Title	End-to-end throughput evaluation of consensus TPC algorithm in multihop wireless networks
Author(s)	YU, Yu; SHAH, Shashi; TAN, Yasuo; LIM, Yuto
Citation	2015 International Wireless Communications and Mobile Computing Conference (IWCMC): 941-946
Issue Date	2015-08
Type	Conference Paper
Text version	author
URL	http://hdl.handle.net/10119/13474
Rights	This is the author's version of the work. Copyright (C) 2015 IEEE. 2015 International Wireless Communications and Mobile Computing Conference (IWCMC), 2015, 941-946. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.
Description	

End-to-end Throughput Evaluation of Consensus TPC Algorithm in Multihop Wireless Networks

Yu YU Shashi SHAH Yasuo TAN and Yuto LIM
School of Information Science, Japan Advanced Institute of Science and Technology (JAIST)
1-1 Asahidai, Nomi, Ishikawa, 923-1292 JAPAN
Email: {yuyu_is, s1420206, ytan, ylim}@jaist.ac.jp

Abstract—**The key factor of influencing the network capacity performance is the effect of interference power of receiving nodes, which is obtained from the other transmitting nodes in multihop wireless networks (MWNs) that are simultaneously using the same channel. Minimizing total interference power can improve overall network capacity and reduce total energy consumption. In this paper, we propose a consensus transmit power control (CTPC) algorithm to maximize end-to-end throughput in MWNs. The CTPC algorithm tunes the nodes' transmit powers to maximize the average end-to-end throughput with a consensus coefficient. Simulation results reveal that the CTPC algorithm enables all the traffic flows to accomplish the maximum average end-to-end throughput. At the same time, the total interference power and the total power consumption are decreasing. Only in the dense MWNs, under usual threshold of received signal strength indicator (RSSI) setting, the CTPC algorithm cannot achieve good performance. In addition, an advanced wmediumd emulator over the StarBED testbed is used to further verify the performance evaluation of CTPC algorithm.**

Index Terms—**transmit power control, consensus coefficient, interference minimization, end-to-end throughput, network emulation, multihop wireless networks.**

I. Introduction

Recently, the number of wireless devices has increased tremendously. In 2009, the world wide radio forum (WWRF) offered a vision for future wireless communication called, "7 trillion wireless devices serving 7 billion people by 2017" [1]. As a result of 7 trillion wireless devices, wireless network is the real ubiquitous network around our daily life. However, most wireless communication devices, such as laptops, tablet PCs and smart-phones, are battery-based equipments. Therefore, one very important issue for these devices is the reduction of the energy consumption. In this paper, we proposed a consensus TPC algorithm that enables all data flows to accomplish the maximum end-to-end throughput in MWNs, and at the same time decrease the total interference power and the total power consumption.

WMN is a network of computers or other electronic equipments that are connected by wireless communication links. The difference between MWN and traditional wireless networks is that all the nodes work cooperatively to send the packets to its destination in MWN. That means a node will send packets to a neighbour node that it can communicate directly. The neighbour node, in its turn, forwards the packets to one of its neighbour nodes and keeps on. This process terminates when the packet reaches its ultimate destination. Each link over which packets are sent is referred to as a hop; the set of links is called path, which is discovered by using a distributed routing algorithm; and the particular characteristic of transmission is called multi-hop fashion. Due to the multihop fashion, MWN is introduced as a promising approach for next generation wireless networks to enable cooperative and self-organized communication, even with the absence of infrastructure. Some examples of this architecture are the adhoc mode architecture of 802.11, wireless multihop network of 802.11 or wireless mesh network.

Wireless devices normally are battery dependent with low radio frequency power, therefore the communication range would be limited. In traditional wireless networks, each node has a wider transmission range and consumes more energy than the nodes using multihop fashion. As a result of the transmission range, the simultaneous communications are limited in traditional wireless networks. Transmit power control (TPC) is a technical mechanism used in radio communications to reduce the power of a radio transmitter to the minimum necessary to maintain the link with a certain quality. Decreasing the transmit power of each node can limit the transmission range of each node, not only numbers of simultaneous communications could increased, but also the battery capacity of each wireless devices. The advantage of TPC is that it improves the performance of network, such as end-to-end throughput, network capacity, and etc. However, under multihop wireless environments, excessive reductions in transmit power increases the number of transmission hops. This increases the network traffic load and induces additional interference in the multihop network. Therefore, the trade-off between the transmit power reduction and the number of transmission hops is extremely significant, which means a suitable TPC algorithm can maximize the network performance.

A. Related Works

Typical TPC algorithms in wireless networks are used for the sensor networks, such as: local mean algorithm (LMA) [2], and local minimum spanning tree (LMST) [3]. LMA is a typical power control algorithm that gives emphasis to the power conservation while keeping the connectivity of the sensor network. It mainly focuses on network lifetime rather than other performance metrics. In LMST, each node builds its local minimum spanning tree independently and only keeps on-tree nodes that are one hop away as neighbours in the final topology. This algorithm is used for dynamic wireless ad-hoc network with limited mobility. The topology under LMST has a small average node degree (close to the theoretical bound), and a small average radius. However, the free space model used in this algorithm is a primitive prototype that would be enhanced. Other TPC algorithm such as max-min power (MMP) algorithm aims for objective to maintain the best possible modulation and coding scheme (MCS) of each link while decreasing the transmission power as much as possible. However, each link with the best possible MCS does not lead to optimized capacity of the whole network. The study in [4] proposed a distributed transmit power control (DTPC) algorithm for maximizing end-to-end throughput in wireless multihop networks. It is shown that DTPC improves the end-to-end throughput performance for the single flow existing networks. Moreover, it is known that there are limitations of TPC for indoor wireless local area networks [5].

B. Motivation

The proposed DTPC in [4] does not consider at all the issue of multi-flow traffics in various multihop wireless network topologies. First, the DTPC is modified to support the multi-flow traffics. Then, the modification of DTPC leads to the proposed of CTPC algorithm and its consensus coefficient to maximize the average end-to-end throughput by controlling the transmit power that is similar to DTPC algorithm.

Besides that, the realistic interference model is considered for the numerical simulation in this paper. Unlike the previous interference model [6], the RSSI threshold of interference model is used to define the nodes are within or outside the transmission range of a receiving node. For the end-to-end throughput in MWNs, we use throughput calculation, which is under the spatial reuse as described in [7]. In this paper, the routing protocol, scheduling, fairness and others are not considered for the motivation to observe the aftermath of TPC algorithm on the network performance of the MWNs.

Another motivation is to introduce a network emulator for the MWNs. Normally, other algorithms and routing protocols were evaluated by network simulators. But the network emulator cannot only support the real-time execution, but also provide better result reliability. The proposed CTPC algorithm has been evaluated under both simulation and emulation. For the emulation, the advanced wmediumd [8] has been implemented on large scale network emulation testbed, which is called StarBED [9][10].

C. Organization

The rest of this paper is organized as follows. The system model, interference model, and spatial reuse calculation are introduced in Section II. The proposed consensus TPC algorithm is described in Section III. In Section IV, the scenarios, parameters, and the architecture framework of the wmediumd emulator over StarBED facilities are described. Numerical simulation and emulation results are presented in Section V. Finally, we summarize the paper with conclusions and directions for future work in Section VI.

II. SYSTEM MODEL

In this section, the system model and assumption issues are described. The system model is defined as follows:

- Channel gain (in decibels) between node i and node j is depend on log-distance pathloss model, PL_0 is assumed as Friis free space model

$$PL_{ij} = PL_o + 10 \cdot \alpha \cdot \log_{10}\left(\frac{d_{ij}}{d_0}\right) - W_{ij} + X_\sigma \quad (1)$$

where $PL_o = 20 \cdot \log_{10}(d_0)$

- Power ratio (no unit) between node i and node j is

$$G_{ij} = \frac{1}{10^{\left(\frac{PL_{ij}}{10}\right)}} \quad (2)$$

- Signal to interference and noise ratio (no unit) from node i to node j is

$$SINR_{ij} = \frac{G_{ij}P_i}{\eta_j B + \sum_{k\in\mathcal{X},k\neq i} G_{kj}P_k} \quad (3)$$

- Rate of transmission (bit/s) from node i to node j is

$$R_{ij} = B\log_2\left(1 + \frac{1}{\Gamma}SINR_{ij}\right) \quad (4)$$

Some notations and definitions are list in TABLE I.

TABLE I: Notations and definitions

P_i	transmit power of node i
P_{max}	maximum transmit power
d_{ij}	distance between node i and node j
W_{ij}	wall attenuation from node i to node j
X_σ	shadowing attenuation
G_{ij}	channel gain from node i to node j
η_j	thermal noise of node j
$SINR_{ij}$	SINR from node i to node j
z	number of flows
F_z	achievable rate of zth flow
R_{ij}	achievable rate from node i to node j
B	channel bandwidth
U	average of the achievable rate of all the flows
n	total number of nodes in a network
m	total number of nodes in a flow
M	total number of flows in a network

A. Interference Model

The interference model is divided into two parts, within parts and outside parts. For within parts, nodes are considered as neighbour nodes. For outside parts, nodes can be considered as interference nodes if and only if they are transmitting packets. The interference level of one node is defined as the total interference power of all other transmitting nodes outside of its RSSI threshold. For example, node A has its RSSI range, and if the value of $Transmit\ Power_C - \text{Pathloss}_{CA} \geq RSSI\_TH_A$, then the node C is considered as within node A's transmission range, so node C is a neighbour node of node A. Oppositely, if the value of $Transmit\ Power_E - \text{Pathloss}_{EA} \leq RSSI\_TH_A$, then the node E is considered as outside of node A's transmission range, which means node E is an interference node of node A if it transmits packets to its neighbours. (see Fig. 1).

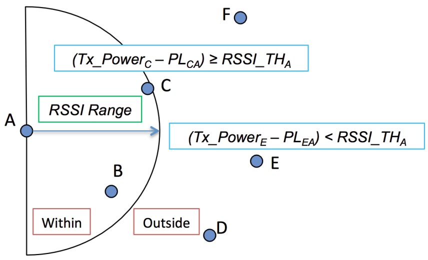

Fig. 1: Interference Model

B. Spatial Reuse Calculation

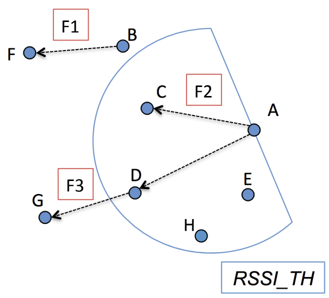

Fig. 2: Spatial Reuse Calculation

Based on the interference model, all the nodes within the transmission range cannot do simultaneous communication while outside nodes can communicate simultaneously. E.g., in Fig. 2, when node A is communicating with node D, node B can communicate with node F, and there is no simultaneous communication between node E and H. The rate between two nodes should take into account the spatial reuse [11] and shared link. In this paper, the rate should first divide the total number of transmitting nodes within its transmission range, and then divide the total number of flows shared with the link. E.g, node C, D, E, and H are within node A's RSSI threshold, so they are identified as neighbour nodes. Others are identified as interference nodes if they communicate with each other. When calculating the rate between node A and C, first computing the total number of transmitting nodes within the RSSI range, using the link rate divide the total number of transmitting nodes (D, A). Although node C is included, but it only receive packets, it should not be regard as a transmitting nodes. Second, calculating the total number of flows which are using the shared link between node A and C, and then using the link rate divide the number of flows. As a results, $Rate_{AC} = LinkRate_{AC}/(2 \times 1)$.

III. Consensus TPC algorithm

In MWNs, when multi-flow situation exists, the proposed CTPC algorithm is defined as two steps. First step, maximizing the minimum link rate of each flow. Because the end-to-end throughput between a source and destination is restricted by the lowest link rate. Second step, calculating the average rates of all existing flows to make all link rates converge on the calculated average rates by adjusting the transmit power of each node. In addition, adjustment of consensus coefficient can optimize the end-to-end throughput.

$$
\begin{aligned}
F &= \underset{P}{Max} \quad min\{R_{12}, R_{23}, \ldots R_{(m-1)(m)}\} \\
U &= \underset{P}{Max} \quad \Big(Mean\{F_1, F_2, \ldots F_z\}\Big) \times C \qquad (5) \\
P &= [P_1, P_2, \ldots P_n] \quad 0 \leq P_i \leq P_{max}
\end{aligned}
$$

Algorithm 1 Consensus TPC Algorithm

01: **Definition**: t is timeslots, C is consensus coefficient
02: **Input**: Initialize $P_i(0) = P_{max}$
03: **Ountput**: Transmit power for timeslot t
04: **Begin**
05: Measure $SINR_{ij}(t)$
06: Calculate $R_{ij}(t)$
07: Share $R_{ij}(t)$ or $SINR_{ij}(t)$ with neighbour nodes
08: Calculate next target rate of each flow $F_z(t+1)$ where

$$F_z(t+1) = Mean\{R_{ij}(t)\}$$

09: Calculate next target rate of all flows $U(t+1)$ where

$$U(t+1) = Mean\{F_z(t)\}$$

10: Calculate $U'(t+1) = U(t+1) \times C$
11: **If** $U'(t+1) = R_{ij}(t)$
12: $P_i(t+1) = P_i(t)$
13: Set $t \leftarrow t+1$. Go to step 17
14: **else**
15: Calculate $P_i(t+1)$ from $U'(t+1)$
16: Set $t \leftarrow t+1$. Go to step 4
17: **End**

Algorithm 1 reveals the proposed consensus TPC algorithm, which operates based on the time slot and observes the following steps:

1) All the transmitting nodes set the initial transmit power to the maximum transmit power P_{max}.
2) The transmitting node i which using the transmit power decided for the time t to sends the packet to its receiving node j.
3) Upon the receiving packet, the receiving node j measures its $SINR_{ij}$ and feeds it back to its transmitting node i.
4) Based on the $SINR$ feedback, the transmitting node i calculates its current link rate $R_{ij}(t)$.
5) Each transmitting node shares the information of $SINR(t)$ with its neighbouring nodes. As a sharing method, the overhearing technique can be used[12].
6) The next target rate of each flow $F_z(t+1)$ is determined

as the average value of the recognized adjacent link rates of each flow, as follows:

$$F_z(t+1) = Mean\{R_{ij}(t)\} = \frac{1}{m}\sum\nolimits_{ij\in\{aware\ links\}} R_{ij}(t) \tag{6}$$

where m is the total number of aware links of z^{th} flow.

7) The next target $U(t+1)$ is determined average value of aware flows, as follows:

$$U(t+1) = Mean\{F_z(t)\} = \frac{1}{M}\sum\nolimits_{z\in\{aware\ flows\}} F_z(t) \tag{7}$$

where M is the total number of aware flows.

8) Update the next target $U'(t+1)$ as follows:

$$U'(t+1) = U(t+1) \times C \tag{8}$$

9) If the next target rate $U'(t+1)$ 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 ends. Otherwise, from (4), the next transmit power $P_i(t+1)$ is calculated to obtain the next target rate $U'(t+1)$, as follows:

$$P_i(t+1) = min\left\{\frac{\left(2^{(\frac{U(t+1)}{B})}-1\right)\left(I_j(t)+\eta_j B\right)}{g_{ij}}, P_{max}\right\} \tag{9}$$

where $\frac{I_j(t)+N_j(t)}{g_{ij}}$ is derived from the $SINR_{ij}$, and $I_j(t) = \sum_{k\in\mathcal{X},k\neq i} G_{kj}P_k$. Then, the operation continues from Step 2).

IV. Evaluation Scenario and Environment

Based on the system model, interference model, and spatial reuse calculation, which are described in Section II, network throughput and power consumption of a given MWN can be evaluated. In this paper, routing and scheduling algorithms are not focused. We assume that a static routing and a time division multiple access (TDMA) protocol are used to evaluate proposed CTPC algorithm. Not only network simulation, but also network emulation are used for evaluation in this paper.

A. Scenarios and Parameters

Two scenarios including multi-flow are used to evaluate the CTPC algorithm. The topologies are depicted in Fig. 3 and Fig. 4. The 6 nodes scenario would take into account both shared link and spatial reuse. 25 nodes scenario has a star topology with the coverage area of 500 m $\times$ 500 m. There is only one destination (node 1) with 6 flows, and average hop count is 4. Network scale is changed to verify the limitations of CTPC algorithm. The original network scale is identified as sparse network. The coverage area of 100 m $\times$ 100 m is identified as dense network, which means the distance between every two neighbour nodes in each flow is less than 20 m.

The system parameters are listed in TABLE II. Network simulation operates on the premise that the intermediate node can transmit and receive the data packets simultaneously without self-interference.

In TABLE II, the † mark means that the RSSI threshold is fixed at a value in order to find out the transmit power

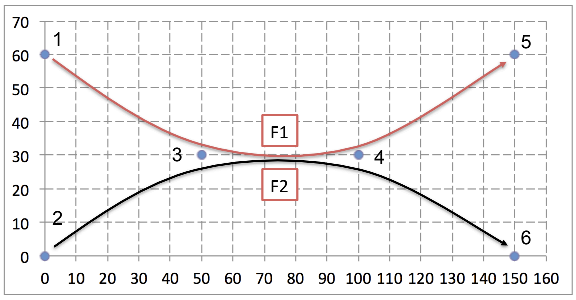

Fig. 3: Share rate network topology of 6 nodes

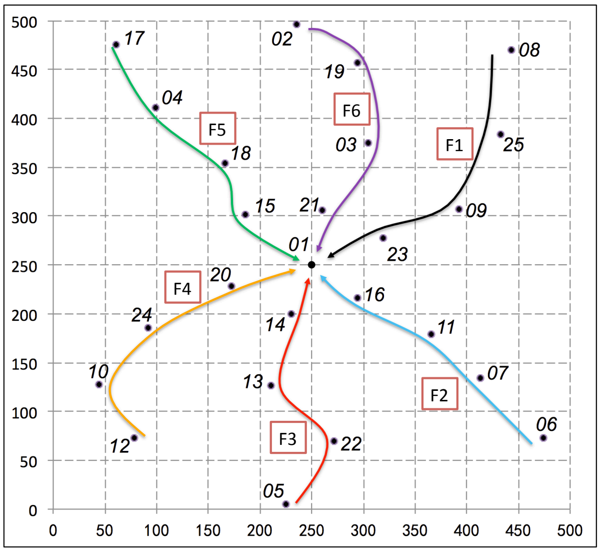

Fig. 4: Star network topology of 25 nodes

limitation of CTPC algorithm when it is used to evaluate dense network topology scenario.

B. Emulation Environment

For the emulation environment, advanced wmediumd emulator is implemented on StarBED. StarBED is a large-scale wired-network testbed managed by the National Institute of Information and Communications Technology of Japan at the Hokuriku StarBED Technology Center located in Ishikawa prefecture, Japan [9]. The core of StarBED consists of a cluster of around 1100 standard PCs, the *experiment nodes*, which have redundant full connectivity by means of a switch cluster. Virtualization techniques such as VMware can be employed to increase the number of logical experiment nodes. QEMU is used for wmediumd emulator architecture. In addition to the core experiment network, there is a dedicated management network that controls and monitors node and switch activity. Nodes can be loaded with the appropriate software, controlled, and monitored by using the management network, thus not affecting the experiments [13].

Fig. 5 depicts the wmediumd emulator architecture. Wmediumd is developed by Javier Lopez and Javier Cardona, cozybit

TABLE II: Parameters for simulation and emulation

Parameter	Value
Minimum distance between nodes (d_0)	1 m
Maximum transmit power (P_{max})	0.1 Watt
Attenuation constant (α)	4.0
Wall attenuation (W_{ij})	0 dB
Shadowing parameter (X_σ)	8 dB
Noise level (η)	–174 dBm
Channel bandwidth (B)	10 MHz
Value depends on the choice of coding and modulation parameters, and the BER requirement (Γ)	1
Consensus coefficient (C)	Variable
RSSI threshold†	Variable

Inc. It only supports that multiple experiment nodes emulated on one host. The advanced wmediumd adds new modules of communication, control, etc. Communication module supports experiment nodes communicate with others that are implemented on other hosts. Channel control module collects information of each experiment nodes and gives instructions to them. Mhop module is a user space module. The functions, such as multihop fashion and TPC algorithm, are implemented in this module. The emulation architecture environment is implemented on StarBED facilities. For each experiment node, it acts as an independent wireless node base on different QEMU. Due to this novel architecture, the use of real hosts leads it possible to realistically emulate wireless network environments.

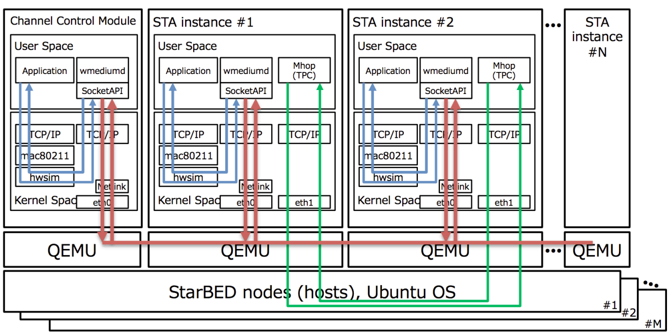

Fig. 5: Wmediumd emulator architecture

V. Numerical Results and Discussions

A. Simulation Results

Average end-to-end throughput is defined as $\bar{U}$, and average transmit power of each node is defined as $\bar{P}$. The *RSSI_TH* is set to –70 dBm. Default consensus coefficient is set to 1.

TABLE III reveals the network performance without TPC algorithm and with CTPC algorithm. With CTPC algorithm, the average end-to-end throughput is improved more than 3 *times* than No TPC algorithm used situation, and the total

TABLE III: The network performance w/o TPC and w/ CTPC

		no TPC	CTPC	CTPC / no TPC
6 nodes	$\bar{P}$(dBm)	20	15.82	79.1%
	$\bar{U}$(Mbps)	0.8888	2.7683	3.11 *times*
25 nodes	$\bar{P}$(dBm)	20	18.97	94.85%
	$\bar{U}$(Mbps)	0.1539	0.4880	3.17 *times*

energy consumption had been reduced. For 6 nodes scenario, results reveal that nodes 1, 2, and 4 decrease their transmit power to 8.63 dBm, and node 3 maintains its original transmit power as 20 dBm. While the transmitting nodes decrease their transmit power, the interference level also decrease. These make link rate increase. Increased minimum link rate influences the end-to-end throughput. For 25 nodes scenario, results reveal that only the source nodes of each flow maintain their original transmit power, and other transmitting nodes decrease their transmit power. Moreover, the transmit power decrease much sharper if the node is closer to destination node.

1) Influence of Consensus Coefficient: Consensus coefficient is changed to optimize the average end-to-end throughput. 25 nodes scenario is used, because the interference level is complex. "*RSSI_TH* $= -90$ dBm" is fixed to achieve wider transmission range. Consensus coefficient is set from 1.2 to 0.6. Fig. 6 plots the average transmit power vary with consensus coefficient, and Fig. 7 plots the average end-to-end throughput vary with consensus coefficient. As the consensus coefficient gets smaller, the end-to-end throughput gets greater. It is not infinite ascribable to the limitations of existing hardware specification. Following the minimum transmit power of sensors (10 dBm), it is reasonable that consensus coefficient decreases until 0.8.

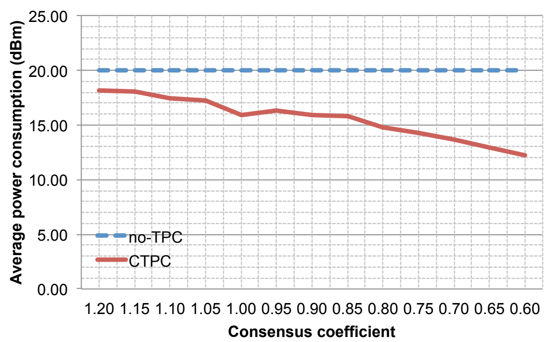

Fig. 6: Influence of average transmit power

2) Influence of RSSI Threshold: Network performance is analysed with different RSSI threshold. While the network scale shrinks from sparse (Fig. 4) to dense (100 m × 100 m), CTPC algorithm does not work well. Because in dense network, the distance between nodes are short, all the nodes with small RSSI threshold become neighbours, which means all the nodes share the communication medium simultaneously. In

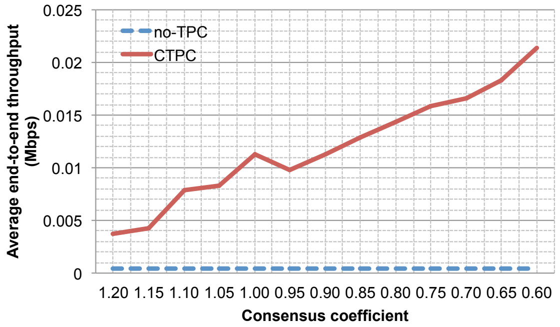

Fig. 7: Influence of average end-to-end throughput

TABLE IV, the results indicate that either minimum transmit power or RSSI threshold of the existing hardware specification is required to be changed in order to cope with the dense wireless network topology when TPC algorithm is applied.

TABLE IV: The network performance with different RSSI threshold.

RSSI Threshold *(dBm)*		–70	–50	–37.04
RSSI Range *(m)*		133.0	42.2	20.0
$\bar{P}$(Watts)	No TPC	0.2	0.2	0.2
	CTPC	0.0736	0.1506	0.1622
	CTPC/No TPC *(%)*	36.8	75.3	81.1
Minimum *P* (dBm)		11.65	–0.56	12.4
$\bar{U}$ (Mbps)	No TPC	0.0007	0.0040	0.2162
	CTPC	0.0006	0.034	0.5725
	CTPC/No TPC *(times)*	0.86	8.74	2.65

B. Emulation Results

In this subsection, a comparison between simulation and emulation is done with the 6 nodes scenario. For the emulation, 6 hosts PCs are set up as 6 experiment nodes. The minimum transmit power of each node is set to 0 dBm, and *RSSI_TH* is set to –90 dBm. The emulation runs 600 seconds, 5 times.

TABLE V: The comparison between simulation and emulation

		no TPC	CTPC	CTPC / no TPC
Simulation	$\bar{P}$(dBm)	20	19.28	96.4%
	$\bar{U}$(Mbps)	0.5925	0.5925	1 *times*
Emulation	$\bar{P}$(dBm)	20	19.37	96.85%
	$\bar{U}$(Mbps)	0.59	0.68	1.15 *times*

CTPC algorithm improves end-to-end throughput only by 1.15 times as compared with no TPC algorithm. The reasons are that emulation has delay, and limitation of hardware specification. Simulation results is identical because under the condition of $RSSI\_TH = -90$ dBm, all of the nodes become neighbours, CTPC algorithm has no effects.

VI. Concluding Remarks

In this paper, the CTPC algorithm had been presented to maximize the end-to-end throughput in MWNs. The simulation results reveal that CTPC algorithm can improve end-to-end throughput and can reduce the total power consumption. The parameter of Consensus coefficient can exhibit the tradeoff of the average end-to-end throughput and the average power consumption. With the current hardware specifications of the transmit power and the RSSI threshold, the CTPC algorithm does not work well. However, the CTPC algorithm enables all data flows to accomplish the maximum end-to-end throughput when the values of the transmit power and the RSSI threshold are further reduced beyond their specification setting. On the other hand, the emulation results also depict the advantage of CTPC algorithm. Future research work will be conducted to investigate the performance of CTPC algorithm with different kind of network topologies (i.e., grid and random) in both sparse and dense environments.

References

[1] *OUTLOOK: Visions and research directions for the wireless world.* WWRF(World Wide Radio Forum), July, 2009. [Online]. Available: http://www.wireless-world-research.org

[2] M. Kubisch, H. Karl, A. Wolisz, L. Zhong, and J. Rabaey, "Distributed algorithms for transmission power control in wireless sensor networks," in *Wireless Commun. and Networking, (WCNC 2003)*, vol. 1. IEEE, Mar. 2003, pp. 558–563.

[3] N. Li, J. Hou, and L. Sha, "Design and analysis of an MST-based topology control algorithm," *Wireless Commun., IEEE Transactions on*, vol. 4, no. 3, pp. 1195–1206, May 2005.

[4] H. H. Choi and J. R. Lee, "Distributed transmit power control for maximizing end-to-end throughput in wireless multi-hop networks," in *Ubiquitous and Future Networks (ICUFN)*, July 2012, pp. 74–79.

[5] V. Shrivastava, D. Agrawal, A. Mishra, S. Banerjee, and T. Nadeem, "Understanding the limitations of transmit power control for indoor wlans," in *Proc. of the 7th ACM SIGCOMM Conf. on Internet Measurement*, ser. IMC '07, New York, USA, 2007, pp. 351–364.

[6] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," in *Proc. of the 11th Annual Int. Conf. on Mobile Computing and Networking*, ser. MobiCom '05, New York, USA, 2005, pp. 73–87.

[7] X. Guo, S. Roy, and W. Conner, "Spatial reuse in wireless ad-hoc networks," in *Vehicular Technology Conf., (VTC 2003-Fall)*, vol. 3. IEEE, Oct. 2003, pp. 1437–1442.

[8] Cozybit, "wmediumd," June 2011. [Online]. Available: https://github.com/cozybit/wmediumd

[9] T. Miyachi, K. Chinen, and Y. Shinoda, "StarBED and SpringOS: Large-scale general purpose network testbed and supporting software," in *Proc. of the 1st int. conf. on Performance evaluation methodolgies and tools*. ACM, 2006, p. 30.

[10] J. Nakata, S. Uda, T. Miyachi, K. Masui, R. Beuran, Y. Tan, K. Chinen, and Y. Shinoda, "StarBED2: Large-scale, realistic and real-time testbed for ubiquitous networks," in *Testbeds and Research Infrastructure for the Develop. of Networks and Communities, (TridentCom 2007)*. IEEE, 2007, pp. 1–7.

[11] T. S. Kim, H. Lim, and J. C. Hou, "Understanding and improving the spatial reuse in multihop wireless networks," *Mobile Computing, IEEE Transactions on*, vol. 7, no. 10, pp. 1200–1212, 2008.

[12] H. C. Le, H. Guyennet, and V. Felea, "OBMAC: An overhearing based MAC protocol for wireless sensor networks," in *Sensor Technologies and Applicat., (SensorComm 2007)*. IEEE, 2007, pp. 547–553.

[13] R. Beuran, L. T. Nguyen, T. Miyachi, J. Nakata, K. Chinen, Y. Tan, and Y. Shinoda, "QOMB: A wireless network emulation testbed," in *Global Telecommun. Conf., (GLOBECOM 2009)*. IEEE, 2009, pp. 1–6.