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Distributed Transmit Power Control for Maximizing End-to-End Throughput in Wireless Multi-hop Networks

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Abstract Wireless multi-hop networks have a *solidarity property*, in which each multi-hop link interferes mutually and so an increase in one link's rate results in a decrease of the other links' rate. In a multi-hop link, the end-to-end throughput between a source and destination is restricted by the lowest link rate, so the *max-min fair allocation* on the link rates is an optimal strategy to maximize the end-to-end throughput. In this paper, we verify that if the wireless links have a solidarity property, the max-min fair allocation has all link rates *equal*, so we propose a transmit power control (TPC) algorithm that decides the transmit power of multi-hop nodes to equalize all link rates. The proposed algorithm operates in a distributed manner, where each node averages the recognized link rates around itself, allocates its transmit power to achieve this average rate, and iterates this operation until all link rates become equal. Intensive simulation shows that the proposed TPC algorithm enables all link rates to converge on the same value, and thus maximizes the multi-hop end-to-end throughput while decreasing the power consumption of multi-hop nodes.

Keywords Transmit power control · Distributed power control · Throughput maximization · Multi-hop network

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1 Introduction

Developments in wireless technologies have enabled the enjoyment of various wireless services, and a tremendous increase in the number of wireless devices. The World Wide Radio Forum (WWRF) has offered a vision for future wireless communication called, “7 trillion wireless devices serving 7 billion people by 2017” [1]. Wireless communication capability would be embedded in every object, everywhere, as well as in personal handheld devices. In order to provide ubiquitous services for such pervasive and huge number of wireless devices, it is reasonable to consider direct communication-based wireless networking technologies in addition to the infrastructure-based communication technologies. Direct communication technologies enable two adjacent devices to directly share information without infrastructures, so they are suitable to be applied to infrastructure-less communication environments, such as mobile ad hoc networks (MANET) and ubiquitous sensor networks (USN). The wireless devices would have low radio frequency (RF) power, and so their communication range would be limited. Therefore, multi-hop transmission through the direct communication with neighboring nodes is necessary to connect with a node that is out of coverage.

For multi-hop communication, we need to find a routing path for connection, allocate radio resources for transmission, and transmit data reliably for reception. In multi-hop environments, the increasing number of nodes increases the traffic load on the network. This also increases the interference among nodes and so the performances are degraded [2]. One of the most effective interference control methods is transmit power control (TPC), which decreases the transmit power of nodes, and so easily mitigates the strong interference in the network. However, excessively small transmit power increases the number of transmission hops. This grows the network traffic load and induces additional interference in the multi-hop network. Therefore, by considering this tradeoff relation in terms of the transmit power level, the transmit power of multi-hop nodes should be decided suitably to maximize the overall multi-hop network performances.

The typical TPC algorithms in wireless multi-hop networks are mainly based on the condition of individual links [3]. Some studies have used the minimum transmit power level that guarantees the signal-to-interference plus noise ratio (SINR) required at the receiving node depending on the quality of service (QoS) of the transmitted packets, aiming at achieving not only interference mitigation but also power saving [4–6]. Others have controlled the transmit power based on the packet size [7, 8]. Therein, greater packet size leads to higher bit error rate (BER), and the transmit power increases with an increase in the packet size. In another approach, the transmit power was determined based on the channel state information (CSI) to maintain a constant BER at the receiver [9]. The transmit power has also been incremented for control packets to prevent interference from hidden nodes in an IEEE 802.11 system [10]. The common power level has also been determined from the perspective of the overall network capacity in order to guarantee the rates of bi-directional links [11].

The objective of typical TPC algorithms in wireless multi-hop networks is mainly to minimize the transmit power consumption while ensuring the QoS (i.e., SINR or BER) of each individual link on the multi-hop path [3]. Such a power minimization problem subject to the SINR constraint can guarantee the required end-to-end rate of a multi-hop link, but cannot maximize it, because the achievable SINR value that maximizes the end-to-end rate of a given multi-hop link is not known. This achievable SINR varies depending on the transmit power of each multi-hop node due to the mutual interference. Therefore, the transmit powers of all nodes should be considered jointly to maximize the end-to-end rate in a given inter-link interference situation. However, this joint operation causes a significant overhead because it requires information sharing among nodes and complex calculations to determine the optimal transmission power in each node. Therefore, in order to maximize the multi-hop end-to-end performance, we should consider both the integrated control of transmit power of participating nodes and the overhead required for this integrated TPC.

We propose a distributed TPC algorithm to maximize the end-to-end throughput in wireless multi-hop networks. We consider the facts that the multi-hop links have a *solidarity property* due to the inter-link interference, and that the multi-hop end-to-end throughput is restricted by the lowest link rate. By verifying that the wireless links with the solidarity property maximize the minimum rate when all link rates are equal, the proposed algorithm decides the transmit powers of nodes to equalize all link rates, thus maximizing the multi-hop end-to-end throughput. Moreover, it is designed to operate in a distributed manner where each node autonomously decides its transmit power by sharing information with only its adjacent nodes in order to reduce system overhead and complexity.

The paper is organized as follows. In Sect. 2, we describe the optimization problem for maximizing multi-hop end-to-end throughput. In Sect. 3, we investigate the solidarity property in wireless links and explain our proposed TPC algorithm in detail. In Sect. 4, we provide simulation results and discuss their performances. Finally, a conclusion is given in Sect. 5.

2 Problem Description

Fig. 1 shows a wireless multi-hop link consisting of n hops from a source to a destination. We define some notation as follows:

- P_i: transmit power of node i
- N_i: noise power of node i
- I_i: interference power received at node i
- g_{ij}: channel gain from node i to node j
- $SINR_{ij}$: SINR from node i to node j
- R_{ij}: achievable rate from node i to node j

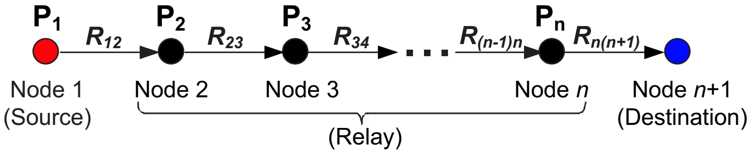


Fig. 1 Wireless multi-hop link.

The end-to-end rate from the source node to the destination node is constrained by the smallest value of the link rates in the multi-hop [12], and it is defined as

$$R_{e2e} := \min\{R_{12}, R_{23}, \cdots, R_{n(n+1)}\}. \tag{1}$$

Our objective is to obtain the transmit powers of all the transmitting nodes that maximize the end-to-end rate R_{e2e}. This is described as the following optimization problem:

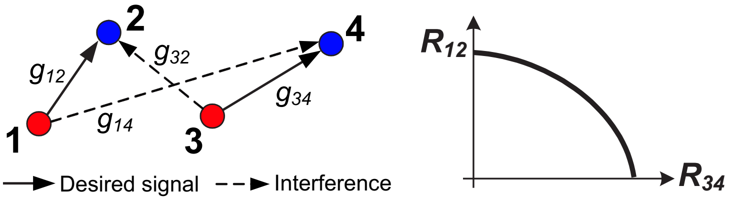
$$\begin{aligned}
\max_{\mathbf{P}} R_{e2e} &= \max_{\mathbf{P}} \min\{R_{12}, R_{23}, \cdots, R_{n(n+1)}\} && (2)\\
\text{s.t.} \quad \mathbf{P} &= [P_1, P_2, \cdots, P_n] && (3)\\
R_{ij} &= log_2(1 + SINR_{ij}) \ \text{ for } i \in \{1, 2, \cdots, n\} \text{ and } j = i + 1 \\
&= log_2\left(1 + \frac{P_i g_{ij}}{I_j + N_j}\right) \\
&= log_2\left(1 + \frac{P_i g_{ij}}{\sum_{\forall k, k \neq i,j} P_k g_{kj} + N_j}\right) \text{[b/s/Hz]} && (4)\\
P_i &\leq P_{max} \quad \text{for } \forall i \in \{1, 2, \cdots, n\} && (5)
\end{aligned}$$

where $\mathbf{P}$ is the vector consisting of the transmit powers of all nodes, P_{max} is the maximum transmit power, and I_j is given by $\sum_{\forall k, k \neq i,j} P_k g_{kj}$ as the sum of interferences from other transmitting nodes that use the same resource. Therefore, the objective function for the proposed TPC is to obtain the transmit power vector $\mathbf{P}$ that maximizes R_{e2e}. Since R_{e2e} is determined as the minimum link rate, we need a strategy that maximizes the minimum link rate (i.e., max-min strategy).

3 Proposed Transmit Power Control

3.1 Solidarity Property in Wireless Links

The rate set of wireless links that use the same radio resource at the same time has a solidarity property due to the mutual interference [13]. The solidarity property is defined as:



(a) Two wireless links (b) Relation of two link rates

Fig. 2 Example of wireless links whose set of rates has the solidarity property.

Definition 1 *A subset* $\mathcal{X}$ *of* $\mathbb{R}^n$ *has a solidarity property iff for all* $i \in \{1, 2, \cdots, n\}$*, for all* $\mathbf{x} \in \mathcal{X}$ *where* $\mathbf{x}_i > 0$*, and for all* $0 < \alpha_i < \epsilon$ *where* $\epsilon > 0$ *is sufficiently small, the variation of* $\mathbf{x}_i$*,* $\mathbf{x}_i \pm \alpha_i$*, induces variations of the other elements,* $\mathbf{x}_j \mp \alpha_j$ *for* $\forall j$*,* $j \neq i$*, and* $0 < \alpha_j < \epsilon$*, and therefore, the changed vector* $\mathbf{y} = \mathbf{x} \pm \alpha_i \mathbf{e}_i \mp \sum_{j \neq i} \alpha_j \mathbf{e}_j$ *where* $\mathbf{e}_i$ *is a unit vector still belongs to* $\mathcal{X}$*.*

In other words, if a small increase and decrease of one element causes a small decrease and increase of all the other elements, we can say that the set of such elements has the solidarity property. A simple example of two wireless links is illustrated in Fig. 2. The rates of link 12 and link 34 are respectively given by

$$R_{12} = log_2 \left(1 + \frac{P_1 g_{12}}{P_3 g_{32} + N_2}\right) \tag{6}$$

$$R_{34} = log_2 \left(1 + \frac{P_3 g_{34}}{P_1 g_{14} + N_4}\right) \tag{7}$$

and their relation is illustrated in Fig. 2. It is always possible to increases the rate of one link at the expense of the other. Therefore, the rate set of such wireless links has the solidarity property.

A characteristic of a set with the solidarity property is that all components of the max-min fair vector are equal. This is formulated as the following proposition:

Proposition 1 *If a set* $\mathcal{X}$ *has the solidarity property, then the* max-min fair allocation $\mathbf{x}$ *on* $\mathcal{X}$ *has all components equal. That is,* $\mathbf{x}_i = \mathbf{x}_j$ *for all* i *and* j *when the minimum value of* $\mathbf{x}$ *is maximized.*

Proof Suppose that the contrary that there is a max-min fair allocation vector $\mathbf{x}$ such that $\mathbf{x}_i \neq \mathbf{x}_j$ for some $i \neq j$ on $\mathcal{X}$ with the solidarity property. Let $\mathbf{x}_i$ be the largest component of $\mathbf{x}$. Then, for sufficiently small ϵ such that $0 < \epsilon < \min_j\{\mathbf{x}_i - \mathbf{x}_j\}$, we have

$$\mathbf{x}_i > \mathbf{x}_j + \epsilon \quad \text{for } \forall j \neq i \tag{8}$$

According to the definition of the solidarity property, for $0 < \alpha_i, \alpha_j < \epsilon$, we can find another vector $\mathbf{y} \in \mathcal{X}$ such that

$$\mathbf{y} = \mathbf{x} - \alpha_i \mathbf{e}_i + \sum_{\forall j \neq i} \alpha_j \mathbf{e}_j. \tag{9}$$

That is, $\mathbf{y}_i = \mathbf{x}_i - \alpha_i$ and $\mathbf{y}_j = \mathbf{x}_j + \alpha_j$ for $\forall j \neq i$. This satisfies $\mathbf{y}_i > \mathbf{x}_i - \epsilon > \mathbf{x}_j$ and $\mathbf{y}_j > \mathbf{x}_j$ for $\forall j \neq i$. Therefore, all elements of $\mathbf{y}$ are greater than $\mathbf{x}_j$, i.e.,

$$\max\{\min(\mathbf{y})\} > \max\{\min(\mathbf{x})\} = \mathbf{x}_j \tag{10}$$

which contradicts the definition of max-min fair allocation. □

3.2 Proposed Algorithm

The rate set of links consisting of the wireless multi-hop link has the solidarity property as they use the same resource. Thus, from Proposition 1, in order to maximize the minimum link rate of the multi-hop link, all link rates should be equal. Also, the multi-hop end-to-end rate is determined by the minimum link rate, so it is maximized when all link rates are equal. Therefore, the proposed TPC algorithm controls the transmit power of each node to equalize all link rates (i.e., $R_{12} = R_{23} = \cdots = R_{n(n+1)}$), so that the multi-hop end-to-end rate is maximized.

As shown in (4), the rate R_{ij} of link ij is related to the transmit powers of all the other nodes ($P_k, \forall k \neq i, j$) as well as the transmit power of node i (P_i). Thus, the control of one node's transmit power influences all the other nodes' rates. This interaction makes it difficult to calculate the value of equal link rate in a closed form. Therefore, the proposed algorithm adopts an iterative method to obtain the final equal rate value. At each step, each node recognizes the rate value of its neighboring nodes, averages the recognized rate values, and uses this average rate as its next target rate, which is an appropriate strategy to make one link rate equal to the neighbors' link rate. Thereafter, each transmitting node decides its transmit power to achieve the target rate individually. However, the transmit power decided by each node also changes the interference effect among nodes, so the target rate cannot be achieved at one time. Thus, the rate-average strategy is repeated until all link rates converge on the same value, and finally maximizes the multi-hop end-to-end rate. Moreover, this distributed operation requires the rate information of only adjacent links for averaging, so it significantly decreases the information-sharing overhead.

Fig. 3 shows the flow chart of the proposed distributed TPC algorithm, which operates based on the time slot and observes the following steps:

1. All transmitting nodes set the initial transmit power to the maximum transmit power P_{max}.
2. The transmitting node i sends the packet to its receiving node j using the transmit power $P_i(t)$ decided for the time t.
3. Upon receiving the packet, the receiving node j measures its $SINR_{ij}$ and feeds it back to its transmitting node i.
4. On the basis of the SINR feedback, the transmitting node i calculates its current link rate $R_{ij}(t) = log_2(1 + SINR_{ij}(t))$.

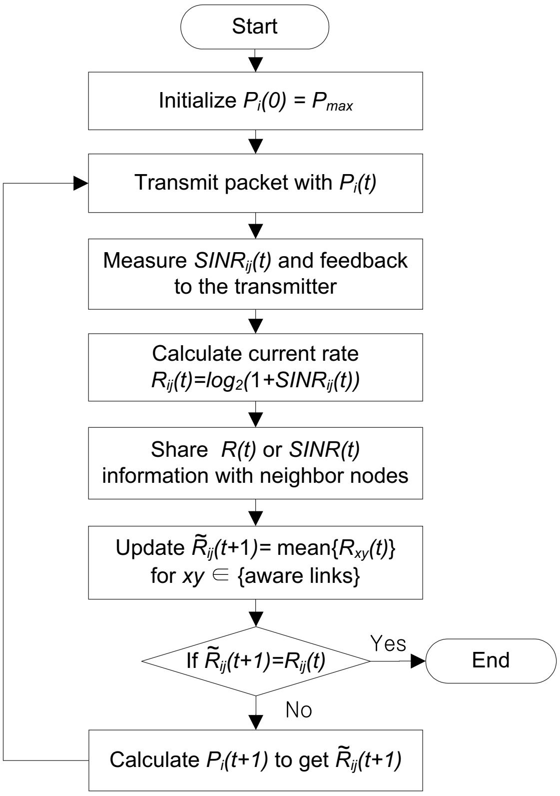


Fig. 3 Proposed distributed transmit power control algorithm.

5. Each transmitting node shares the information of $R(t)$ or $SINR(t)$ with its neighboring nodes.[1] As a sharing method, the overhearing technique can be used [14]. With this technique, the node overhears the SINR feedback of the adjacent nodes. Therefore, the SINR information of adjacent links can be shared among nodes, without additional signaling for sharing.
6. The next target rate $\widetilde{R}_{ij}(t+1)$ is determined as the average value of the recognized adjacent link rates, as follows:

$$\begin{aligned}\widetilde{R}_{ij}(t+1) &= \text{mean}\{R_{xy}(t)\} \\ &= \frac{1}{K} \sum_{xy \in \{\text{aware links}\}} R_{xy}(t)\end{aligned} \tag{11}$$

   where xy is a link whose rate value is known, and K is the total number of aware links, including the link ij.
7. If the next target rate $\widetilde{R}_{ij}(t+1)$ is the same as the current target rate $R_{ij}(t)$, the $P_i(t)$ is decided as the final transmit power and the iteration

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[1] Note that the rate and SINR can be converted to each other.

Table 1 Simulation Parameters

Parameter	Value
Distance btw. source and destination	1000 m
Minimum distance between nodes	10 m
Number of transmission hops	1∼16
Information-sharing range	1∼10 hops
Maximum transmit power	23 dBm
Distance-dependent path loss	$128.1+37.6log_{10}R$ [dB], R in km
Channel bandwidth	10 MHz
Noise figure	9 dB
Threshold for convergence check	10^{-2}

ends. Otherwise, from (4), the next transmit power $P_i(t+1)$ is calculated to obtain the next target rate $\widetilde{R}_{ij}(t+1)$, as follows:

$$P_i(t+1) = \min\left\{ \frac{\left(2^{\widetilde{R}_{ij}(t+1)} - 1\right)(I_j(t) + N_j(t))}{g_{ij}},\ P_{max} \right\} \qquad (12)$$

where $\frac{I_j(t)+N_j(t)}{g_{ij}}$ is derived from the $SINR_{ij}$. Thereafter, the operation continues at Step 2.

4 Results and Discussions

In this paper, the routing algorithm is not our focus, so we assume that each node is connected via multi-hop after routing. We consider a linear topology and a one-way transmission flow from a source to a destination, as shown in Fig. 1. Table 1 shows the simulation parameters. The distance between the source node and the destination node is fixed at 1000 m, and the number of transmission hops is varied by controlling the number of relay nodes between them. The relay node is deployed randomly on the line connecting the source node with the destination node, and the requirement of minimum distance between nodes is 10 m. The information-sharing range varies with 1∼10 hops, within which the nodes can share their rate or SINR value. We also assume that the relay node is a full-duplex relay; therefore, it is possible to receive and transmit packets simultaneously without self-interference [15].[2] The maximum power is set to 23 dBm, and the channel parameter observes the 3GPP evaluation methodology [16]. As conventional schemes for comparison, we consider a scheme using the maximum equal power without TPC and the SINR-based TPC algorithm with several target SINR values [4–6].

Fig. 4 shows the received signal strength (RSS) in the two-dimension plane when the maximum equal power, the SINR-based TPC with the target SINR

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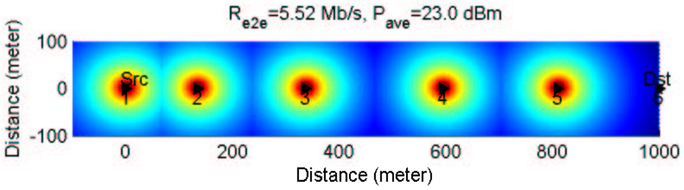
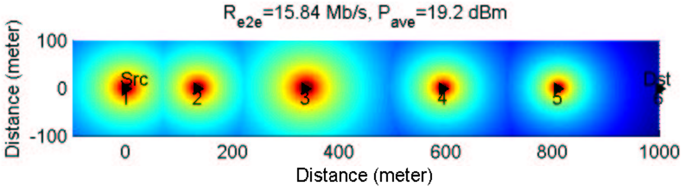
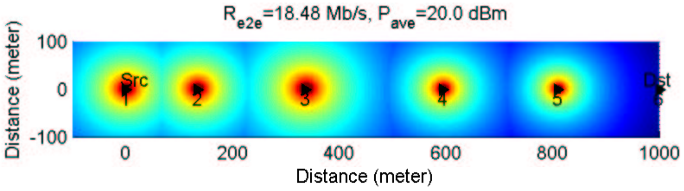
[2] The full-duplex relay can decrease the per-hop processing delay, and thus increase the multi-hop end-to-end rate. However, this relay type generates more interference among links, and thus makes the proposed TPC algorithm more effective.



(a) Maximum equal power allocation



(b) SINR-based TPC (target SINR γ=3 dB)



(c) Proposed TPC

Fig. 4 Distribution of received signal strength in two-dimension.

γ=3 dB, and the proposed TPC are applied to 5-hop transmission. While the conventional scheme shows a uniform RSS distribution, the SINR-based TPC and the proposed TPC schemes show dynamic RSS distribution, because a different transmit power is assigned to each node. It is shown that in this example, the proposed TPC has an improved end-to-end throughput (18.48 Mb/s) by using sightly increased transmission powers (an average power of 20 dBm), compared to the SINR-based TPC.

Fig. 5 shows the throughput of each link and the transmit power of each node according to the iteration of the proposed algorithm. As iteration proceeds, the link throughputs converge, but the transmit powers become different. Upon convergence, the node that initially has the best link throughput (i.e., node 5) shows the lowest transmit power, and the node that initially has the worst link throughput (i.e., node 3) maintains the maximum transmit power. The nodes with good link quality reduce their transmit power and decrease the interference to the other nodes, but the nodes with bad link quality maintain or slightly reduce their transmit power, in order to equalize all link rates. It should be noted that the final transmit power is inversely proportional to the initial link throughput. The iteration process is stopped if the Euclidean length of a transmission power vector $\mathbf{P}$ (i.e., norm of $\mathbf{P}$) is less than 10^{-2}, which corresponds to a tight condition for convergence check, because in practical systems, set of possible bit rate is determined by several MCS

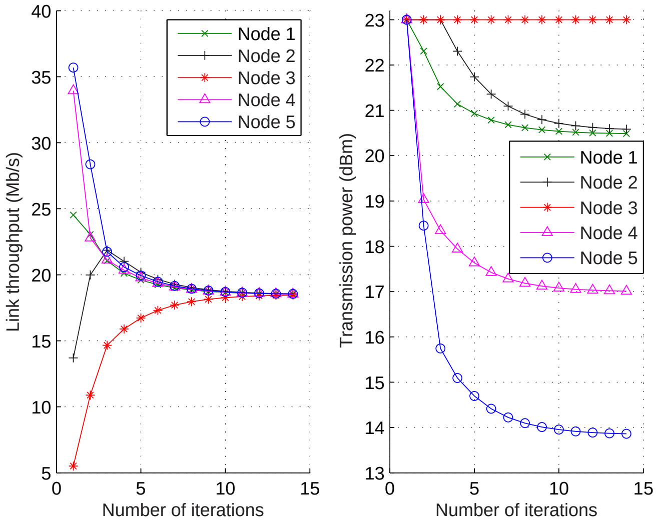


Fig. 5 Link throughput and transmission power vs. number of iterations.

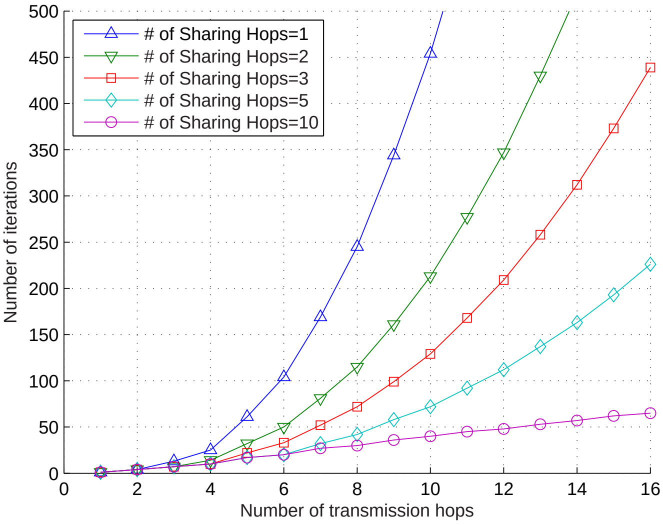


Fig. 6 Number of iterations vs. number of transmission hops and number of sharing hops.

levels. Therefore, the number of iterations can be reduced further by relaxing the convergence condition if the channel variation and node mobility become more dynamic.

Fig. 6 shows the number of iterations needed for convergence, according to the number of transmission hops and the number of sharing hops. As the

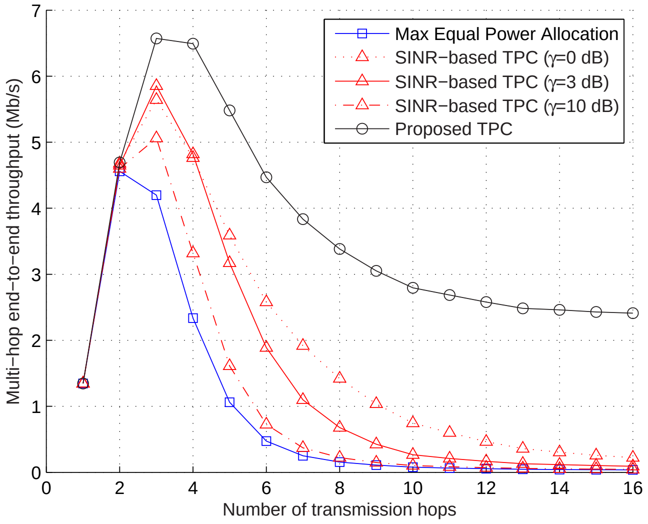


Fig. 7 Multi-hop end-to-end throughput vs. number of transmission hops.

number of hops increases, the number of iterations increases exponentially, because an increased number of nodes means that more time is required to equalize all the link rates. However, as the number of sharing hops increases, the convergence becomes faster. This is because the increase in the number of sharing hops offers more adjacent link rates for averaging.

Fig. 7 shows the performance of the multi-hop end-to-end throughput versus the number of transmission hops. The schemes using TPC outperform the conventional maximum equal power allocation without TPC. Compared with the SINR-based TPC with a target SINR (γ) fixed at 0, 3, or 10 dBm, the proposed TPC shows better throughput performance. This is because the proposed TPC algorithm dynamically achieves an SINR value that maximizes the end-to-end throughput, while the SINR-based TPC algorithm achieves a static target SINR. As the number of hops increases, the end-to-end throughput increases sharply, but eventually decreases and maintains a constant level in both schemes. The scheme without TPC has a peak throughput at the two-hop transmission, and the schemes with TPC have a peak at the three-hop transmission. The increase in the number of hops initially improves the link budget and thus enhances the end-to-end throughput, but the excessive number of hops causes more interference and degrades the end-to-end throughput. This means that not only the optimal TPC, but also the optimal selection of transmission hops is required for maximizing the end-to-end throughput in the given multi-hop environment.

Fig. 8 shows the performance of total transmission power consumption of all the transmitting nodes versus the number of transmission hops. The maximum equal power allocation scheme uses a fixed maximum transmit power

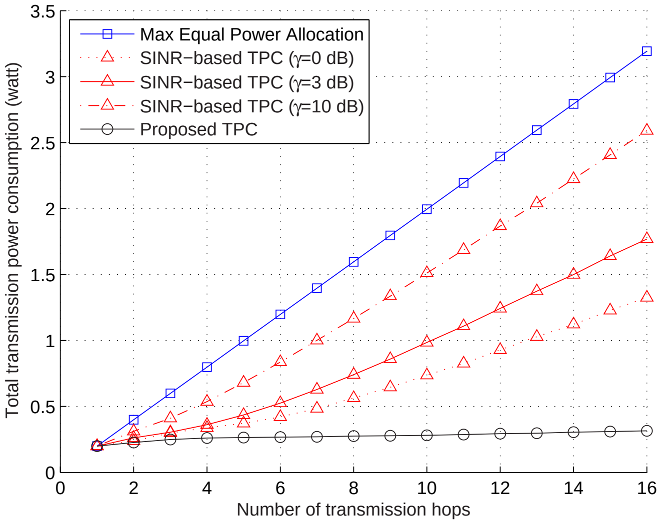


Fig. 8 Total transmission power consumption vs. number of transmission hops.

in all the nodes, so the total power consumption increases linearly according to the number of hops. On the other hand, the SINR-based and the proposed TPC algorithms use decreased transmission power. Particularly, the proposed TPC reduces the transmit power adaptively depending on the increase of interference due to the increased number of hops, and therefore, it exhibits very low power consumption. Moreover, the SINR-based TPC shows a tradeoff in performance between the end-to-end throughput and the total transmission power consumption according to the target SINR value.

5 Conclusion

By applying the fact that wireless links with the solidarity property maximize the minimum rate when all link rates are equal, we proposed the TPC algorithm, which determines the transmit powers of nodes to equalize all the link rates and thus maximize the multi-hop end-to-end throughput. Simulation results showed that the proposed algorithm makes all link rates equal, regardless of the number of transmission hops and the information-sharing range. Therefore, the proposed TPC algorithm maximizes the multi-hop end-to-end throughput and additionally leads to significant energy savings at the transmitting nodes by adjusting the transmit powers. We expect the basic concept of the proposed scheme to be applicable to all other distributed and cooperative systems that involve the max-min objective function and the solidarity property. In future research, we will investigate the proposed TPC algorithm when multi-flow exists in various multi-hop topologies, and present a joint routing and TPC algorithm for optimizing network performances.

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