Design and Field Test of an Optimal Power Control Algorithm for Base Stations in Long Term Evolution Networks

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Abstract

An optimal power control algorithm based on convex optimization is proposed for base stations in long term evolution networks. An objective function was formulated to maximize the proportional fairness of the networks. The optimal value of the objective function was obtained using convex optimization and distributed methods based on the path loss model between the base station and users. Field tests on live networks were conducted to evaluate the performance of the proposed algorithm. The experimental results verified that, in a multi-cell multi-user scenario, the proposed algorithm increases system throughputs, proportional fairness, and energy efficiency by 9, 1.31 and 20.2 %, respectively, compared to the conventional fixed power allocation method.

Keywords: Convex optimization, objective function, proportional fairness, power control, field test on live networks

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1. Introduction

Long term evolution (LTE) is considered one of the key standards on the roadmap to establish 4G wireless communications, and orthogonal frequency division multiple access (OFDMA) was selected as the air interface solution for the downlink. In LTE networks, heterogeneous networks are a promising technique to meet increasing demand for wireless services and boost throughputs. However, as network architecture becomes more complex, interference becomes very complicated, and an efficient power control algorithm is required to effectively suppress interference and improve system performance.

Current research on downlink power control schemes focuses on formulating the optimization problem, obtaining the optimal solution under certain conditions (e.g. transmission rate, power, and user signal to interference plus noise ratio (SINR)), and improving system performance. In these studies [1-8], both power control and resource assignment schemes are considered, and resources (e.g. frequency and power resources) are allocated to each user in real time based on the exchange of a large amount of information (e.g. interference level, frequency and power resource allocation, and user distribution) among base stations (BSs). Joint scheduling and power allocation problem was investigated for OFDMA wireless networks [9] and a centralized improved iterative water-filling algorithm was proposed and discussed. Distributed power control has been used [10] to reduce inter-cell interference (ICI), especially when there was lack of cooperation between BSs. A distributed power control heuristic algorithm was proposed [11], which allocated downlink power for each resource block (RB) according to received channel quality indication (CQI) feedback. A scheme for joint scheduling, power allocation, and modulation and coding scheme (MCS) selection to maximize the overall weighted throughput with proportional fairness [12] has also been proposed. A novel framework of cognitive radio assisted cooperation (CRAC) for downlink transmissions in OFDMA was proposed [13]. One of promising novelties is that the proposed CRAC considers joint resource allocation which includes transmission mode selection, relay station allocation, and transmit power/sub-channel allocation, to cost-effectively provide services and applications. These power control schemes mainly aimed to configure the power resource for each user combined with the spectrum assignment, while maintaining each user's SINR and quality of service (QOS) requirements.

However, none of the above realizations were applied and tested on live LTE systems. These optimization problems find a configuration of channel selection and power allocation that improves network performance. They have high combinatorial complexity and are difficult to solve for large networks. In general, there is a lack of efficient algorithm operating in a distributed manner and ensuring global optimality for joint optimization.

This paper considers the downlink of OFDMA systems, where a physical resource block (PRB) of downlink frame structure contains two types of subcarriers, a reference signal (RS) and a date carrier for physical downlink shared channel (PDSCH) and other physical channels. RS energy per resource element (EPRE) is constant, given by the reference signal power parameter provided by higher layers. The ratio of PDSCH EPRE to RS EPRE is denoted by P_A. If P_A is small the total downlink transmit power is small, whereas large P_A implies the total downlink transmit power is also large. On live networks, RS EPRE and P_A are usually configured empirically, and PDSCH EPRE and transmit power of each subchannel are identical. To provide larger coverage, the total downlink transmit power of the BS is usually large.

A convex distributed algorithm optimizing the overall power consumption of the BSs is proposed and analyzed here to alleviate inter-cell interference and improve cell edge spectrum efficiency. The transmission power of each BS subchannel for a live network is the same, and the proposed optimal power control algorithm optimizes the power resource without demanding joint optimization of power and frequency resources. Optimizing the power level of all BSs in large networks can significantly reduce inter-cell interference and optimize the overall network performance. A major challenge, particularly for co-channel heterogeneous networks of LTE-Advanced, is the appropriate setting of transmit power levels at different tiers of marco/pico/femto BSs.

The proposed algorithm features a fast convergence rate and low complexity, without requiring a large amount of information interaction among BSs. Most importantly, the proposed scheme can be deployed on live networks and can be validated and tested in the field. On live networks, the proposed optimal power control algorithm can optimize power level configuration for newly added BSs, as well as optimizing allocation of power resource of existing networks based on the user distribution pattern.

The main contributions of this work are as follows:

1) Real LTE Networks were considered at the design stage, in which PDSCH EPRE is identical in each subchannel, and the proposed optimal objective problem can be resolved by optimal allocation of BS power level. Based on optimal allocation of BS power, inter-cell interference can be reduced greatly in large networks and joint scheduling of the frequency resource for users among cells is not required. The proposed optimal power control algorithm simplifies the high combinatorial complex optimizing problem and is effective in improving large network performance;
2) During analysis, it became clear that maximizing the sum of throughputs leads to very low throughput for some users, and a novel optimization objective was introduced, to maximize the sum of the proportional fair utility, which significantly decreases BS power consumption and improves the cell edge user throughput;
3) Extensive evaluation of the proposed optimal power control algorithm was performed in a real LTE deployment in Shanghai City and the various improvements highlighted.

The proposed power control algorithm is described in Section 2, with field test procedures and results presented in Section 3, and compared to system level simulation. The outcomes are summarized in Section 4.

2. Proposed Power Control Algorithm

2.1 Network Architecture and Problem Formulation

Consider the downlink of an OFDMA system consisting of N BSs with fixed transmit power levels, where the total system bandwidth, B, is divided into N_{RB} resource blocks (RBs), each containing N_{RE} resource elements (REs). Each RB is composed of N_{sc} successive subcarriers over N_{sy} symbols with full frequency reuse across the cell. U active users are uniformly distributed in the coverage range of each BS node. Users and BSs are each equipped with one receive and one transmit antenna. Let k be the index of user terminals, $k \in \{1, 2, \ldots, U\}$, and i be the index of BSs, $i \in \{1, 2, \ldots, N\}$. In this paper, optimization BS power is configured based on medium and long term user distribution and network condition, and only the slow fading channel is considered. The International mobile telecommunications-advanced (IMT-A) was used to model path loss in a slow fading channel. Transmission power of each BS resource element (RE) on the network is assumed identical. Thus, SINR is constant across the frequencies. If user k is associated with BS.i, its SINR is

$$SINR_{i,k}(P) = \frac{P_i \times G_{i,k}}{B \times \sigma^2 + \sum_{j=1(j \neq i)}^{N} P_j \times G_{j,k}}, \tag{1}$$

where $G_{i,k}$ is the channel gain from BS.i to user k; σ^2 is the power spectral density (PSD) of the background additive white Gaussian noise (AWGN), P_i is the transmit power of BS.i, and $P = [P_1, P_2 \cdots P_N]$ represents the BSs downlink transmitter power. The achievable throughput of UE_k can be expressed as

$$T_{i,k}(P) = B_{i,k} \times \ln(1 + SINR_{i,k}), \tag{2}$$

where $B_{i,k}$ represents the allocated bandwidth for UE_k.

The optimization problem to maximize the sum of throughputs can be formulated as

$$\begin{aligned} &\max \sum_{i \in N} \sum_{k \in U} T_{i,k}(P) \\ &s.t \quad P_{\min} \leq P_i \leq P_{\max} \;\; \forall i \in N \end{aligned}, \tag{3}$$

where P_{max} and P_{min} are the maximum and minimum transmission power of a BS node, respectively.

Maximizing the sum throughputs often leads to very low throughput for some users and does not ensure any fairness with respect to the distribution of power [14-15]. A novel optimization object is defined for the proportional fair utility, F,

$$F_{i,k}(P) = \ln\left(B_{i,k} \times \ln(1 + SINR_{i,k})\right), \tag{4}$$

with gradient

$$D_{SINR} F_{i,k} = \frac{1}{\ln(1 + SINR_{i,k})} \times \frac{1}{1 + SINR_{i,k}}, \tag{5}$$

which is larger than the gradient of $T_{i,k}$ when $SINR_{i,k}$ < e-1. Thus, $F_{i,k}$ increases more significantly than $T_{i,k}$ for lower $SINR_{i,k}$. To maximize the sum of proportional fair utilities, the optimization problem can be formulated as

$$\begin{aligned} &\max \sum_{i \in N} \sum_{k \in U} F_{i,k}(P) \\ &s.t \quad P_{\min} \leq P_i \leq P_{\max} \;\; \forall i \in N \end{aligned}. \tag{6}$$

By improving lower $SINR_{i,k}$, the overall proportional fair utility will be greatly increased. Therefore, maximizing the sum of proportional fair utilities can significantly improve SINR of cell edge users and fairness to users. Optimization problems (3) and (6) find the optimal power configuration that maximizes the sum of $T_{i,k}$ and $F_{i,k}$, respectively.

2.2 Proposed Optimization Power Control Algorithm

To simply the problem, the proposed power control algorithm assumes spectral resources are allocated equally among users on average [15-17]. Thus, optimization problems (3) and (6) can be simplified to

$$\begin{aligned} &\max \sum_{i\in N}\sum_{k\in U} T_{i,k}(P) = \frac{B}{U}\times \max \sum_{i\in N}\sum_{k\in U} \ln\left(1+SINR_{i,k}\right), \\ &s.t \quad P_{\min} \le P_i \le P_{\max} \end{aligned} \tag{7}$$

and

$$\begin{aligned} &\max \sum_{i\in N}\sum_{k\in U} F_{i,k}(P) = \sum_{i\in N}\sum_{k\in U} \ln\left(\frac{B}{U}\right) + \max \sum_{i\in N}\sum_{k\in U} \ln\left(\ln\left(1+SINR_{i,k}\right)\right), \\ &s.t \quad P_{\min} \le P_i \le P_{\max} \end{aligned} \tag{8}$$

respectively.

Maximization of the overall proportional fair utility problem is called scheme 1 and maximization of the total throughput problem is called scheme 2.

Convex optimization was employed to solve the optimization problems. A convex approximation algorithm [17] and a low-complexity distributed algorithm [18-19] were applied consecutively to maximize total system throughput and proportional fairness. First, non-convex problems (7) and (8) were transformed into a series of convex problems by utilizing the lower bound for any $z \ge 0$ and $z_0 \ge 0$,

$$\ln(1+z) \ge \alpha \ln(z) + \beta, \tag{9}$$

which is tight at $z=z_0$ when the approximation constants are chosen as

$$\begin{aligned} \alpha &= \frac{z_0}{1+z_0} \\ \beta &= \ln(1+z_0) - \frac{z_0}{1+z_0}\ln(z_0) \end{aligned} . \tag{10}$$

With this lower bound, optimization problems (7) and (8) can be approximated as

$$\max \sum_{i\in N}\sum_{k\in U} \alpha_{i,k} \ln(SINR_{i,k}) + \beta_{i,k}, \tag{11}$$

and

$$\max \sum_{i\in N}\sum_{k\in U} \ln\left(\alpha_{i,k}\ln(SINR_{i,k})+\beta_{i,k}\right), \tag{12}$$

respectively, where

$$\begin{aligned} \alpha_{i,k} &= \frac{SINR_{i,k}}{1+SINR_{i,k}} \\ \beta_{i,k} &= \ln(1+SINR_{i,k}) - \alpha_{i,k}\ln(SINR_{i,k}) \end{aligned}. \tag{13}$$

The lower bound achievable total throughput (11) and proportional fair utility (12) are concavified by the transformation $p_i = e^{\lambda_i}$. When the approximation constants $\alpha_{i,k}$ and $\beta_{i,k}$ are fixed for each user, these become standard concave maximization problems. Indeed, each constraint is constant and each term in the objective function is concave since they are the sum of the linear and concave term. (where log-sum-exp, e.g. $f(x)=\log(e^{x_1}+\cdots+e^{x_n})$ is convex [20]).

The successive convex approximation algorithm alternates between steps

(a) fix $\left\{\alpha_{i,k}^{t}, \beta_{i,k}^{t}\right\}$, solve (11)–(12) and obtain $\left\{P^{t+1}, P^{t+1}=\left[P_1^{t+1}, P_2^{t+1}, \cdots P_N^{t+1}\right]\right\}$;

(b) update parameters $\left\{\alpha_{i,k}^{t+1}, \beta_{i,k}^{t+1}\right\}$ according to (13) using $\left\{P^{t+1}, P^{t+1}=\left[P_1^{t+1}, P_2^{t+1}, \cdots P_N^{t+1}\right]\right\}$.

In the process of successive convex approximation, the solutions to concave problems (11) and (12) are required. The convex optimization problems are

$$\min_{\lambda} \sum_{i=1}^{N} -r_i(\lambda), \tag{14}$$

and

$$\min_{\lambda} \sum_{i=1}^{N} -f_i(\lambda), \tag{15}$$

where

$$\begin{aligned} r_i(\lambda) &= \sum_{k\in U}\alpha_{i,k}\ln\left(\frac{e^{\lambda_i}\times PL_{i,k,i}}{B\times\sigma_{i,k}^2+\sum_{j=1(j\neq i)}^{N} e^{\lambda_j}\times PL_{i,k,j}}\right)+\beta_{i,k} \\ s.t \quad & P_{\min} \le e^{\lambda_i}, e^{\lambda_j} \le P_{\max} \end{aligned}, \tag{16}$$

and

$$f_i(\lambda)=\sum_{k\in U}\ln\left(\alpha_{i,k}\ln\left(\frac{e^{\lambda_i}\times PL_{i,k,i}}{B\times\sigma_{i,k}^2+\sum_{j=1(j\neq i)}^{N}e^{\lambda_j}\times PL_{i,k,j}}\right)+\beta_{i,k}\right). \tag{17}$$

$$s.t \quad P_{\min}\le e^{\lambda_i},e^{\lambda_j}\le P_{\max}$$

The corresponding Lagrangians are

$$\mathcal{L}_r(\lambda,y,\omega)=\sum_{i\in N}-r_i(\lambda)+\left\langle y,e^{\lambda_i}-P_{\max}\right\rangle+\left\langle \omega,P_{\min}-e^{\lambda_i}\right\rangle, \tag{18}$$

and

$$\mathcal{L}_f(\lambda,y,\omega)=\sum_{i\in N}-f_i(\lambda)+\left\langle y,e^{\lambda_i}-P_{\max}\right\rangle+\left\langle \omega,P_{\min}-e^{\lambda_i}\right\rangle. \tag{19}$$

The Distributed Lagrangian Primal-Dual Subgradient Algorithm (DLPDS) algorithm [19] was used to find the Lagrangian saddle points and optimal values. Obtaining the optimal value of convex optimization problem (15) is described, and the same method applies to (14).

The Lagrangian for each BS node is

$$\mathcal{L}_{fi}(\lambda,y,\omega)=-f_i(\lambda)+\left\langle y,e^{\lambda_i}-P_{\max}\right\rangle+\left\langle \omega,P_{\min}-e^{\lambda_i}\right\rangle, \tag{20}$$

and the process steps are:

(a) The initial power value is exchanged between BS nodes.

(b) Initialize $\alpha_{i,k}^{(0)}$ and $\beta_{i,k}^{(0)}$ using (13) based on the initial power of BS nodes ($p_i^{(0)}$) and the path loss model.

(c) Initialize outer iteration counter q=1.

(d) Initialize inner iteration counter t=1.

(e) Each BS.i node maintains three vectors of $N\times 1:\{\lambda_i,y_i,\omega_i\}\ \forall i\in N$, the initial value of λ_i is the initial power configuration of the N BS nodes, the initial value of y_i and ω_i are random numbers.

(f) At each time, t, each BS node obtains the three vectors $\{\lambda_i(t),y_i(t),\omega_i(t)\}$ of all neighbor BS nodes and generates $\{\lambda_i(t+1),y_i(t+1),\omega_i(t+1)\}$ according to the following rules:

$$\begin{cases} v_\lambda^i(t)=\sum_{i=1}^{N}1/N\cdot\lambda_i(t) \\ v_y^i(t)=\sum_{i=1}^{N}1/N\cdot y_i(t)\ , \\ v_\omega^i(t)=\sum_{i=1}^{N}1/N\cdot\omega_i(t) \end{cases} \tag{21}$$

$$\partial(t) = 0.1/\sqrt{t}$$
$$\begin{cases} \lambda_i(t+1) = P_{\lambda_i}\left[v_\lambda^i(t) - \partial(t) D_\lambda \mathcal{L}_{fi}\left(\lambda_i(t), y_i(t), \omega_i(t)\right)\right] \\ y_i(t+1) = P_{y_i}\left[v_y^i(t) + \partial(t) D_y \mathcal{L}_{fi}\left(\lambda_i(t), y_i(t), \omega_i(t)\right)\right] \\ \omega_i(t+1) = P_{\omega_i}\left[v_\omega^i(t) + \partial(t) D_\omega \mathcal{L}_{fi}\left(\lambda_i(t), y_i(t), \omega_i(t)\right)\right] \end{cases}, \quad (22)$$

where $D_\lambda \mathcal{L}_{fi}$, $D_y \mathcal{L}_{fi}$ and $D_\omega \mathcal{L}_{fi}$ are the gradients

$$\begin{aligned} &\forall m \in N \text{ and } m = i \\ &D_\lambda \mathcal{L}_{fi}(\lambda, y, \omega) = -\left\{\sum_{k=1}^{U} \frac{\alpha_{i,k}}{\alpha_{i,k} \ln(SINR_{i,k}) + \beta_{i,k}}\right\} + \left\langle y_m, e^{\lambda_m}\right\rangle - \left\langle \omega_m, e^{\lambda_m}\right\rangle, \end{aligned} \quad (23)$$

$$\begin{aligned} &\forall m \in N \text{ and } m \neq i \\ &D_\lambda \mathcal{L}_{fi}(\lambda, y, \omega) = \\ &\sum_{k=1}^{U}\left\{\frac{\alpha_{i,k}}{\alpha_{i,k}\ln(SINR_{i,k}) + \beta_{i,k}} \times \frac{e^{\lambda_m} \times PL_{i,k,m}}{B \times \sigma_{i,k}^2 + \sum_{j=1(j\neq i)}^{N} e^{\lambda_j} \times PL_{i,k,j}}\right\} + \left\langle y_m, e^{\lambda_m}\right\rangle - \left\langle \omega_m, e^{\lambda_m}\right\rangle \end{aligned}, \quad (24)$$

$$\begin{aligned} &D_y \mathcal{L}_{fi}(\lambda, y, \omega) = e^{\lambda_m} - P_{\max} \\ &D_\omega \mathcal{L}_{fi}(\lambda, y, \omega) = P_{\min} - e^{\lambda_m} \quad \forall m \in N \end{aligned}, \quad (25)$$

where P_{λ_i}, P_{y_i} and P_{ω_i} are the projection operators onto the set λ_i, y_i and ω_i, respectively. The scalars $1/N$ are non-negative weights and the scalars $\partial(t)$ are step-sizes.

(g) When $\left(\sum F\left(P^{t+1}\right) - \sum F\left(P^{t}\right)\right) \leq \sigma$, the convex function is convergent, the inner iteration will be terminated and provides the solution $P_i^{(q)} = \exp\left(\lambda_i^{t+1}\right)$, σ is usually less than 1×10^{-3}.

(h) Repeat steps (f)–(g), until $\left(\sum F\left(P^{t+1}\right) - \sum F\left(P^{t}\right)\right) \leq \sigma$.

(i) Update elements of $\alpha_{i,k}^q, \beta_{i,k}^q$ using (13) at $SINR_{i,k}\left(P_i^{(q)}\right)$.

(j) Set q=q+1.

(k) Repeat steps (d)–(j) until convergence. (When $\left(\sum F\left(P^{q+1}\right) - \sum F\left(P^{q}\right)\right) \leq \delta$ the function is convergent and δ is usually lower than 1×10^{-3}.)

In the proposed scheme, P_{max} and P_{min} are constant constraints. In traditional marco-only networks, P_{max} and P_{min} are the same for all BSs. In heterogeneous networks, P_{max} and P_{min} are different for different tiers of marco/pico/femto BSs. Once the user deployment model is obtained, the algorithm process is the same for marco-only and heterogeneous networks. The computation complexity of the whole algorithm is $O(N^2)$.

The flowchart of the proposed optimal power control method is shown in **Fig. 1**. Optimal power control starts with measurement of path loss. Then the BS nodes exchange initial power and calculate initial values of the parameters α, β according to the SINR. Based on these parameter values, the inner iteration is executed using DLPDS. After the inner iteration condition is satisfied, α, β are updated based on the current BS power allocation. If the objective function is convergent, the algorithm terminates. Otherwise, a new inner iteration is performed based on the updated parameters.

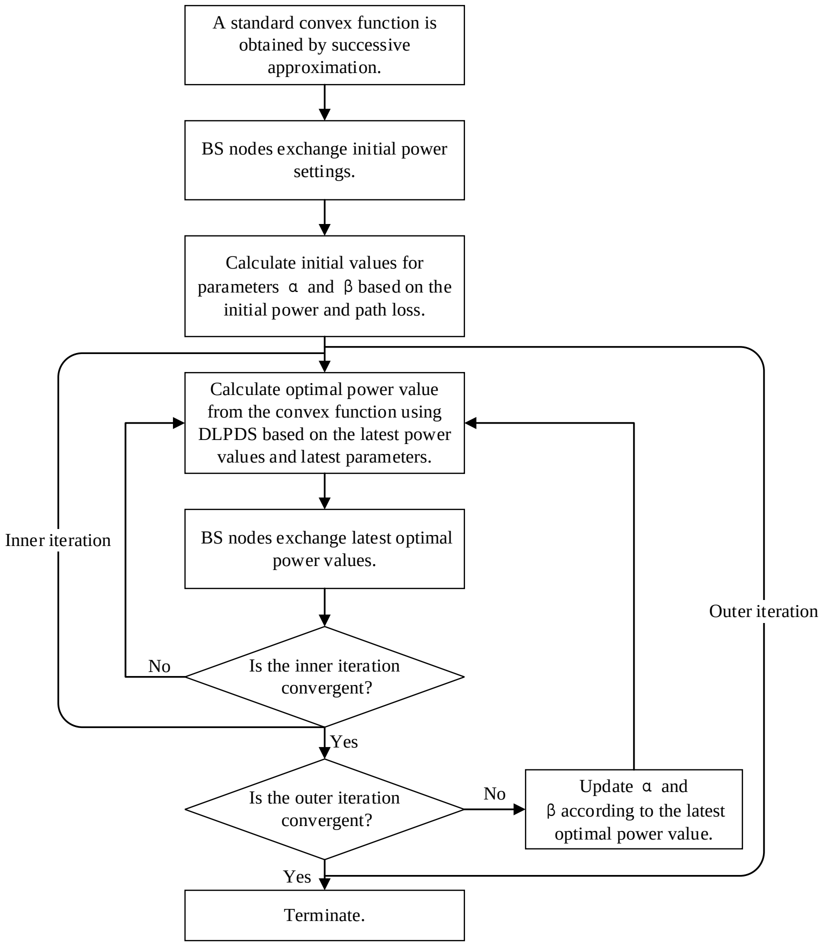

Fig. 1. Flowchart for the proposed optimal power control algorithm

2.3 Simulation Results

The performance of the proposed optimal power control schemes 1 and 2 were evaluated by computer simulation. The simulation parameters are shown in **Table 1**, and conform to 3GPP specifications. System throughput and network proportional fairness from the proposed schemes were compared with those for a fixed power scheme, where each BS transmits with the maximum power in the downlink. In the simulation, BSs average the allocation of frequency resource among users without considering frequency resource scheduling. In the network architecture, the central BS node is labelled as BS.1 and other BS nodes as BS.2–BS.7, successively.

Table 1. Parameters used in the computer simulation

Simulation Parameters	Settings
Network Layout	7 Omni BS nodes
Max/Min power	20/5 W
Inter-site distance	500m
Coverage Radius of BS	2/3*ISD
Number of users	30
Bandwidth	20MHz
Traffic model	Full buffer
Distance-dependent Path loss model	PL(dB)=128.1+37.6log10(R),R in Km

The effectiveness of the proposed optimal power control schemes are illustrated with a particular user distribution, where all users of BS.1, BS.2, BS.4, and BS.6 are in the central region and all users of BS.3, BS.5, and BS.7 in an edge region. Fifty iterations of user deployment were performed. **Fig. 2** shows user cumulative density function (CDF) throughput for the different BS power control schemes. **Table 2** shows simulation results from one of the 50 different user deployments.

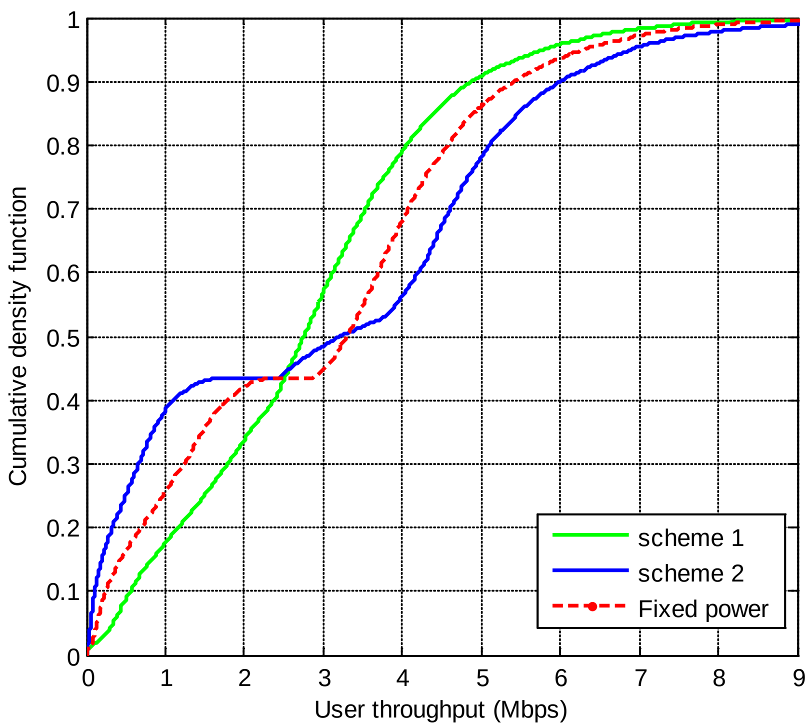

Fig. 2. User throughput for different BS power control schemes in a particular user distribution scenario

Table 2. Simulation results for any round of user deployment in a particular user distribution scenario

BS & Performance		**Fixed power**	**Scheme1**	**Scheme2**
Power configuration (W)	BS.1	20	5.12	6.65
	BS.2	20	5.13	20
	BS.3	20	20	5.30
	BS.4	20	5.12	20
	BS.5	20	20	5.27
	BS.6	20	5.12	20
	BS.7	20	20	5.34
5%-ile User Throughput levels		0.12Mbps	0.34Mbps	0.05Mbps
Throughput/cell		87.18Mbps	84.44Mbps	89.66Mbps
Proportional fairness		226.50	261.56	/

Cell edge user throughput gains are achieved when the BS nodes power are allocated based on maximizing system proportional fair utility. The main reason is that power for BS.1, BS.2, BS.4, and BS.6 is decreased. Maximizing the system throughput power control algorithm reduces power for BS.3, BS.5, and BS.7 and sacrifices edge user throughput to obtain total system throughput gains. Lower throughput users in optimal power control scheme 2 are more than in scheme 1 (**Fig. 2**), e.g. scheme 2 throughputs of users less than 0.3 Mbps (blue line) accounts for 20 %, whereas scheme 1 throughputs of users lower than 0.3 Mbps (green line) accounts for only 4 %. Scheme 2 higher throughput users are also larger than scheme 1, e.g. 80 % of scheme 1 users (blue line) are less than 5.2 Mbps, whereas 80 % of the scheme 2 users (green line) are less than 4 Mbps. For this user distribution simulation, maximizing the system proportional fair utility power control scheme enhances the cell edge user throughput by reducing BSs power and inter-cell interference. In contrast, to improve total system throughput, maximizing system throughput power advances the cell center users throughput, but cell edge user throughput is greatly reduced.

Rather than maximizing the throughput sum, i.e. $\sum_{i\in N}\sum_{k\in U} T_{i,k}(P)$, which leads to very low throughput for some users, the proposed method maximizes the sum of proportional fair utilities, i.e. $\sum_{i\in N}\sum_{k\in U} F_{i,k}(P)$, which can be seen as an equilibrium between user fairness and throughput. Extensive evaluation was performed maximizing the proportional fair utility power control scheme for computer simulation and for live LTE networks in Shanghai City. Maximizing the proportional fair utility power control scheme is from here on referred to the optimal power control scheme.

The performance of the optimal power control algorithm with the fixed power scheme was investigated. Fifty rounds of user deployment were performed, with users uniformly distributed in each BS coverage area. **Fig. 3** shows user throughput CDF for different BS power control schemes, and **Fig. 4** shows outer iteration results for the optimal power control algorithm. The proposed algorithm converges quickly, with the inner iteration converging after 30 iterations. **Table 3** shows the simulation results from one round of user deployment.

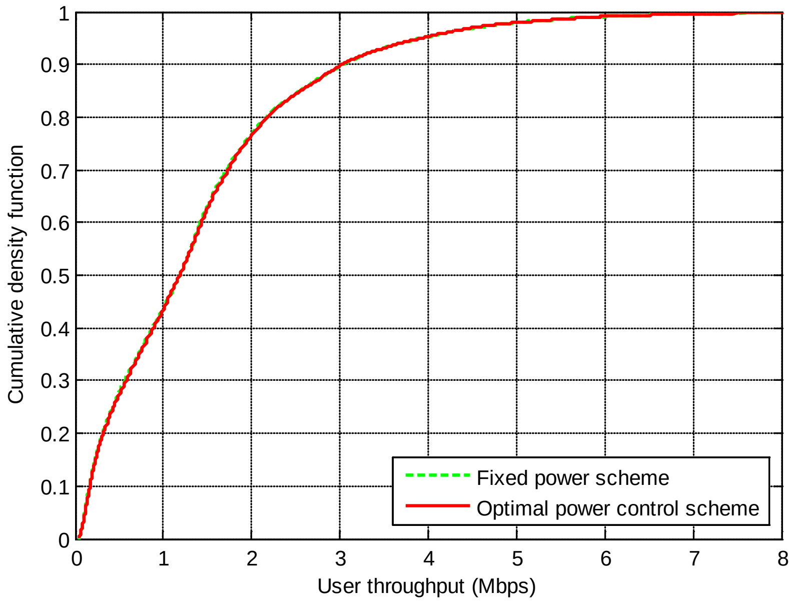

Fig. 3. User throughput for different power schemes

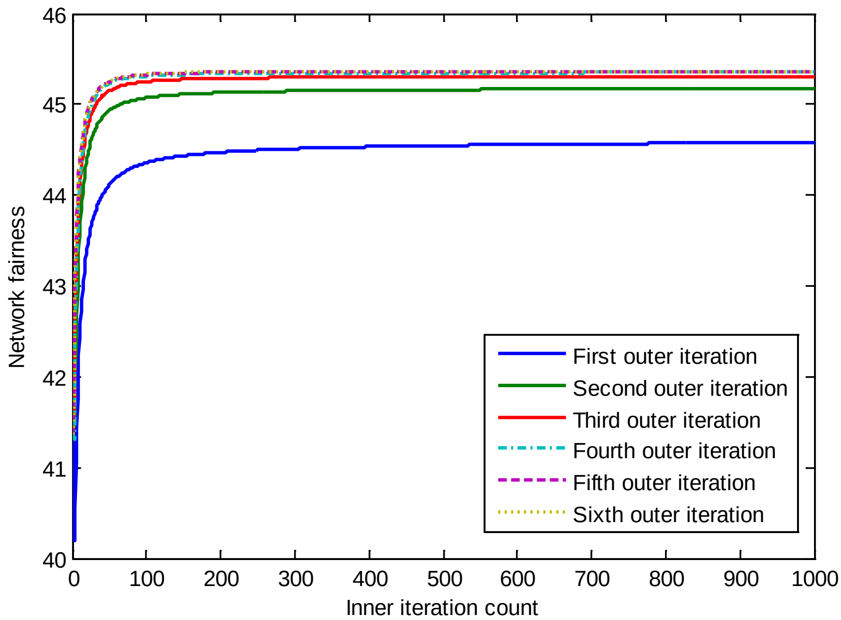

Fig. 4. Outer iteration for a typical round of user deployment

The optimal power control scheme achieves a 1.7 % improvement at the fifth percentile user throughput CDF levels and a 9.7 % improvement of network proportional fairness. Cell throughputs are also slightly improved, and network power consumption decreases by 56 %. Thus, the proposed scheme significantly improves energy efficiency while guaranteeing system throughput performance.

Table 3. Simulation results in any round of user deployment

BS & Performance		Fixed power	Optimization power
Power configuration (W)	BS.1	20	6.64
	BS.2	20	5.57
	BS.3	20	5.68
	BS.4	20	9.24
	BS.5	20	14.09
	BS.6	20	10.93
	BS.7	20	9.05
Proportional fairness		41.36	45.37
Throughput/cell		39.52 Mbps	39.93 Mbps

In simulation, system throughput for the optimal power control scheme decreased slightly for the specific user distribution scenario and increased slightly for the uniform users distribution scenario compared to the fixed power scheme. The optimal power control algorithm trades off between fairness and throughput based on the particular user deployment scenario. Although cell center user throughputs were reduced, overall user throughput and network performance was retained. Thus, the proposed control system can improve user fairness and maintain system throughput. For the uniform user distribution scenario, throughput in each simulation was always enhanced slightly.

3. Field Evaluation

Numerical simulations verified the performance of the proposed optimal power control algorithm. However, it is critical to test the proposed algorithm on live networks to verify real world effectiveness.

3.1 Field Testing Area

Field tests were conducted on two different districts in Shanghai, China, denoted as Area A and Area B, as shown in **Figs. 5 6**, respectively.

Area A was located in the more rural area of the city and contained two BS nodes, denoted as AP.1 and AP.2, each of which contained three sectors. Equipment at these BS nodes was supplied by Alcatel Lucent and tests were conducted over the 2.316 GHz band using 20 MHz bandwidth. Maximum and minimum BS downlink transmission power were 20 W and 5 W, respectively.

Area B was located in the downtown area of the city and contained nine BS nodes, denoted as BS.1–BS.9. BS.1 and BS.2 were small omni BSs, whereas the other nodes included three sectors. The BS nodes used ZTE equipment and tests were conducted over the 2.1 GHz band using 15 MHz bandwidth. Maximum and minimum downlink transmission power for the small BSs (BS.1 and BS.2) were 5 W and 1 W, respectively, and 15 W and 5 W, respectively, for the other BSs.

Fig. 5. Area A

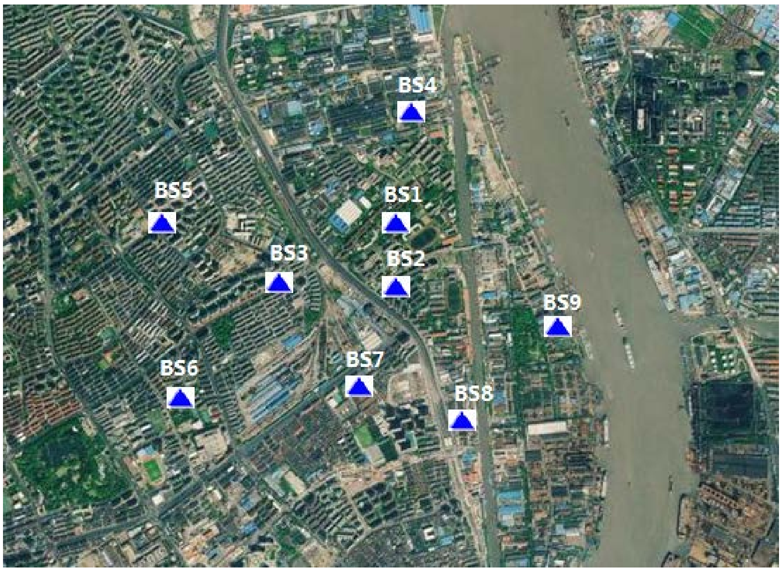

Fig. 6. Area B

3.2 Test Locations

In Area A, tests were performed in a simple environment that contained two test cells and two users. Cell 1 and 2 of AP.1 were selected as test cells and one user was deployed in each cell. To evaluate the proposed algorithm, tests were performed in two scenarios, as shown in **Fig. 7.** Scenario 1, deployed a test terminal to Position.1-1 of cell 1 and another to Position.1-2 of cell 2. Scenario 2 deployed a test terminal to Position.2-1 of cell 1 and another to Position.2-2 of cell 2.

Fig. 7. Test locations in Area A

A multi-cell multi-user scenario was implemented for Area B. Three adjacent cells (BS1, BS2, and cell 1 of BS3) were selected as test cells, and two users were deployed in each test cell, as shown in **Fig. 8**. The test terminals were located at L.1 and L.2 in the BS.1, L.3 and L.4 in the BS.2, and L.5 and L.6 in the cell 1 of BS.3 coverage areas.

Fig. 8. Test locations in Area B

3.3 Performance Results

Energy efficiency was defined as the ratio of system throughput to BS power consumption, and several tests were performed for each scenario (>3) to estimate reproducibility.

First, network performance was tested for a fixed power configuration. Using the measured path loss information from the fixed power scheme, the optimal power values for the test cells were derived using the proposed optimal power control algorithm. Network performance was then tested after implementing the optimal power values.

Field test and simulation results for scenario 1 in Area A are shown in **Table 4**. In the test case, field test throughputs in the field test were enhanced by 17.5 % and proportional fairness increased by 4.8 % compared with the fixed power scheme, while energy efficiency was increased by 289 % in cell 1 and 94 % in cell 2.

Table 4. Field test and simulation for scenario 1 in Area A

Network Performance		**Fixed power**		**Optimal power**	
		Cell 1	Cell 2	Cell 1	Cell2
Power configuration (W)		17.31	17.31	8.87	5.73
Throughput (Mbps)	Field test results	11.13	17.14	22.21	11.02
		11.13+17.14=28.27		22.21+11.02=33.23	
	Simulation results	22.09	36.51	28.25	29.28
		22.09+36.51=58.60		28.25+29.28=57.53	
Proportional fairness	Field test results	5.25		5.50	
	Simulation results	6.70		6.72	
Energy efficiency (Mbps/W)	Field test results	0.64	0.99	2.50	1.92
	Simulation results	1.28	2.11	3.19	5.11

Field test and simulation results for scenario 2 in Area A are shown in Table 5. In the test case, proportional fairness was increased by 3 % compared with the fixed power scheme, while maintaining the same throughput performance, while energy efficiency was increased by 132 % in cell 1 and by 110 % in cell 2.

Table 5. Field test and simulation for scenario2 in Area A

Network Performance		**Fixed power**		**Optimal power**	
		Cell 1	Cell 2	Cell 1	Cell2
Power configuration (W)		17.31	17.31	9.35	7.57
Throughput (Mbps)	Field test results	7.64	25.27	9.58	23.17
		7.64+25.27=32.91		9.58+23.17=32.75	
	Simulation results	25.63	31.48	28.24	28.78
		25.63+31.48=57.11		28.24+28.78=52.02	
Proportional fairness	Field test results	5.26		5.40	
	Simulation results	6.69		6.70	
Energy efficiency (Mbps/W)	Field test results	0.44	1.46	1.03	3.06
	Simulation results	1.48	1.82	3.02	3.80

Tables 6 and 7 show field test and simulation results for Area B. In the multi-cell multi-user scenario, field test throughputs were enhanced by 9 % and proportional fairness by 1.31 % compared with the fixed power scheme, while energy efficiency was increased by 20.2 %.

Simulation and field tests demonstrate that the proposed optimal power control algorithm can provide significant energy savings and enhance fairness among users, while guaranteeing system throughputs. This is mainly due to reducing BS power, which decreases interference among the cells.

Table 6. Field test and simulation results of each cell in Area B

Network Performance		**Fixed power**			**Optimal power**		
		Cell 1	Cell 2	Cell 3	Cell1	Cell 2	Cell 3
Power configuration (W)		3.45	3.45	13.75	1.51	3.45	13.75
Throughput (Mbps)	Field test results	19.69	28.42	20.42	19.49	37.67	17.54
	Simulation results	18.75	39.23	18.98	11.10	47.33	25.80
Proportional fairness	Field test results	4.56	5.31	4.65	4.52	5.84	4.34
	Simulation results	4.49	5.92	4.48	3.70	6.32	5.06

Table 7. Field test and simulation results of system in Area B

Network Performance		Fixed power	Optimal power
Power configuration (W)		3.45/3.45/13.75	1.51/3.45/13.75
System throughput (Mbps)	Field test results	68.53	74.70
	Relative improvement	9.0 %	
	Simulation results	76.95	84.18
	Relative improvement	9.4 %	
System proportional fairness	Field test results	14.52	14.71
	Relative improvement	1.3 %	
	Simulation results	14.98	15.08
	Relative improvement	1.3 %	
System energy efficiency (Mbps/W)	Field test results	3.32	3.99
	Relative improvement	20.2 %	
	Simulation results	3.73	4.50
	Relative improvement	20.6 %	

4. Conclusion

An optimal power control algorithm was proposed based on convex optimization and the distributed method. The proposed scheme was applied to live networks, and implemented in a field trial with simple and complex network deployments. Field test results were consistent with the simulation results, and compared to fixed BS power control, the proposed algorithm can increase system throughputs, proportional fairness and energy efficiency by 9, 1.31 and 20.2 % respectively, in a multi-cell multi-user scenario.

The conclusion is that by decreasing BS transmission power, better interference suppression can be obtained.

The proposed scheme can effectively improve cell edge throughput and user fairness, while reducing energy use and help realize Green Communication.

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