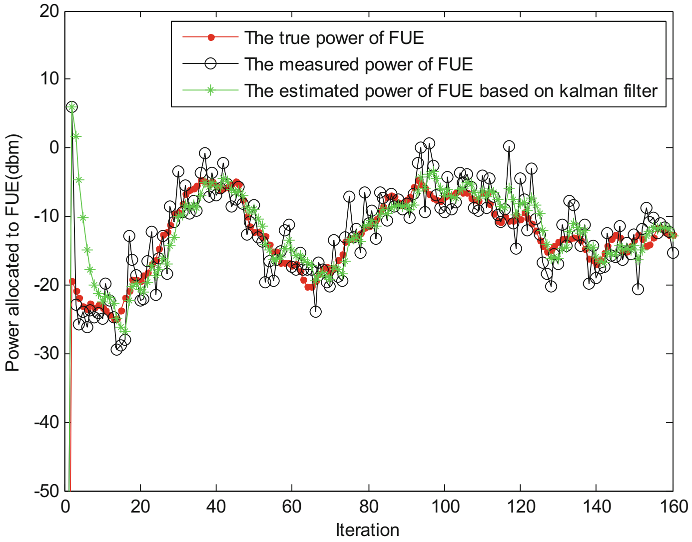

Fig. 5. Power allocated to FUE

Figure 6 compares the measured deviation and estimated deviation based on Kalman filter. As can be viewed from Fig. 6, the estimated deviation is smaller than the measured deviation.

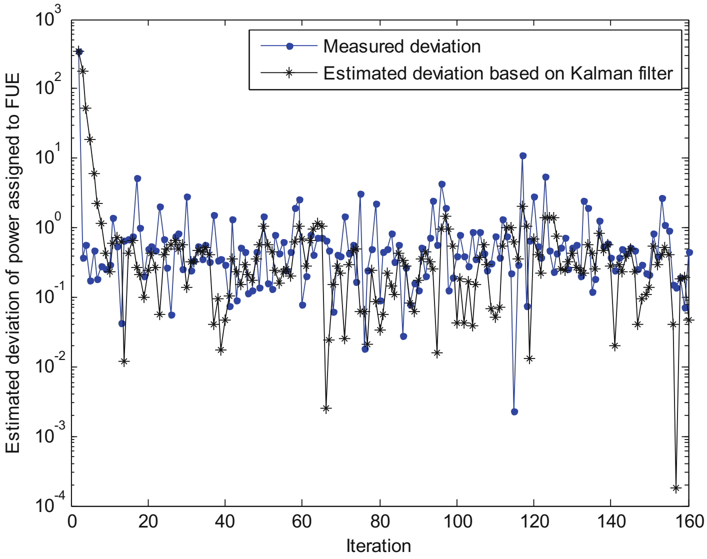

Fig. 6. Estimated deviation of power allocated to FUE

5 Conclusion

In this paper, we have proposed a hierarchical power control scheme based on Kalman filter in two-tier heterogeneous networks. Kalman filter is used to estimate the power P_L and P_f. Then user's transmit power P_0 and P_j can be determined according to P_L and P_f respectively. Through simulations we have proved that using Kalman filter can effectively reduce the measurement errors.

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