

Evaluation of Power Control Strategies for Dense Wireless Networks

Caio R. Santos and Francisco R. P. Cavalcanti

Abstract—This paper presents a comparative analysis of power control algorithms for dense wireless uplink networks. Three approaches are evaluated under noise- and interference-limited scenarios: DPC, MaxSum, and MaxProd. Results show that DPC provides higher energy efficiency, while MaxProd achieves a balanced trade-off between system capacity and user fairness.

Keywords—6G, Power Control, Dense Wireless Networks, Energy Efficiency, User Fairness.

I. INTRODUCTION

The evolution of mobile networks toward sixth-generation (6G) systems aims to meet the increasing demand for high data rates and low latency in uplink communications. Simultaneously, modern communication systems are expected to achieve high levels of energy efficiency. Furthermore, improved energy and spectral efficiency in the uplink direction are required due to the continuous growth of user-generated traffic [1]. In addition, 6G networks are expected to mitigate outage events and performance degradation at cell edges, which is particularly important for mission-critical applications. To reconcile these requirements, a promising approach is network densification by employing small cells, thereby increasing the number of access points (APs) within a given coverage area. However, shorter inter-AP distances, wider bandwidths (up to 400 MHz), and universal frequency reuse significantly exacerbate co-channel interference. In this context, Power Control (PC) plays a key role as a Radio Resource Management (RRM) technique for balancing energy efficiency and interference mitigation. Several algorithmic approaches have been proposed for power control. One of the most classical methods is Distributed Power Control (DPC) [2]. This approach is widely adopted due to the simplicity of its distributed implementation and its fast convergence towards a universal target Signal-to-Interference-plus-Noise Ratio (SINR). Alternative optimization criteria for power control relax the assumption of a fixed SINR target, enabling greater flexibility in power allocation and in the resulting trade-offs between individual user equipment (UE) capacity and overall system capacity. This work presents a comparative analysis between DPC and two alternative power control algorithms designed to maximize system capacity and enhance fairness. The evaluation is carried out in two simulated dense wireless uplink scenarios in order to investigate the trade-offs among capacity, fairness, and energy efficiency.

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II. SYSTEM MODEL

A. Channel Modeling

The total path gain for user k over a particular transmitter-receiver (TX-RX) link, as in [3], is given by

$$g_k = \frac{p_{r,k}}{p_{t,k}} = x(\sigma_X) \frac{c}{d^n} r^2(\sigma_r), \quad (1)$$

where $p_{r,k}$ and $p_{t,k}$ are the received and transmitted power for user k to a particular AP uplink respectively; c is a constant, d is the TX-RX distance and n is the distance-dependent path gain exponent; $x(\sigma_X)$ is a lognormal random variable specified by the standard deviation σ_X of its corresponding zero-mean normal distribution, that represents the shadowing effect; the factor $r(\sigma_r)$ represents the fast fading effect over the received signal magnitude for that particular link and is modeled by a Rayleigh random variable with unitary mean power. The UE-AP association is based on a maximum path-gain criterion.

B. Evaluation Scenarios

The system model considers the uplink of a single-channel wireless communication system composed of M APs and K scheduled UEs randomly distributed within an area of dimensions $L \times L$ meters. To evaluate the performance of the PC algorithms, two specific scenarios were considered:

1) **Noise-Limited Scenario (Urban micro-cell)**: In this scenario, the APs are deployed with an inter-site distance (ISD) of 250 m. This configuration represents a dense urban coverage scenario, where the AP-UE distance is the dominant factor affecting the quality of the wireless link between each AP and its associated UE. As long as the number of active UEs is low, system performance is expected to be primarily noise-limited.

2) **Interference-Limited Scenario (Ultra-Dense Network)**: This scenario represents an industrial private-network environment in which the APs are deployed with a reduced ISD of 50 m. The dense deployment is designed to support mission-critical sensors and robotic devices. Under these conditions, the reduced distance among active UEs significantly exacerbates co-channel interference, making it the expected dominant factor limiting overall wireless network performance.

III. POWER CONTROL ALGORITHMS

This section presents the Key Performance Indicators (KPIs) and the power control algorithms to be compared.

A. Key Performance Indicators

1) **SINR (Signal-Interference-plus-Noise Ratio)**: The SINR (γ_k) is the main indicator of link quality between the k -th UE and its serving AP. It represents the ratio between the desired signal power and the sum of interference and thermal

noise powers. The received SINR for user k at a given AP is expressed as follows:

$$\gamma_k = \frac{g_k p_{t,k}}{\sum_{j \neq k} g_j p_{t,j} + p_n}, \quad (2)$$

where p_n is the noise power, g_k and p_k are the path gain and transmitted power for user k , respectively.

2) *Channel Capacity*: The mapping from SINR to channel capacity can be approached using the Shannon equation:

$$C_k = B \log_2(1 + \gamma_k). \quad (3)$$

C_k [bits per second] is the Shannon Limit for UE k using a channel of bandwidth B representing the theoretical upper bound on the information rate.

3) *Sum Capacity*: It represents the metric obtained from the sum of the instantaneous data rates of all K users in the system.

$$C_{sum} = \sum_{k=1}^K C_k. \quad (4)$$

4) *Energy Efficiency*: Indicates how much energy is required to transmit and correctly receive each data bit [bits/Joule] and is defined as:

$$E = \frac{C_{sum}}{\sum_{k=1}^K p_{t,k}}. \quad (5)$$

B. Distributed Power Control Algorithm

The DPC algorithm follows a target-SINR criterion, denoted by γ_{tar} , which represents the desired SINR value for all users. The algorithm is decentralized in nature, meaning that each user adjusts its transmission power using only its own SINR measurement at a given time instant. The optimization problem leading to the DPC algorithm can be formulated and solved through multiple mathematical approaches. The original DPC algorithm as originally proposed by Foschini and Miljanic in [2] was derived from a control-theoretic perspective. In this work we derive it through the stochastic gradient descent method applied to a log-quadratic cost function. It is shown that, for a unitary step size, the gradient-based update rule converges exactly to the classical multiplicative form of the DPC algorithm. This unified approach not only validates the classical algorithm but also extends the optimization framework to more modern power-control criteria based on SINR utility functions [4]. Specifically, for the DPC case, the optimization problem is formulated as the minimization of the following cost function:

$$J(P) = \frac{1}{2} \sum_{k=1}^K (\gamma_{tar} - \gamma_k)^2, \quad (6)$$

where $\mathbf{P}$ is the vector of transmit powers $\mathbf{P} = [p_1 \ \dots \ p_k]$ and the minimization will be performed over $\mathbf{P}$. By applying the *Stochastic Gradient Descent* (SGD) method, the following iterative update rule on time t is obtained ¹:

$$p_k(t+1) = p_k(t) \cdot \frac{\gamma_{tar}}{\gamma_k(t)}. \quad (7)$$

¹The derivation of the equations (7), (9) and (11) are omitted due to space constraints.

If $\gamma_k < \gamma_{tar}$, the user increases its transmission power; if $\gamma_k > \gamma_{tar}$, the transmission power is reduced. This process continues until convergence to the optimal solution, if such a solution exists.

C. MaxSum Algorithm

The MaxSum algorithm is designed to maximize the sum of the SINRs of all users in the system and can be used as a proxy to maximizing the actual sum of capacities. Unlike DPC, it prioritizes spectral efficiency and overall system capacity. The corresponding objective function is defined as follows:

$$J(P) = \sum_{k=1}^K \gamma_k. \quad (8)$$

Applying stochastic gradient descent (SGD) to maximize the objective function over $\mathbf{P}$ yields the following expression:

$$p_k(t+1) = p_k(t) + \mu g_k \left(\frac{1}{I_k} - \sum_{i \neq k} \frac{\gamma_i}{I_i} \right), \quad (9)$$

where $I_k = \sum_{j \neq k} p_j(t) g_j + p_n$ is the interference plus noise term with respect to the k -th UE and μ is a constant step-size.

D. MaxProd Algorithm

It is desirable that a PC algorithm searches for a solution that balances fairness and capacity. An intuitive proposal for an objective function of this sort is the following product criterion, which we will call the MaxProd criterion:

$$J(P) = \prod_{k=1}^K \gamma_k. \quad (10)$$

By maximizing the function over $\mathbf{P}$, the following power update rule for the MaxProd algorithm is obtained:

$$p_k(t+1) = p_k(t) + \mu g_k \left(\frac{1}{\gamma_k I_k} - \sum_{i \neq k} \frac{1}{I_i} \right), \quad (11)$$

where I_k and μ assume the same meanings as in eq. (9). The term $\frac{1}{\gamma_k}$ acts as a fairness-promoting factor: users experiencing low SINR tend to increase their transmission power, whereas users with high SINR tend to reduce or maintain their power levels near the current operating point.

IV. RESULTS AND ANALYSES

A. Simulation Parameters

For the simulations the noise-limited scenario is configured with $M=9$, $K=4$ and $L=750$ meters. The interference-limited scenario is configured with $M=4$, $K=2$ and $L=100$ meters. The Monte Carlo simulation is used to model the random nature of wireless networks, such as user positioning and channel effects. In each simulation run, the users are randomly positioned within the simulation area, and the system captures a snapshot containing the users' locations and channel gains. Within each snapshot, each algorithm independently adjusts the transmission power through successive small steps, simulating temporal evolution. The transmission powers are strictly constrained by maximum (p_{max}) and minimum (p_{min}) power limits. For DPC, the target SINR (γ_{tar}) was chosen to correspond to a channel capacity of 10 Mbps. After convergence, the data are collected and the UEs are repositioned.

This procedure is repeated 1000 times. Finally, the data from all simulation runs are aggregated to generate a Cumulative Distribution Function (CDF) of KPIs.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Bandwidth (B)	100 MHz
Noise power (p_n)	10^{-12} W
c	10^{-4}
n	4
Shadowing standard deviation (σ_X)	8.7 dB
Step-size (μ)	$[10^{-3}, 10^{-4}]$
SINR-target (γ_{tar})	-11.44 dB
Minimum tx power (p_{min})	1 mW
Maximum tx power (p_{max})	1 W

B. Results

In this section, the simulation results are presented and discussed. On the left side of Fig. 1, the scale corresponding to the 10th percentile values of channel capacity for the different scenarios is shown. On the right side, the median values of the sum capacity are presented, enabling a comparison among the evaluated scenarios.

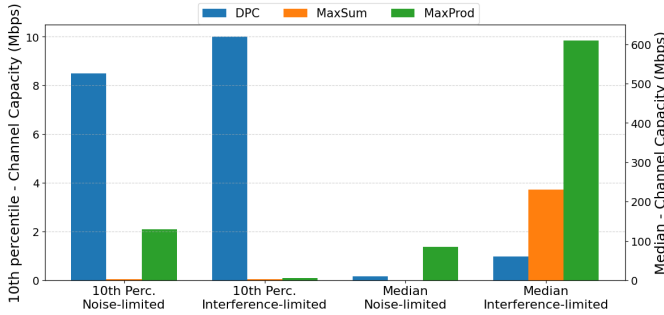


Fig. 1. Channel Capacity: 10th percentile and Median.

Next, Fig. 2 presents the median sum-capacity values across the scenarios, while the right side shows the median energy-efficiency values displayed on a logarithmic scale.

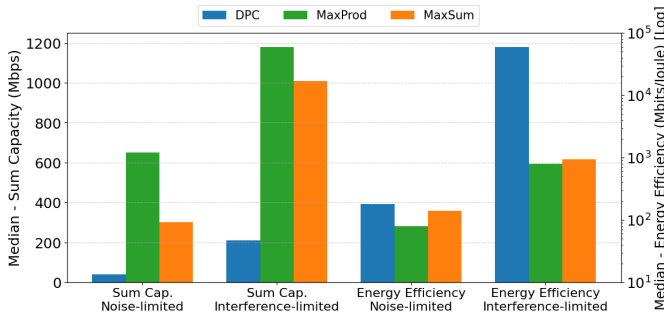


Fig. 2. Median Sum Capacity and Median Energy Efficiency.

C. Discussion

In the noise-limited scenario, the coverage area is relatively large for only 4 APs, leading to larger inter-UE distances and reduced interference levels. In this context, DPC drives users to operate with lower power levels than they otherwise could, prioritizing fairness and energy efficiency. As a result, the algorithm is more suitable for applications that require more precise control of energy consumption, especially in scenarios where energy efficiency is the main KPI. MaxSum prioritizes users with high channel gains and may reduce the transmission power of users with degraded channel conditions (notice its very low edge UE performance) in order to decrease the interference caused to users with favorable channel conditions. MaxProd, on the other hand, seeks that no user experiences a severely degraded link quality, which translates into higher values than MaxSum for both the 10th percentile and the median channel capacity (in this case, higher also than DPC). With the reduction of the coverage area (interference-limited scenario), users become closer to each other, and co-channel interference becomes the dominant factor in the SINR calculation. DPC remains useful for ensuring that all users operate close to the target capacity value. By attempting to maximize the sum capacity, MaxSum generates interference peaks that reduce overall system performance. MaxProd achieves a more balanced coordination of the transmission powers, preventing nearby users from significantly degrading each other's performance. In terms of convergence, DPC was the fastest requiring a few tens of iterations, while MaxSum and MaxProd were slower requiring sometimes several hundred iterations.

V. CONCLUSIONS

There is a clear trade-off among individual user capacity, aggregate sum capacity, and energy efficiency. The DPC algorithm proves to be essential in scenarios where there is a clear performance target (e.g. in Internet of Things - IoT - applications) while maintaining high energy efficiency. On the other hand, for best effort traffic, DPC results in severe underutilization of the system resources, with relatively low resulting median UE data rate and total sum capacity. In contrast, MaxProd emerges as the most balanced solution for the typical user, as it avoids both the spectrum underutilization observed in DPC and the low capacity experienced by the worst-case users in MaxSum, making it a promising approach for dense 5G and 6G networks.

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