Transport Density vs. Channel Access Time in Wireless Networks: Power Control and Efficient MAC Design

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***Abstract*— Power control plays an important role in the design and operation of wireless networks. In this paper, we first define two critical metrics, *transport density* and *channel access time* to measure the system performance. The trade-off between these two metrics as a function of the peak power constraint is discussed in two cases, a fixed peak power case and an adjusted peak power case. Our analysis shows that the adjusted peak power constraint outperforms the fixed one in terms of both transport density and channel access time. Based on these observations, a novel and fully distributed energy-efficient MAC scheme with adjusted peak power constraint is proposed to schedule the concurrent transmissions in an efficient way. Better performance can be achieved by balancing between transport density and channel access time. Simulation results confirm the expected gains relative to standard MAC schemes: the transport density is increased by more than 50% compared to CSMA and by about a factor of 3 compared to ALOHA.**

I. Introduction

A. Motivation

In a wireless network of n links sharing the same frequency bandwidth with each link corresponding to a transmitter and an associated receiver, the goal of power control is to adjust the transmit powers such that the signal-to-interference-plus-noise ratio (SINR) of each receiver meets a given threshold required for acceptable performance. The SINR for the ith receiver is given by

$$\rho_i = \frac{a_{ii} P_i}{\sum_{j \neq i} a_{ij} P_j + \eta}, \tag{1}$$

where a_{ij} is the static channel gain from the jth transmitter to the ith receiver, P_i is the power of the ith transmitter, and η is the noise power. Each receiver has a minimal SINR requirement $\rho > 0$. The iterative distributed power control algorithm [1]

$$P(k+1) = FP(k) + u, \tag{2}$$

converges to a minimal power solution P^*, where $P = (P_1, \cdots, P_n)^T \in \mathbb{R}_+^n$ (denoted as $P > 0$) is the column vector of transmit power, $u = \left(\frac{\rho\eta}{a_{11}}, \frac{\rho\eta}{a_{22}}, \ldots, \frac{\rho\eta}{a_{nn}}\right)^T$, and F is a matrix with

$$F_{ij} = \begin{cases} 0, & \text{if } i = j \\ \frac{\rho a_{ij}}{a_{ii}}, & \text{if } i \neq j \end{cases} \tag{3}$$

where $i, j \in \{1, 2, \cdots, n\}$. (2) can be rewritten in the form

$$P_i(k+1) = \frac{\rho}{\rho_i(k)} P_i(k), \tag{4}$$

where $\rho_i(k)$ is the current SINR for ith receiver at time k, and $P_i(k)$ is the power of the ith transmitter at time k.

The distributed power control algorithm with peak power constraint has been proposed in [2] as follows

$$P_i(k+1) = \min\left\{\frac{\rho}{\rho_i(k)} P_i(k), p_{\max}\right\}, \tag{5}$$

where $p_{\max}$ is the peak power constraint for all transmitters.

However, the problem using (5) is that a transmitter may hit its peak power at some iteration point with its receiver's SINR less than the desired threshold [3]. As a result, the transmitters cannot guarantee that their associated receivers achieve the desired SINR threshold even though they continue to transmit at peak power while the power of those nodes that satisfy the SINR condition at the same iteration point will converge to a feasible solution less than the peak power constraint. In other words, those links that transmit at peak power are undesirable in the network since they cannot meet their SINR threshold but still cause interference to the other links. From a view of energy-efficient MAC design, this is doubly wasteful: on the one hand, transmitting at peak power in vain is very energy-inefficient; on the other, it causes high interference. Hence, it is of great importance to design a MAC scheme with better power control. For a pool of link candidates, we update the nodes' transmit power using (4) and shut down any node whose transmit power hits the peak power. After some iteration, the remaining links will converge to some feasible power within the peak power constraints.

The key questions now are: (i) what peak power constraints should we choose, a fixed peak power constraint for every node or a different peak power constraint for different nodes? (ii) Given a large number of link candidates, how can we schedule more concurrent transmissions in a faster way, *i.e.,* is there a tradeoff between scheduling and efficiency? In this paper, we will address these questions.

B. Related Work

Much of the study on cellular network power control started in the 1990s such as in [1], [4], [5]. An efficient and

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distributed power control algorithm for cellular systems, now commonly referred to as the Foschini-Miljanic algorithm, was provided in [1]. [6], [7] proposed joint power control and scheduling algorithms. Moreover, constrained power control has been studied in [8], [9] since the maximum transmit power of a mobile user is limited. A heuristic scheduling scheme is provided in [6] to determine a maximum subset of concurrently active links by shutting down the link with the minimum SINR until all the SINR requirements are satisfied. However, it is not distributed since one node needs all the SINR information from other nodes in order to decide if it can transmit or not. In [10] we proposed a MAC scheme that includes the peak power constraint in a natural way. Similar idea is applied to the MAC scheme in this paper, which is fully distributed and less complex.

II. System Model and Performance Metrics

A. System Model

We consider a wireless network on the plane $\mathbb{R}^2$ where n transmitters are uniformly distributed in a $l \times l$ square and their associated receivers are uniformly located in the circle centered at these transmitters with radius R_i iid Rayleigh distributed with expectation $\mathbb{E}[R_i]$. Assume that the static channel gain is $a_{ij} = \max\left\{\left(\frac{d_0}{d_{ij}}\right)^\gamma, 1\right\}$, where γ is the path loss exponent, d_0 is the normalization distance, and d_{ij} is the distance between transmitter j and receiver i. Also, assume that all nodes in the wireless network share the same frequency bandwidth.

B. Channel Access Time

In [11], the concept of contractive interference functions is introduced to study the distributed power control law. [11, Theorem 1] states that if I is a contractive interference function, then it has a unique fixed point P^* and for every initial vector $P(0)$, the sequence $P(k+1) = I(P(k))$ converges geometrically to P^* as follows $\|P(k) - P^*\|_\infty^{\mathbf{v}} \leq c^k \|P(0) - P^*\|_\infty^{\mathbf{v}}$, where $\|\mathbf{x}\|_\infty^{\mathbf{v}} = \max_i \left|\frac{x_i}{v_i}\right|$ for a given vector $\mathbf{v} > 0$ and $I(P(k)) = FP(k) + u$, or, elementwise, $I_i(P(k)) = \frac{\rho}{\rho_i(k)} P_i(k)$ for (4). In the following, considering $\mathbf{v} = \mathbf{1}$ results in $\|\mathbf{x}\|_\infty = \max_i |x_i|$.

Convergence time is a critical parameter in the evaluation of a distributed power control algorithm. In [11], the convergence time K_δ[1] is defined as follows:

Definition 1. [11] The convergence time K_δ is defined to be the smallest k such that $\|P(k) - P^*\|_\infty \leq \delta$.

Note that $\|P(k) - P^*\|_\infty \leq c^k \|P(0) - P^*\|_\infty$. Letting $c^k \|P(0) - P^*\|_\infty \leq \delta$ and if $c < 1$, it is shown that $K_\delta = \left\lceil \frac{1}{\ln c} \ln \frac{\delta}{\|P(0) - P^*\|_\infty} \right\rceil$, where $\lceil x \rceil$ denotes the smallest integer great than x.

We can learn two things from this definition: (i) From the mathematical definition of convergence, the fact that $P(k)$ converges to P^* is equivalent to the statement that for $\forall \delta > 0$, there is an integer K_δ such that $k \geq K_\delta$ implies $\|P(k) - P^*\|_\infty \leq \delta$. Therefore, the convergence time condition follows from the convergence directly. (ii) This definition enables us to obtain a theoretical convergence time for the distributed power control algorithm. From [1], $P^* = (I - F)^{-1} u$ as long as the Perron–Frobenius eigenvalue of F is less than 1. However, the information of the theoretical minimal power solution P^* is usually not available to the nodes if there is no centralized controller. Since the SINR requirement ρ is known to all nodes, we can redefine the convergence time similarly and extend it to an energy-efficient MAC scheme where power control is used in the channel access phase to decide what subset of links is good to transmit. We call the time that the network spends in this phase the channel access time which is defined as follows:

Definition 2. (Channel Access Time) The channel access time $K_{\delta'}$ is defined to be the smallest k such that $\|\boldsymbol{\rho}(k) - \boldsymbol{\rho}\|_\infty \leq \epsilon$, where $\boldsymbol{\rho}(k) = [\rho_1(k), \rho_2(k), \cdots, \rho_n(k)]$ and $\boldsymbol{\rho} = \rho \mathbf{1}_{n\times 1}$.

Next, we will show that these two definitions are equivalent.

Lemma 3. *K_ϵ and K_δ are equivalent in the sense that there exists an $\epsilon(\delta)$ such that $K_{\epsilon(\delta)} = K_\delta$.*

Proof: First, note that for any $k \geq 1$,

$$\begin{aligned} P_i(k) &= I_i(P(k-1)) \\ &= \rho \frac{\sum_{j \neq i} a_{ij} P_j(k-1) + \eta}{a_{ii}} \\ &> \rho \frac{\eta}{a_{ii}} \\ &\geq \rho \frac{\eta}{\max_i \{a_{ii}\}}. \end{aligned}$$

Hence, for $k \geq 0$ and $\forall i \in \{1, 2, \cdots, n\}$, $P_i(k)$ is lower bounded by $p_{\min} = \min\left\{\rho \frac{\eta}{\max_i\{a_{ii}\}}, \min_i \{P_i(0)\}\right\}$. Assume that the initial power $P_i(0) > 0$ for $\forall i \in \{1, 2, \cdots, n\}$. Hence, $p_{\min} > 0$.

$$\begin{aligned} \|\boldsymbol{\rho}(k) - \boldsymbol{\rho}\|_\infty &= \max_i \{|\rho_i(k) - \rho|\} \\ &= \max_i \left\{\left|\frac{\rho P_i(k)}{P_i(k+1)} - \rho\right|\right\} \\ &= \rho \max_i \left\{\left|\frac{P_i(k) - P_i(k+1)}{P_i(k+1)}\right|\right\} \\ &\leq \frac{\rho}{p_{\min}} \max_i \{|P_i(k) - P_i(k+1)|\} \\ &\leq \frac{\rho}{p_{\min}} \max_i \{|P_i(k) - P_i^*|\} + \\ &\quad \frac{\rho}{p_{\min}} \max_i \{|P_i(k+1) - P_i^*|\} \\ &= \frac{\rho}{p_{\min}} \|P(k) - P^*\|_\infty + \\ &\quad \frac{\rho}{p_{\min}} \|P(k+1) - P^*\|_\infty \\ &\leq \frac{\rho(1+c)}{p_{\min}} \|P(k) - P^*\|_\infty. \end{aligned}$$

[1] K_δ is called the convergence time of the iteration in [11]. We use the convergence time in this paper for brevity and clarity.

Hence, choosing $\epsilon = \frac{\rho(1+c)}{p_{\min}}\delta$ and $\|P(k) - P^*\|_\infty \leq \delta$ implies $\|\boldsymbol{\rho}(k) - \boldsymbol{\rho}\|_\infty \leq \epsilon$. By definition, it is possible to have $K_\epsilon = K_\delta$.

This holds intuitively since that $P(k)$ converges to P^* implies that $\boldsymbol{\rho}(k)$ converges to $\boldsymbol{\rho}$ if the powers are updated using (4). Therefore, the channel access time can be obtained once every receiver's SINR is within the error range ϵ which is much simpler than the form in [11]. Another difference is that the original definition is transmitter-centric while the channel access time is receiver-centric.

C. Transport Density

Similarly to the transport capacity in [12], [13], we will use the following variation of the transport density in [14].

Definition 4. (Transport Density) The transport density is defined as the sum of the products of bits and the distances of all scheduled links whose SINR satisfies $\|\boldsymbol{\rho}(k)-\boldsymbol{\rho}\|_\infty \leq \epsilon$, averaged over the network realizations. It is denoted as T. Assume that all n links in a wireless network are located within a $l \times l$ region and within a time slot, a link will carry the same number of bits (W) regardless of its length as long as it can be scheduled successfully, *i.e.*, its SINR requirement can be satisfied. Then, the transport density is

$$T = \frac{W}{l^2}\mathbb{E}\left[\sum_{i=1}^{n} d_{ii} 1_{\{|\rho_i(k)-\rho| \leq \epsilon\}}\right],$$

where 1_A is the indicator function and d_{ii} is the link distance of link i.

Its unit is $\text{bits} \cdot \text{m}/\text{m}^2$. Note that $\boldsymbol{\rho}(k) \to \boldsymbol{\rho}$ can only be achieved in the limit as $k \to \infty$. Therefore, it is reasonable to loosen the convergence condition to be that the error of SINRs is within some range $\epsilon \ll 1$.

This metric is a precise indicator of a network's capacity. For link scheduling, maximizing the transport density is more meaningful than maximizing the number of successfully scheduled links as in [10] since a longer link contributes more to the transport capacity than a shorter link.

III. Energy-Efficient MAC scheme with Peak Power Constraint

The goal of our work is to design an energy efficient MAC scheme with a peak power constraint that achieves a high transport density at small channel access time.

A. A Novel MAC Scheme

Our proposed MAC scheme with Peak Power Constraint (MAC/PPC) operates in a totally distributed way. Each transmitter only needs to know its channel gain and its associated receiver's SINR. No information from other nodes is needed. Compared to the D^{2}PC-MAC scheme in [10], this MAC scheme is fully distributed and less complex. Each transmitter makes the decision to transmit or not independently by checking if its transmit power is greater than its peak power constraint.

In the algorithm, we implement the power control algorithm in (4) and eliminate the link i as soon as its transmit power reaches $p_{i,\max}$. Thus, the remaining links can satisfy their SINR conditions, and their powers will converge to some $P_i^* < p_{i,\max}$. Consequently, the remaining links constitute the subset of links that can transmit concurrently with minimal power levels. The details are given in the following algorithm:

Algorithm 1 MAC/PPC

1: Run the distributed power control algorithm for a given set S of n links with initial power $P_i(0) = \rho\eta/a_{ii}$;
2: If any link i's power $P_i(k) \geq p_{i,\max}$, shut down the link immediately;
Run the algorithm until the SINRs for the remaining links satisfy the condition $\|\boldsymbol{\rho}(k) - \boldsymbol{\rho}\|_\infty \leq \epsilon$ for a given ϵ

In **Algorithm 1**, the choice of peak power is a key parameter that will affect the system performance. There exists a trade-off between the transport density and the channel access time when choosing different peak power in **Algorithm 1** as we discuss in the following.

B. Fixed Peak Power Case

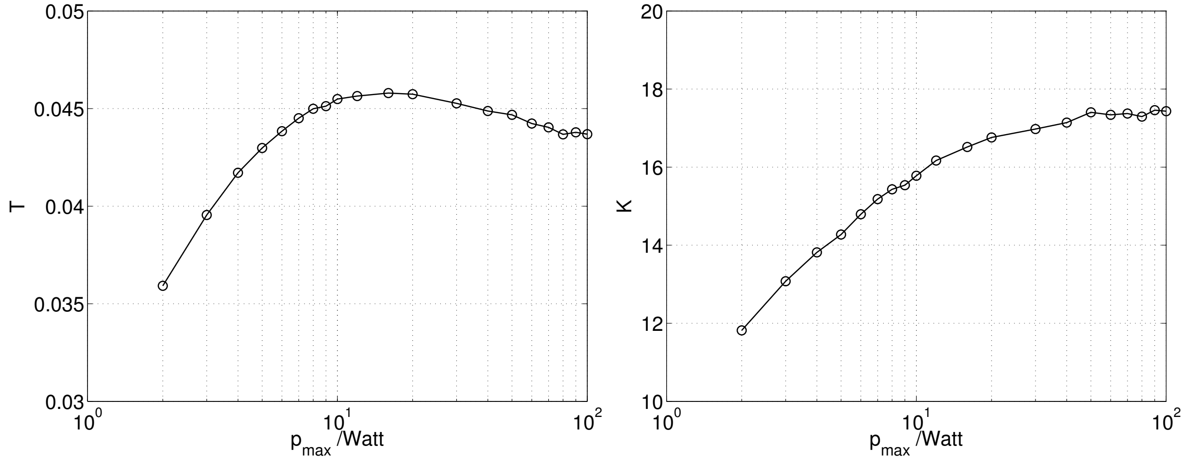
To see how the choice of peak power affects the transport density and the channel access time, we first set $p_{i,\max}$ to be the same peak power $p_{\max}$ for each node.

Fig. 1 shows the influence of different peak power $p_{\max}$ on the transport density and channel access time when jointly scheduling the links and updating the powers using **Algorithm 1** for a fixed number of total links. As illustrated in Fig. 1(a), the transport density is a concave function of the peak power $p_{\max}$. Larger $p_{\max}$ does not necessarily generate higher transport density. The maximum is achieved around 15 in this setup. On the other hand, the channel access time always increases with the peak power. That means, it is undesirable to choose the peak power too large since it will increase the channel access time without any benefit for the transport density. Hence, the peak power parameter needs to be tuned such that the transport density and the channel access time are well balanced. Here, in our setup, the range between $[8, 20]$ is a good choice.

C. Adjusted Peak Power Case

Fig. 1 shows the case of fixed peak power constraint for every node. It might be inefficient since the link distances are different. Normally, a long link tends to need a higher power level while lower power likely guarantees the convergence of short links' SINR. So when a short link cannot coexist with the other links, it will take more time to shut it down if the same (and usually large for short links) peak power constraint is set for every node. Therefore, it is preferable if the peak power constraint can be adjusted based on the link distance or a function of link distance, *i.e.*, channel gain a_{ii}. A candidate is to set

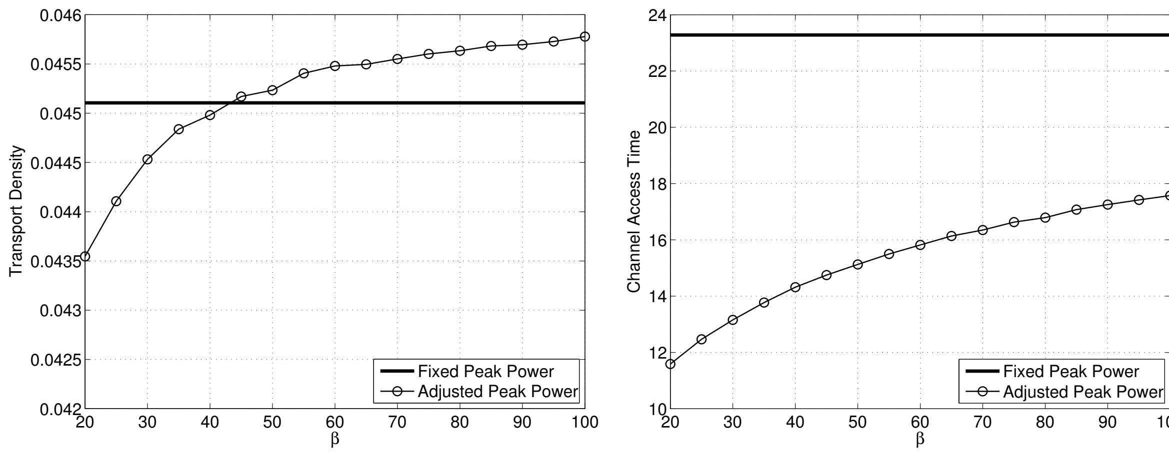
$$p_{i,\max} = \min\left\{\beta\rho\eta/a_{ii}, p_{\max}\right\}, \tag{6}$$



(a) Transport Density vs. Peak Power

(b) Channel Access Time vs. Peak Power

Fig. 1: Transport density and channel access time as a function of $p_{\max}$ with $n = 50$, $l = 20$, $\mathbb{E}[R_i] = 1$, $\rho = 12$ dB, $\epsilon = \rho/100$, $\gamma = 4$, $d_0 = 0.1$, $\eta = 10^{-6}$, $P_i(0) = \rho\eta/a_{ii}$. The results are averaged over 10000 realizations for each $p_{\max}$.



(a) Transport Density vs. β

(b) Channel Access Time vs. β

Fig. 2: Transport density and channel access time as a function of adjusted peak power parameter β with $n = 50$, $l = 20$, $\mathbb{E}[R_i] = 1$, $\rho = 12$ dB, $\epsilon = \rho/100$, $\gamma = 4$, $d_0 = 0.1$, $\eta = 10^{-6}$, $P_i(0) = \rho\eta/a_{ii}$, $p_{\max} = 10$. The results are averaged over 10000 realizations for each β.

where $p_{i,\max}$ is the individual peak power constraint for node i, $p_{\max}$ is the peak power choice mentioned in the fixed peak power case and β is a parameter that adjusts the dynamic range of this variable.

Fig. 2 shows the channel access time and transport density as a function of parameter β given a fixed number of total links and compares the adjusted peak power case with the fixed peak power case. The fixed peak power case has nothing to do with the parameter β and therefore is flat. In Fig. 2(a), it is illustrated that the transport density using adjusted peak power in (6) is better than that using the fixed peak power when β is greater than 45. There is no penalty for the performance gain in transport density. On the contrary, the channel access time is dramatically improved compared to the fixed peak power case. Therefore, it can increase the transport density and reduce the channel access time at the same time by using adjusted peak power. As a result, it can outperform the fixed peak power case easily.

Fig. 3 illustrates the trade-off between the channel access time and transport density with varied parameter β and $p_{\max}$. For fixed peak power case, a longer channel access time is needed to obtain the maximal transport density. Also, this plot can serve as a tool for MAC design, *i.e.*, given an acceptable channel access time and transport density, $p_{\max}$ and β can be chosen properly based on this plot. Moreover, the upper envelope of the curves with different β (illustrated as the dashed curve in Fig. 3) can serve as the best achievable performance curve for $n = 50$. In a wireless system with any number of links, a similar performance curve can be obtained for MAC design to select proper values for the parameters $p_{\max}$ and β.

Remarks.

- $\|\boldsymbol{\rho}(k) - \boldsymbol{\rho}\|_\infty \leq \epsilon$ is not the strict convergence condition. It might occur that there is no power solution even if $\|\boldsymbol{\rho}(k) - \boldsymbol{\rho}\|_\infty \leq \epsilon$ is satisfied or no link gets scheduled. However, simulation shows that for $n = 50$,

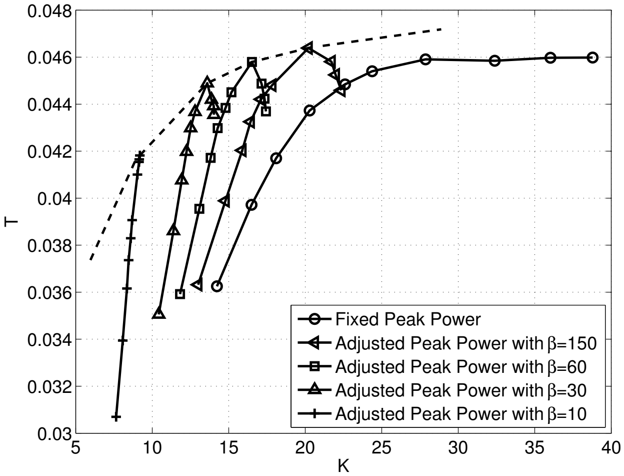


Fig. 3: Transport density vs. channel access time for two peak power cases with varied $p_{\max} \in [2, 100]$, $n = 50$, $l = 20$, $\mathbb{E}[R_i] = 1$, $\rho = 12$ dB, $\epsilon = \rho/100$, $\gamma = 4$, $d_0 = 0.1$, $\eta = 10^{-6}$, $P_i(0) = \rho\eta/a_{ii}$, $\beta = 60$. The dashed curve is the upper envelope for all β. The results are averaged over 10000 realizations.

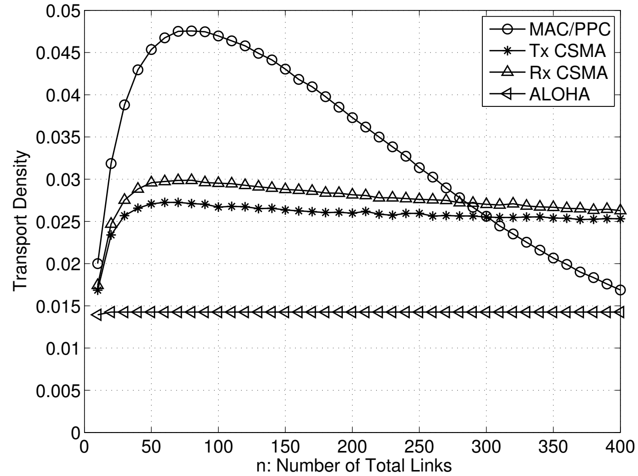


Fig. 4: Transport density of successfully scheduled links vs. the number of total links for differenct schemes with $\alpha = 1.5$, $l = 20$, $\mathbb{E}[R_i] = 1$, $\rho = 12$ dB, $\epsilon = \rho/100$, $\gamma = 4$, $d_0 = 0.1$, $\eta = 10^{-6}$, $P_i(0) = \rho\eta/a_{ii}$, $\beta = 60$, $p_{\max} = 10$. For each n, the results are averaged over 10000 realizations.

the estimated convergence probability (defined in [15]) for the scheduled links is 99.4% for the fixed peak power case and 99.9% for the adjusted peak power case which is surprisingly good. This issue can be solved simply by setting the desired SINR slightly greater than the SINR requirement such that the condition implies convergence.

- A wireless network usually has a power constraint that is limited by hardware or regulations. Here, we assume that both the fixed peak power and the adjusted peak power discussed are no larger than that hard power constraint.

IV. Comparison with ALOHA and CSMA

For the purpose of comparison, we use the CSMA scheme implemented as follows: if a receiver's interference power level is smaller than a threshold, the receiver sends a feedback signal to its transmitter to set the transmit power to be

$$P_i = \frac{\alpha\rho\eta}{a_{ii}}, \tag{7}$$

where $\alpha > 1$ serves as a marginal protection to tolerate interference from other links; otherwise, it is impossible to satisfy the receiver i's SINR. The CSMA scheme is described in detail in [10]. Denote this CSMA scheme above as Rx-CSMA since it uses the receiver to "sense" the channel. Similarly, Tx-CSMA lets the transmitter detect the power level and compares it to its predefined threshold to decide if it can transmit. Also, define ALOHA as scheduling each link independently with probability p. ALOHA can be optimized by choosing p as a function of the total number of links n. The ALOHA's transport density is obtained by optimizing over different p, *i.e.*, $T_{\mathrm{ALOHA}} = \max_{p\in[0,1]} T_{\mathrm{ALOHA}}(p)$, where $T_{\mathrm{ALOHA}}(p)$ is the transport density of ALOHA for a given p. The power that ALOHA uses is also given in (7).

Fig. 4 shows the transport density of different schemes. ALOHA has the smallest transport density due to its randomness. Rx-CSMA and Tx-CSMA roughly converge to a maximum asymptotically since they essentially create a guard zone around the receivers or transmitters. The figure verifies the statement in [14] that CSMA can increase the spatial reuse by about a factor of 2 compared to ALOHA. MAC/PPC can obtain a higher transport density than ALOHA, Rx-CSMA and Tx-CSMA for most cases. For larger number of total links (n), the transport density for MAC/PPC decreases. It is mainly because the links are too dense and cause too much interference to each other. As a result, the MAC/PPC will shut down most of the links at the very first few iterations even if some of them may converge within the range of $p_{\max}$ later. Even although the transport density of MAC/PPC scheme for larger number of total links decreases, the channel access time is also reduced accordingly as in Fig. 5. The spatial reuse can be increased by as much as more than 50% compared to CSMA and about a factor of 3 compared to ALOHA.

Remarks.

- For larger number of total links, we can use random thinning, *i.e.* ALOHA, such that the active number of links in the network is the same as the number of links that achieves the maximal transport density in Fig. 4. Then the MAC/PPC is employed. As a result, a consistently high transport density could be achieved.
- The values of β and $p_{\max}$ used in the simulations are not optimally chosen. We can formulate an optimization problem to search for the values of these two parameters such that the transport density is maximized with channel access time smaller than some threshold. Or we can define a new metric *transport efficiency* = *transport density*/*channel access time* to combine these

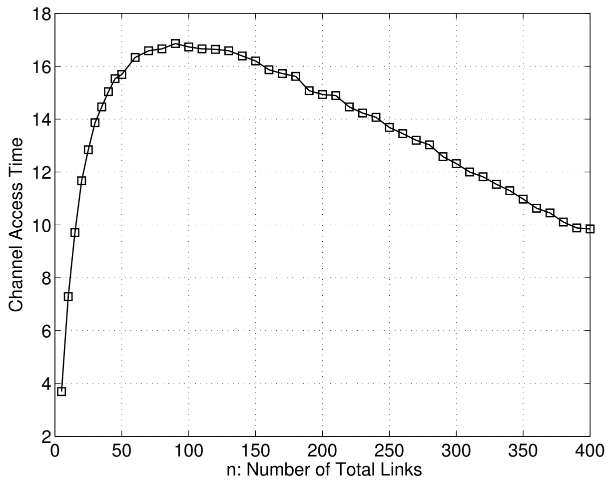


Fig. 5: Channel access time of successfully scheduled links vs. the number of total links with $l = 20$, $\mathbb{E}[R_i] = 1$, $\rho = 12$ dB, $\epsilon = \rho/100$, $\gamma = 4$, $d_0 = 0.1$, $\eta = 10^{-6}$, $P_i(0) = \rho\eta/a_{ii}$, $\beta = 60$, $p_{\max} = 10$. The results are averaged over 10000 realizations.

two system performance metrics. Its advantage is that only one metric needs to be optimized.

- The initial power vector is set to be $P_i(0) = \rho\eta/a_{ii}$. It is the minimal power required for node if all other nodes are idle. The choice builds the connection between the initial power vector and the adjusted peak power constraint, *i.e.*, $p_{i,\max} = \min\{\beta P_i(0), p_{\max}\}$. The initial power vector can reduce the channel access time if it is sufficiently close to the optimal power vector [3]. A better choice might be available.

V. Conclusions

In this paper, we defined two critical performance metrics, transport density and channel access time and discussed the trade-off between them. A novel and distributed MAC scheme was proposed to schedule more concurrent transmissions and therefore increase the spatial reuse. Nodes are allowed to transmit only if their power is lower than some adjusted peak power constraint. With this specially selected constraint, this MAC scheme is easy to implement and fast to converge to minimal powers. Simulation results provide insight into the design of MAC protocol. For wireless networks that are sensitive to delay, our proposed MAC scheme is desirable. Moreover, our MAC scheme only needs the power level and the SINR from its own receiver and therefore is fully distributed and not computationally complex.

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