Joint Scheduling and Power Control for Inter-Hop Interference Mitigation in Wireless Multihop Networks

Hyun-Ho Choi
Dept. of Information and Control Engineering
Hankyong National University
Republic of Korea
Email: hhchoi@hknu.ac.kr

Eui-Seung Son and Eun-Kyoung Paik
Network R&D Laboratory
KT
Republic of Korea
Email: {es.son, eun.paik}@kt.com

Jung-Ryun Lee
School of the Electrical Engineering
Chung-Ang University
Republic of Korea
Email: jrlee@cau.ac.kr

***Abstract*—In wireless multihop network, the inter-hop interference (IHI) is a major factor to deteriorate the end-to-end performances of multihop link. In this paper, we proposed a joint radio resource management with respect to scheduling and power control in order to mitigate the IHI and maximize the resource utilization and the end-to-end rate in the wireless multihop networks. The scheduling algorithm decides the number of orthogonal resources and the transmission time period for simultaneously transmitting links considering the IHI. Moreover, the transmit power control (TPC) algorithm protects the quality of multihop transmission from the collision and severe IHI and optimizes the transmit power and the allocated transmission time jointly. Simulation results show that the proposed schemes using the scheduling and TPC increase the end-to-end rate of multihop link up to 3 times and significantly decrease the total energy consumption of participating nodes, compared to the conventional fixed resource allocation method without TPC.**[1]

***Index Terms*—Power control, scheduling, multihop networks, ad hoc networks.**

I. Introduction

In wireless networks, the multihop transmission suffers from harsh environments such as topology and channel variations due to node mobility, interference from other nodes, hop-by-hop processing overhead, and so on [1]-[4]. Among these impairments, the interference is a main culprit to deteriorate the multihop performances because the severe interference makes bit errors and so induces data retransmissions in practice. The interference happens when two or more transmitters transmit data signal on the same frequency band at the same time. When the interference level is greater than a certain level (i.e., the signal to interference-plus-noise ratio (SINR) is lower than a certain level), the received signal cannot be decoded anymore without error. Especially, the interference level increases in the case of a high node density where there are many active transmissions per unit area. In wireless ad hoc networks, the multihop transmissions are required to transmit data between source and destination because their physical distance is longer than the directly transmitting range. Accordingly, the multihop data delivery is needed and it eventually increases the amount of data traffic to be transmitted and the interference level as the number of transmitted hops is increased. In this paper, we focus on *Inter-Hop Interference (IHI)* that happens among the nodes on the same routing path as they transmit own data by using the same resource at the same time.

Notice that the IHI is more controllable than the interference between different flows because the IHI happens within the same connection flow, on which all nodes are connected and communicated with each other by control signalling. Generally, the interference between different flows is resolved by simply orthogonal frequency allocation or etiquette-based access method like CSMA/CA because it has little controllability and connectivity between other flows. So, this paper focuses on the IHI problem within one connection flow and assumes that the other interference between flows is negligible by using the typical orthogonal frequency allocation method.[2]

Simple approaches to attack the interference problem are the resource partitioning (i.e., scheduling) and transmission power control (TPC) [4]. The strong interference is removed as letting the interferers use the different resource area disjointly. Moreover, the medium interference is efficiently mitigated by the TPC as the interference level is reduced by decreasing the transmission power of interfering nodes. In this context, we consider the scheduling (i.e., how to allocate the frequency and time resources) and the TPC (i.e., how to decide the transmission power at transmitting nodes) to mitigate the IHI in the wireless multihop network.

The typical approach for multihop scheduling is the TDMA-like resource partitioning method [5]. That is to say, each link on the multihop path is allocated the orthogonal and fixed resources, so the IHI cannot happen. However, this approach degrades the resource utilization because it does not reuse the given resource spatially even though it is quite possible, so the simple resource partitioning method is not optimal strategy to maximize the end-to-end performance of mulithop link.

[1]This research was supported by KT.

[2]Compared to cellular networks, the IHI problem can corresponds to the inter-cell interference (ICI) problem although their topologies are different. Thus, we can accept the key concepts of the conventional ICI solutions by considering the different structure between two network types.

Therefore, in this paper, we consider the resource reuse to the multihop link when the transmission nodes are physically separated and the IHI is negligible enough to transmit at the same time. On this scenario, we propose efficient multihop scheduling and TPC algorithms and also present a joint use of two algorithms. The proposed mechanisms allow the resource reuse to improve the resource utilization and control the IHI effectively to maximize the multihop end-to-end data rate. The typical TPC algorithm considers only link quality between the transmitting node and the receiving node, but the proposed TPC algorithm considers the scheduled multihop resources and the quality-of-service of transmitted data [6]. In addition, the joint scheduling and TPC algorithm give more performance gain through a little overhead increment.

The rest of this paper is organized as follows. In Section II, the proposed algorithms are presented. The details of the scheduling, TPC and rescheduling methods are explained. In Section III, the simulation results are shown and discussed. Finally, Section IV concludes this paper.

II. Proposed Scheme

A. Overall Operation

Fig. 1 shows the flow chart of the proposed scheme. First of all, the multihop path between a source and a destination is determined by a routing algorithm. Here, the routing is out of scope and so the use of appropriate routing scheme is assumed. Thereafter, a scheduling is performed on the decided multihop path. The key operation of scheduling is to determine the number of orthogonal resources and the resource amount allocated to each link on the multihop path. After scheduling, the multihop transmission starts according to the scheduling decisions. If the amount of interference is greater than a predetermined threshold (i.e., a collision occurs) during transmission by a certain reason of node movement or radio channel variation, the first try is a TPC. The TPC algorithm adjusts not only the transmission power of interfering node, but also that of interfered node. If the TPC is not enough to reduce the interference, the rescheduling can be additionally performed. This rescheduling operation is limited to be performed between the corresponding interference links for the fast recovery of multihop transmission. In the worst case, the initial routing operation is performed again if the interference level is still higher.

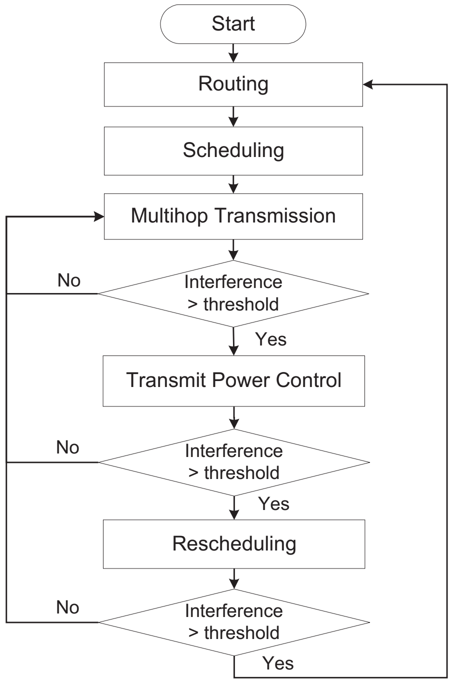

Fig. 1. Flow chart of the proposed scheme.

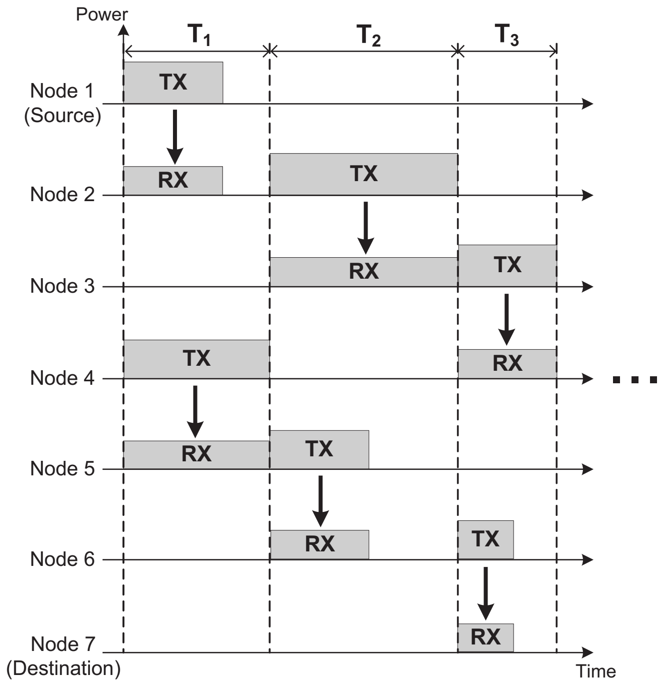

Fig. 2. Example of multihop scheduling in case of six-hop transmission when the number of resources N is 3.

B. Multihop Scheduling

The multihop scheduling aims at allocating the given radio resource (i.e., frequency and time) efficiently to each link on the multihop path with the objective of maximizing the transmission rate of end-to-end link. To achieve this, the scheduling determines two parameters. One is the number of orthogonal resources used without IHI. The other is the length of transmission time used at each link.

1) Decision of the number of resources: Fig. 2 illustrates an example of multihop scheduling in case of six-hop transmission. The proposed multihop scheduling approach basically supports the use of the same resource among far away links without severe interference in order to increase the spectral efficiency. This is similar to the frequency reuse concept in the cellular network, and so the number of orthogonal resources defined here is equivalent to the reuse factor defined in the cellular networks. As shown in Fig. 2, three orthogonal resources (i.e., three different timeslots) using the same frequency band are assigned in hop order and repeatedly. In this case, the links 1→2 and 4→5 use the timeslot 1 at the same time as their interference from the transmitting node 4 to the receiving node 2 is negligible. In this way, the other links with two-hop interference range uses the same timeslot and so the limited resource is reused with reuse factor three. Note that in this case the typical TDMA scheduling method allocates six timeslots and each link uses orthogonal resource. This corresponds to the reuse factor six.

To decide the number of orthogonal resources (i.e., reuse factor), we need to decide the interference range on the given multihop path. To do this, all nodes should measure the received signal strength (RSS) from the other nodes on the path and decide an interfering node set. The interfering node set (Y_i) of a node i on the path is defined as

$$Y_i \in \{y|RSS_{yi} > \text{threshold}\} \tag{1}$$

where RSS_{yi} is the RSS from the transmitting node y to the receiving node i. Therefore, the interference range in the node i is determined by

$$R_i = max\{|y - i|\}, \quad \forall y \in Y_i \tag{2}$$

By synthesizing all R_i value on the path, the number of orthogonal resources N is finally determined as

$$N = max\{R_i\} + \alpha, \quad \forall i \in \text{path and } \alpha \geq 2 \tag{3}$$

where α is a decision parameter and must be more than two in order to satisfy the conditions that make the IHI be negligible. In case of Fig. 2, R_i is measured as 1 in all for $i = 1, 2, \cdots, 6$ and α is set to 2. Thus, $N = max\{R_i\} + \alpha = 1 + 2 = 3$. Note that as α increases, the reuse factor is greater and the interference level is lower, but the spectral efficiency is worse. Obviously, the minimum interference range ($min\{R_i\}, \forall i$) is one, so that the minimum value of N is three (i.e., $N \geq 3$). Therefore, we need three orthogonal resources at least for the multihop transmission.

The N resources (or timeslots) are allocated in connected order, so the timeslot number of the transmission link i→j is expressed as

$$n_{ij} = \{(i-1) \ mod \ N\} + 1, \quad i = 1, 2, 3, ... \tag{4}$$

where mod is the modular operator. For example, when $N = 3$, the frequency band is allocated in order of 1, 2, 3, 1, 2, 3, ... to each link on the path as shown in Fig. 2. In addition, the set of simultaneously transmitting links is expressed as

$$S_m = \{(i,j)|n_{ij} = m, \ \forall \text{ links } i \rightarrow j\} \quad \text{where } m = 1, 2, ..., N. \tag{5}$$

2) Decision of the transmission time: In the multihop transmission, the rate of each link is different, but all links should deliver the data of equal size with respect to the end-to-end transmission [5]. Let R_{ij} be the rate (bps) of link i→j and D_{req} be the transmitted data block size (bits). Then, the required transmission time of each link is given by

$$T_{ij} = \frac{D_{req}}{R_{ij}}. \tag{6}$$

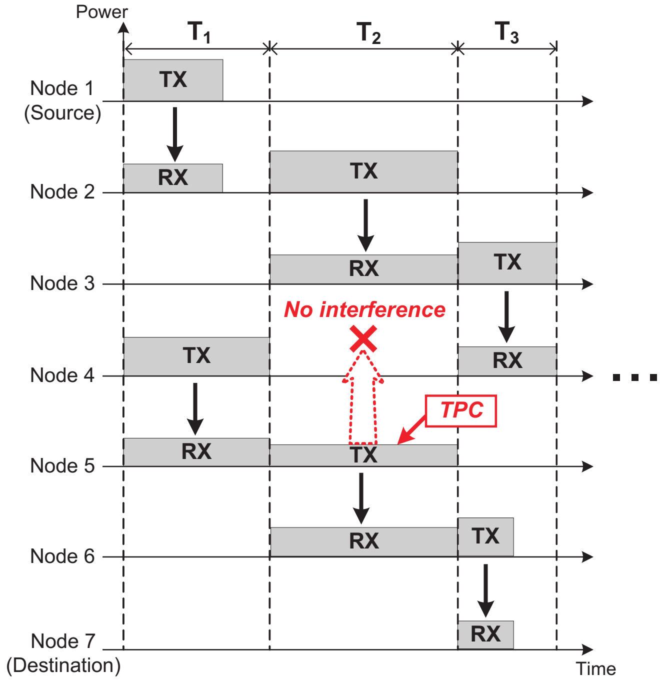

Fig. 3. TPC operation in case of six-hop transmission (N=3).

As shown in Fig. 2, the simultaneously transmitting nodes should be allocated the same transmission time in order to prevent the IHI. Therefore, the transmission time of the m-th simultaneously transmitting links is described as

$$T_m = max\{T_{ij}\}, \quad \forall (i,j) \in S_m \quad \text{where } m = 1, 2, ..., N. \tag{7}$$

Accordingly, the total multihop transmission time is given by

$$T_{multihop} = \sum_{m=1}^{N} T_m. \tag{8}$$

C. Transmit Power Control

Topology change and channel variation due to the node mobility may occur the IHI even though the multihop scheduling is accomplished previously. One of the easiest ways to solve this dynamic IHI problem is a TPC. By reducing the transmission power of the interfering node, the interfered node's SINR can be recovered simply. For this TPC operation, the interfered node recognizing the IHI should request the TPC operation to the interfering node. The new transmission power level decided by the interfering node is the possible lowest power as it uses the entire transmission time allocated, as shown in Fig. 3. Therefore, the new transmission power of interfering node i is derived as

$$\begin{aligned} R_{ij} &= \frac{D_{req}}{T_m} = Wlog_2\left(1 + \frac{P_i g_{ij}}{I_j + N_j}\right) \quad \text{where } (i,j) \in S_m \\ \therefore P_i &= \left(2^{\frac{D_{req}}{T_m W}} - 1\right)\frac{I_j + N_j}{g_{ij}} \end{aligned} \tag{9}$$

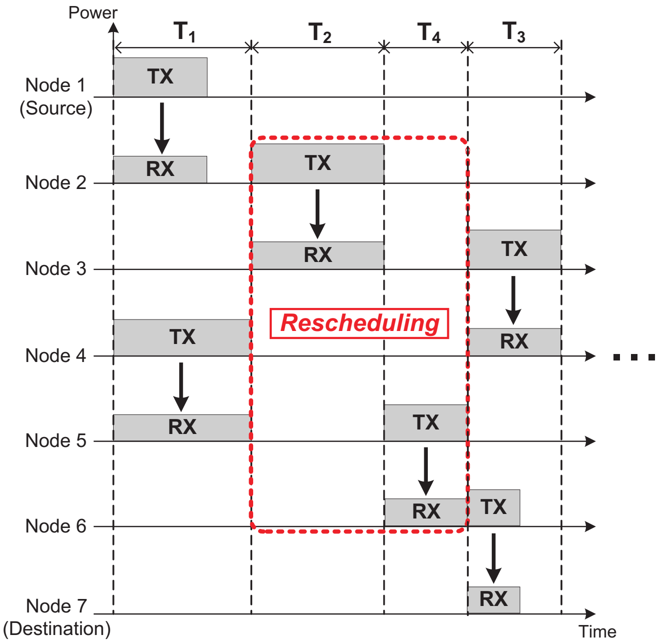

Fig. 4. Rescheduling operation in case of six-hop transmission (N=3).

where W is bandwidth, g_{ij} is channel gain of link i→j, and I_j and N_j are interference and noise levels in the node j, respectively. Here, $\frac{I_j+N_j}{g_{ij}}$ can be obtained from the SINR feedback from the node j to the node i because $SINR_{ij} = \frac{P_{max}g_{ij}}{I_j+N_j}$.

Fig. 3 illustrates the TPC operation when the interfering node is the node 5 and the interfered node is the node 3, so the node 5 reduces its transmission power by using its available transmission time completely. Please compare it with the Fig. 2.

D. Rescheduling for IHI control

If the TPC is not enough to solve the IHI and the interfered node is still existing, we need to consider the rescheduling operation. The difference between the scheduling and the rescheduling is that rescheduling considers only the interference links and so fast interference control is possible. Fig. 4 shows the rescheduling operation. Simply the result of rescheduling is the separation of frequency band between the interference links. As shown, the links 2→3 and 5→6 use the different timeslot by rescheduling operation and there is no interference between them. Details of rescheduling operation is equivalent to the operation of scheduling described in Section II-B, but its application limits to only interference links.

E. Joint Scheduling and TPC

The previously explained TPC algorithm is so simple and practical because it autonomously reduces the transmission power for the interfering node by its utilizing of full transmission time. However, this operation does not include an exact calculation of transmission power because it does not consider the SINR of interfered node. By the way, if the reduced transmission is excessive and the interfered node gets the sufficient SINR quality, this interfered node also can reduce its transmission power and this operation eventually reduces the transmission time and saves the radio resource. In this context, the TPC and scheduling can be jointly executed one by one until they reach the converged scheduling parameter and transmission power value. This joint operation is the repetition of the previous scheduling and TPC operations and so it requires the operational complexity. Nevertheless, it could give more gain in terms of the resource utilization and the multihop performances.

TABLE I
SIMULATION PARAMETERS

Parameter	Values
Node distribution	2-dim. and uniform-randomly deployed
Node's maximum transmission range	150 m
Routing algorithm	Shortest hop routing
Number of hops	Variable (3∼9)
Transmitted block sizes (D_{req})	4095 bytes
Maximum transmission power	20 dBm
Required SINR	3 dB
Parameter α	2
Path loss model	-128.1-37.6 $log_{10}d$ [dB], d in km [7]
Lognormal Shadowing	8 dB
Bandwidth	20 MHz
Noise power spectral density	3.1623e-17
Power consumption for transmission	1.65 W [8]
Power consumption for reception	1.4 W [8]

III. Simulation Results

We performed Monte Carlo simulations to evaluate the proposed algorithms. The used parameters is shown in Table I [7], [8]. We consider the TDMA resource allocation mechanism as a conventional scheme and compare it to some versions of the proposed schemes: without TPC, with TPC, and joint optimized by TPC and rescheduling. The TDMA scheme allocates the resource with the time slot of fixed size. The proposed scheme without TPC performs only the initial scheduling operation, the proposed scheme with TPC performs additional TPC operation after the initial scheduling, and the proposed scheme with TPC and rescheduling executes TPC and rescheduling jointly after the initial scheduling. Note that the proposed TPC and rescheduling operation not only solves the IHI problem, but also considers to improve the resource utilization and the spectral efficiency.

Fig. 5 shows the multihop transmission time versus the number of hops. The multihop transmission time is defined as (8), which is a metric corresponding to the component of multihop transmission delay. The tendency exhibits that the transmission time increases as the number of hops increases. The conventional TDMA scheme allocates the timeslots with a fixed size without considering the rate difference of each link on the multihop path. Therefore, its transmission time linearly increases as the number of hops increases. On the other hand, the proposed schemes use shorter transmission time. Regardless of whether the TPC is applied or not, the transmission time is the same because these two schemes use the same scheduling operation and so its allocated transmission time is equal. However, when both the TPC and rescheduling

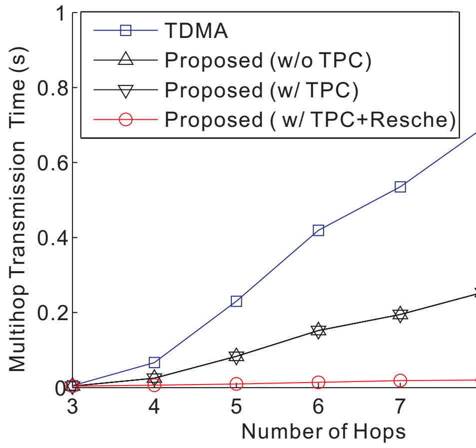

Fig. 5. Multihop transmission time vs. number of hops.

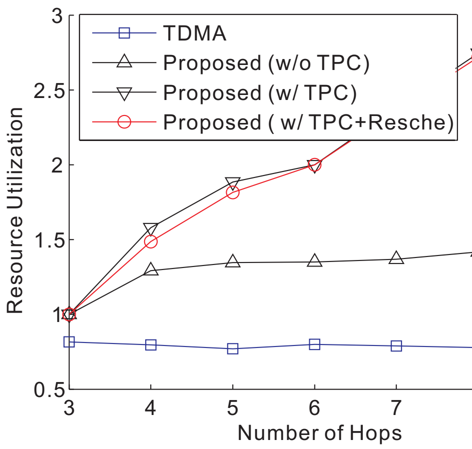

Fig. 6. Resource utilization vs. number of hops.

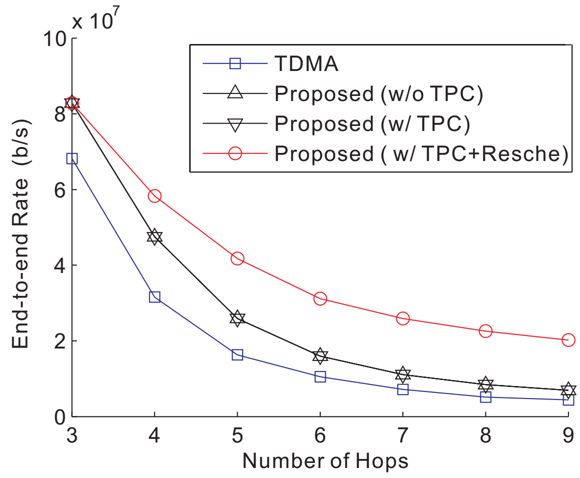

Fig. 7. End-to-end rate vs. number of hops.

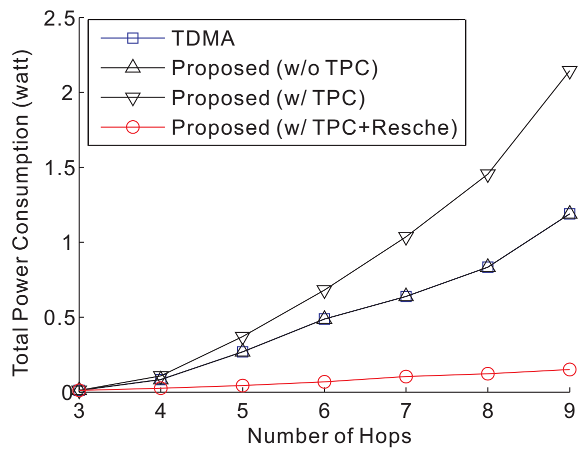

Fig. 8. Total transmit power consumption vs. number of hops.

are applied, its transmission time is significantly decreased because the TPC operation decreases the IHI and increases the link rate, so that eventually the rescheduling operation reduces the transmission time of each link.

Fig. 6 shows the resource utilization versus the number of hops. The resource utilization is defined as the ratio of the actual data transmission time to the total length of offered timeslots. Therefore, its value is proportional to the inverse of resource reuse factor. As shown, the conventional TDMA scheme has the lowest resource utilization. That is, it does not make full use of given resources. On the other hand, the proposed schemes with TPC or TPC+rescheduling shows linearly increasing performance. This is because the TPC operation enlarges the data transmission time by decreasing the transmission power. The proposed scheme without TPC shows the saturated resource utilization. This means that there are unused time of about 50% due to the rate difference among simultaneously transmitting links.

Fig. 7 shows the end-to-end rate versus the number of hops. As the number of hops increase, the end-to-end rate decreases because the level of IHI increases. As shown, the proposed scheme with TPC and rescheduling shows the best performance, but the TDMA shows the worst performance because it does not allocate the radio resources efficiently. The proposed schemes without TPC or with TPC show the same performance because their total multihop transmission time is the same and the transmitted data size is constant.

Fig. 8 shows the total power consumption versus the number of hops. The total power consumption means the sum of transmission power consumption and receiving power consumption in all nodes on the path. Here, we assume that the node enters a sleep mode in idle state where the node does not transmit or receive data. Therefore, the power consumption depends on the actual data transmission and reception time and the transmission power. When only the TPC operation is applied, it induces the increase of transmission time, so that its power consumption increases and shows the worst performance. On the other hand, the TPC and rescheduling scheme shows the best performance because it reduces both the transmission time and power. The conventional TDMA and the proposed scheme without TPC show the same result because their actual data transmission times are equal and their transmission powers are fixed identically.

IV. Conclusions

In this paper, we proposed a joint radio resource management with respect to scheduling and power control in order to mitigate the IHI and maximize the resource utilization and the end-to-end rate in the wireless multihop networks. The scheduling algorithm decides the number of orthogonal resources and the transmission time period for simultaneously transmitting links considering the IHI. Moreover, the transmit power control (TPC) algorithm protects the quality of multihop transmission from the collision and severe IHI and optimizes the transmit power and the allocated transmission time jointly. Simulation results show that the proposed schemes using the scheduling and TPC maximizes the end-to-end rate of multihop link and minimizes the total energy consumption of participating nodes, compared to the conventional fixed resource allocation method without TPC.

References

[1] Mung Chiang, ”Balancing transport and physical Layers in wireless multihop networks: jointly optimal congestion control and power control,” *IEEE Selected Areas in Communications*, vol. 23, no. 1, pp. 104-116, 2005.

[2] Peng-Jun Wan, et al., ”Wireless link scheduling under physical interference model,” *IEEE Infocom 2011*, pp. 838-845, 2011.

[3] A. Bader and E. Ekici, ”Performance Optimization of Interference-Limited Multihop Networks,” *IEEE/ACM Transactions on Networking*, vol. 16, no. 5, pp. 1147-1160, 2008.

[4] R.L. Cruz and A.V. Santhanam ”Optimal link scheduling and power control in CDMA multihop wireless networks,” *IEEE GLOBECOM 2002*, vol. 1, pp. 52-56, 2002.

[5] P. Djukic and S. Valaee ”Delay Aware Link Scheduling for Multi-Hop TDMA Wireless Networks,” *IEEE/ACM Transactions on Networking*, vol. 17, no. 3, pp. 870-883, 2009.

[6] S. Agarwal, et al., ”Distributed power control in ad-hoc wireless networks,” *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 2, pp. F-59-F-66, 2001.

[7] 3GPP, ”Technical Specification Group Radio Access Network; Further Advancements for E-UTRA Physical Layer Aspects (Release 9),” TR 36.814 v1.1.1, June 2009.

[8] Eun-Sun Jung and N.H. Vaidya, ”An energy efficient MAC protocol for wireless LANs,” *IEEE INFOCOM 2002*, vol. 3, pp. 1756-1764, 2002.