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Study of Carrier Sense Threshold and Transmit Power Control for Distributed Wireless Ultra-Dense Networks

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Abstract The promising wireless ultra-dense networks (WUDNs) have been deemed one of the key enabler for realizing the future wireless network, especially 5G technologies. Nonetheless, the system designs of carrier sense threshold and transmit power will be crucial when the huge number of user equipments (UEs) are densely engaged in that data traffic transmission. One practical and effective approach to study the system design is through numerical simulation. In this paper, we formalize the problem of minimizing the energy consumption and maximizing the average end-to-end throughput of WUDN by optimally using the consensus transmit power control (CTPC) scheme. To validate the effectiveness of our proposed scheme, we also focus the impact of the carrier sense threshold (CST) on the trade-off between UE experienced data rate and network energy efficiency.

Keywords System Design, Carrier Sense Threshold, Transmit Power Control, Wireless Ultra-dense Network

1. INTRODUCTION

Nowadays, wireless technologies have become an essential part of life in the whole world, vary with the rapid evolution of the user equipments (UEs), i.e., smartphones, tablets, and other smart wearable wireless devices. Moreover, the UEs also have the exponential growth problem. Cisco visual networking index (VNI) [1] forecasts that mobile devices and connections will grow to 11.6 billion by 2021, which can be describe as the number of mobile-connected devices per capita will reach 1.5, and traffic from wireless and mobile devices will become 78% of Internet traffic. The huge amount of devices will lead to a new paradigm shift in the near future networks, which are called ultra-dense networks (UDNs).

In [2], the UDNs is defined as the density of access points (APs) that are far outweighed the density of users. Ding *et al.* [3] provided a quantitative measure of the density from the AP point of view at which a network can be considered ultra-dense ($\geq 10^3$ cells/km^2). In this paper, the more appropriate definition of wireless UDNs (WUDNs) from the user point of view is described. Let the distance between every two wireless devices, e.g., APs, UEs, etc., is λ. If $0.1 \leq \lambda \leq 10$ in meters, then the network environment is recognized as WUDNs. Here, the value "0.1 meter" represents the minimum distance between two devices. The value "10 meters" is an average value that is calculated as the average density of wireless devices in the metropolis such as Tokyo, Shanghai, or New York.

On the other hand, to solve the dramatic growth of wireless data traffic, the fifth generation networks (5G) is under developing, including collaborative projects such as METIS [4], 5GNOW [5]. 5G and its associated technologies can provide great powerful backhaul and fully functional fronthaul. Under 5G, D2D plays an essential role in a distributed way due to nodes can help each other in relaying information to realize the advantages of spatial diversity, e.g., efficiency, reliability, capacity and transmission range. In WUDNs, wireless end users put more emphasis on its experienced data rate and energy efficiency (EE). To optimize the UE experienced data rate, interference is a problem that cannot be ignored. Common solution is interference coordination, which takes place in the frequency domain, time domain, space domain, power domain, or a combination of them. However, the limited frequency and time domain cannot take the key role for the huge number of UEs. Thus, the consensus transmit power control (CTPC) scheme and carrier sense threshold (CST) control are therefore proposed to optimize the UE experienced data rate and network energy efficiency.

1.1. Related Works

In the space domain, spatial reuse can optimize user experienced data rate and EE in WUDNs. Spatial reuse accommodates more concurrent transmission, which gains higher network capacity. However, the increasing number of concurrent transmission would also bring intolerable interference. IEEE 802.11 media access control (MAC) has employed physical carrier sensing to ensure an adequate level of spatial reuse.

Under the physical carrier sensing, only if the signal strength of an interference is below the carrier sense threshold (CST) of the receiver, interference can do the concurrent transmission. Here, the signal strength is decided by the transmit power and distance based pathloss model. To summaries, increasing the carrier sense threshold (CST) would lead to high interference and also lead to high fairness of communication (concurrent transmission), and vice versa.

In contrast, transmit power control is the most efficient way to reduce the interference. The typical TPC algorithms in wireless networks are: Local Mean Algorithm (LMA) [6], Local Minimum Spanning Tree (LMST) [7] and max-min power (MMP). LMA and LMST are basically used for sensor networks. They are focued on network lifetime and topology control, respectively. MMP is intended to maintain the best possible modulation and coding scheme (MCS) of each link while decreasing the transmission power as much as possible. Choi *et al.* [8] proposed a distributed transmit power control (DTPC) for maximizing end-to-end throughput in wireless multihop networks. Its performance is good but it only supports for the single flow exits environment.

Thus, the motivation of this research is to propose a scheme to achieve best EE with high UE experienced data rate in a distributed manner for WUDNs.

1.2. Organization

The rest of this paper is organized as follows: after presenting the introduction, related works, motivation in Section 1, the system model and interference model are presented in Section 2. The proposed adaptive CST and consensus TPC algorithm are described in Section 3. In Section 4, the proposed scheme has been evaluated with one ultra-dense scenario of chain network topology. The scenario and parameters are described. Numerical simulation results are presented in Section 5. Finally, Section 6 summarizes the paper with conclusions and directions for future work.

2. SYSTEM MODEL

In this subsection, 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 formulated with ITU site-general models [9]. Here, $L(d_0)$ is the pathloss at d_0 (dB) and L_f is the floor penetration loss factor. Thus, the channel gain is

$$L_{ij} = L(d_0) + \alpha \cdot \log_{10}\left(\frac{d_{ij}}{d_0}\right) + L_f(w) \tag{1}$$

  where $L(d_0) = 20 \cdot \log_{10} f - 28$, for a reference distance d_o at 1 meter. Also, if the frequency value is 60 GHz or more, it is assumed propagation within a single room or space, and do not include any allowance for transmission through walls. Under this assumption, the $L_f = 0$ dB for $w = 0$.
- Power ratio (no unit) between node *i* and node *j* is

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

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

$$SINR_{ij} = \frac{G_{ij} \cdot P_i}{\eta_j \cdot B + \sum_{k\in\mathcal{I},k\neq i} G_{kj} \cdot P_k} \tag{3}$$

  where k denotes the interfering node. The interfering nodes are belong to the set $\mathcal{I}$.
- Under the level of *SINR*, the achievable rate of transmission (bit/s) from node *i* to node *j* is expressed with *Shannon capacity* under the additive white Gaussian noise channel model. That is

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

- When multi-flow exists, one link might be shared with multiple concurrent transmission flows. Thus, the shared link rate is defined as

$$R_{ij}^s = \frac{R_{ij}}{\epsilon_{ij}} \tag{5}$$

  where ϵ_{ij} is the total number of flows that sharing the link rate from node *i* to node *j*.
- The end-to-end flow rate of flow z $(F(z))$ is restricted by the lowest link rate, which is defined as

$$R_{F(z)} = \min\{R_{12}^s, \quad R_{23}^s, \quad \cdots, R_{(m-1)(m)}^s\} \tag{6}$$

  where $z \in M$, $m - 1$ is the total hops in flow z.
- Let the $F(z)$ is from source node x_z to its destination node y_z with $m - 2$ relay nodes. The user experience data rate of source node x_z is define as

$$U_{F(z)}^x = R_{F(z)} \tag{7}$$

- The definition of average user experience data rate $(\bar{U})$ is

$$\bar{U} = \frac{\sum_{z=1}^{M} (U_{f(z)}^x)}{M} \tag{8}$$

  where M is the total number of transmitting flows.
- The EE (ψ) of node x is defined as

$$\psi_i = \frac{U_{F(z)}^x \times t_k}{\sum_{k=1}^{m-1} \frac{P_k}{\epsilon_{k(k+1)}} \times t_k} \tag{9}$$

  where $i \in x$, $U_{F(z)}^x$ is given by Equation (7); $m-2$ is total relay nodes in $F(z)$; t is the total time for transmission and $0 \leq P_k \leq P_{\max}$.
- The EE of the overall network can be defined as

$$\psi = \sum_{i=1}^{x} \psi_i \tag{10}$$

  where x is the source node of each flow.

Some notations and definitions are list in Table I

2.1. Interference Model

In this subsection, the interference model is described. It can be divided into two parts for a specific receiver, within parts and outside parts. For within parts, nodes are considered as neighbor nodes. Conversely, outside nodes can be considered

TABLE I: Notations and definitions

d_0	reference distance (m)
α	distance power loss coefficient
d_{ij}	distance between node i and node j (m)
L_f	floor penetration loss factor (dB)
w	number of floors between transmitter and receiver
f	frequency (MHz)
G_{ij}	channel gain from node i to node j (dB)
$SINR_{ij}$	SINR from node i to node j
P_i	transmit power of node i (Watt)
$P_{\max}$	maximum transmit power
η_j	thermal noise of node j
$\mathcal{I}$	the set of interfering nodes
$\mathcal{N}$	the set of neighbor nodes
R_{ij}	achievable rate from node i to node j
B	channel bandwidth (Hz)
ψ_i	EE of node i
ψ	EE of the overall network
n	total number of nodes in a network
M	total number of flows
F_z	end-to-end flow rate of zth flow
m	total number of nodes in a flow
U	average user experienced data rate of all the flows

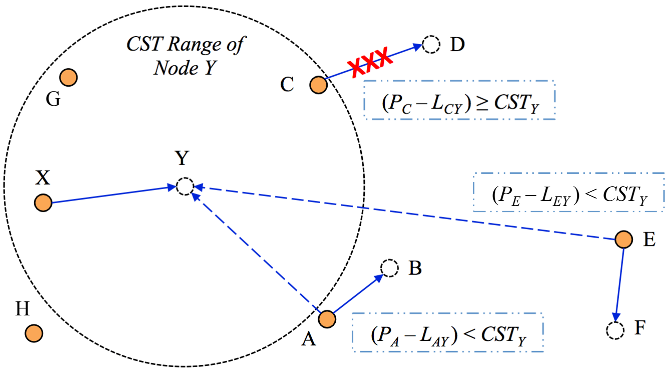

Fig. 1: An example of interference model and spatial reuse

as interference nodes. The interfering nodes will influence the receiver if and only if they are transmitting packets to other receivers. The calculation of the interference level is described in Equation (3). For example, as showed in Fig. 1, for node Y, it has its own CST range. If the transmit power of node A in dBm minus the pathloss between node A and Y is less than the CST value of node Y, then node A belong to the interference nodes set $\mathcal{I}$, same as node E and node H. Conversely, the nodes belong to the neighbor nodes set $\mathcal{N}$, e.g., node C and node G. Moreover, the node H cannot directly communicate with node Y, but node G can directly communicate with node Y.

Based on the interference model, the nodes that belong to the $\mathcal{I}$ can do the simultaneous transmissions due to the spatial reuse. However, this would generate extra interference. The nodes that belong to the $\mathcal{N}$ would not increase the interference level, but would take the carrier-sense multiple access with collision avoidance (CSMA/CA) into consideration. In Fig. 1, when the link rate between node X and Y (R_{XY}) is calculated, the interference from node A and E would directly add into Equation (3), and the neighbor node C should not communicate with its receiver F during this period due to the extremely strong interference. Node C can communicate with node F by other channel access method, e.g., time-division multiple access (TDMA). Moreover, if node Y adjusts its CST, i.e., decrease the value of CST, then, the CST range is extended. In that case, node H is not belong to the $\mathcal{I}$ instead of $\mathcal{N}$, which means node H can directly communicate with node Y.

2.2. *Problem Description*

Within the above setting, the problems can be mathematically formulated as

$$\zeta = \max_{P} \begin{cases} \max\left(\bar{U}\right) \\ \max\left(\psi\right) \end{cases} \tag{11}$$

where $P = [P_1, P_2, \cdots, P_x], \quad 0 \leq P_i \leq P_{\max}$.

3. Proposed Scheme

The proposed scheme contains two algorithms, which are described in the follows subsections.

3.1. *Adaptive CST Algorithm*

Follow the ITU pathloss model with 60GHz frequency, the CST interval is set as 3 dBm. Large value of interval would lead the convergence faster, relatively, small value of the interval would lead to high accuracy. CST range is set from -30 dBm to -90 dBm. The CST is adjusts from maximum value.

Algorithm 1 Adaptive CST Algorithm

01: **Definition**: t is timeslots, *3 dBm* is CST interval
02: **Input**: Initialize $CST_j(0) = CST_{\max}$
03: **Ountput**: CST_j for timeslot $t+1$
04: **Begin**
05: Measure $S_{ij}(t), I_(kj)(t)$
06: Calculate $SINR_{ij}(t)$
07: **if** $SINR_{ij}(t) = 0$
08: $CST_j(t+1) = CST_j(t) + 3$
09: **else**
10: **if** $S_{ij}(t) \geq I_(kj)(t)$
11: Set $t \leftarrow t+1$ Go to step 19
12: **else**
13: $CST_j(t+1) = CST_j(t) - 3$
14: Set i as interference
15: Set $k = \arg\min_{k \in \mathcal{I}} [I_(kj)(t)]$ as signal
16: Set $t \leftarrow t+1$ Go to step 05
17: **endif**
18: **endif**
19: **End**

3.2. *Consensus Transmit Power Control*

Followed topology control through adaptive CST algorithm, consensus TPC algorithm is continued to optimize the UE experienced data rate and EE. When multi-flow situation exists, the proposed CTPC algorithm is described as two steps. First step, maximizing the minimum link rate of each flow. Because the UE experienced data rate between a source and destination is restricted by the lowest link rate. So maximum the minimum link rate could increase the UE experienced data 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 reduce the number of iterations and can achieve the margin of UE experienced data rate.

$$\begin{aligned} R'_{F(z)} &= \max_{P} \quad \min\{R^s_{12}, R^s_{23}, \ldots R^s_{(m-1)(m)}\} \\ W &= \max_{P} \quad \left(\text{mean}\{R'_{f(1)}, R'_{f(2)}, \ldots R'_{F(z)}\}\right) \times C \\ P &= [P_1, P_2, \ldots P_n] \quad 0 \le P_i \le P_{\max} \end{aligned} \tag{12}$$

Algorithm 2 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 $R^s_{ij}(t)$ or $SINR^s_{ij}(t)$
07: Share $R^s_{ij}(t)$ or $SINR^s_{ij}(t)$ with neighbor nodes
08: Calculate next target rate of each flow $R'_{F(z)}(t+1)$ where

$$R'_{F(z)}(t+1) = \text{mean}\{R^s_{ij}(t)\}$$

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

$$W(t+1) = \text{mean}\{R'_{F(z)}(t+1)\}$$

10: Calculate $W'(t+1) = W(t+1) \times C$
11: **If** $W'(t+1) = R^s_{ij}(t)$
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 $W'(t+1) \times \epsilon_{ij}$
16: Set $t \leftarrow t+1$. Go to step 4
17: **End**

Algorithm 2 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 $R_{ij}(t)$, and then calculate its R^s_{ij} with its ϵ_{ij}.
5) Each transmitting node shares the information of R^s_{ij} with its neighbouring nodes. As a sharing method, the overhearing technique can be used[10].
6) The next target rate of each flow $R_{F(z)}(t+1)$ is determined as the average value of the recognized adjacent link rates of each flow, as follows:

$$\begin{aligned} R'_{F(z)}(t+1) &= \text{mean}\{R^s_{ij}(t)\} \\ &= \frac{1}{m}\sum\nolimits_{ij\in\{awarelinks\}} R^s_{ij}(t) \end{aligned} \tag{13}$$

where *m* is the total number of aware links of z^{th} flow.
7) The next target $W(t+1)$ is determined average value of aware flows, as follows:

$$\begin{aligned} W(t+1) &= \text{mean}\{R'_{F(z)}(t+1)\} \\ &= \frac{1}{M}\sum\nolimits_{z\in\{awareflows\}} R'_{F(z)}(t+1) \end{aligned} \tag{14}$$

where *M* is the total number of aware flows.
8) Update the next target $W'(t+1)$ as follows:

$$W'(t+1) = W(t+1) \times C \tag{15}$$

9) If the next target rate $W'(t+1)$ is the same as the current target rate $R^s_{ij}(t)$, 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 $W'(t+1) \times \epsilon_{ij}$, as follows:

$$\begin{aligned} &P_i(t+1) \\ &= \min\left\{\frac{\left(2^{\left(\frac{W(t+1)\times\epsilon_{ij}}{B}\right)} - 1\right)\left(I_j(t) + \eta_j B\right)}{G_{ij}}, P_{\max}\right\} \end{aligned} \tag{16}$$

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).

4. Simulation Scenario and Parameters

One simple scenario with 6 nodes chain topology is used to evaluate the proposed schemes. The topology is depicted in Fig. 2. The 6 nodes chain topology follows the definition of WUDNs. The average distance between 2 nodes is less than 2 meters. There is just one destination (node 6) with 5 flows, which means every nodes except node 6 is transmitting different packets to node 6.

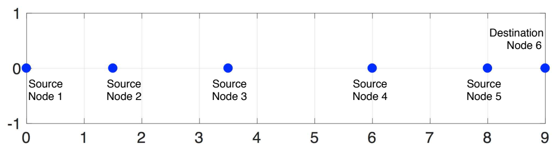

Fig. 2: Chain network topology of 6 nodes

The system parameters are listed in TABLE II. Network simulation operates on the premise that the intermediate node can transmit and receive data packets simultaneously without self-interference [11].

TABLE II: Parameters for simulation

Parameter	Value
Minimum distance between nodes (d_0)	1 m
Frequency (f)	60 GHz
Distance power loss coefficient (α)	22
Floor penetration loss factor (L_f)	0
Maximum transmit power ($P_{\max}$)	0.1 Watt
Minimum transmit power ($P_{\min}$)	1×10^{-7} Watt
Noise level (η)	–174 dBm
Channel bandwidth (B)	100 MHz
Value depends on the choice of coding and modulation parameters, and the BER requirement (Γ)	1
Maximum CST ($CST_{\max}$)	-30 dBm
Minimum CST ($CST_{\min}$)	-90 dBm
CST interval	3 dBm
Consensus coefficient (C)	Variable

5. Numerical simulations

5.1. *Performance of CTPC*

Figure 3 shows UE experienced data rate and transmit power versus number of iterations with single-hop transmission. Single hop is because the CST is fixed for a static minimum value, and all the nodes are transmitting their packets to the same destination simultaneously. There is a great gap of UE experienced data rate among each node. At iteration of “0”, user experienced data rate of node 5 is around 300 Mbps, constantly, node 1, node 2 and node 3 are all less than 5 Mbps. Under the proposed CTPC, the UE experienced data rate of node 1, 2 and 3 is increased to more than 20 Mbps.

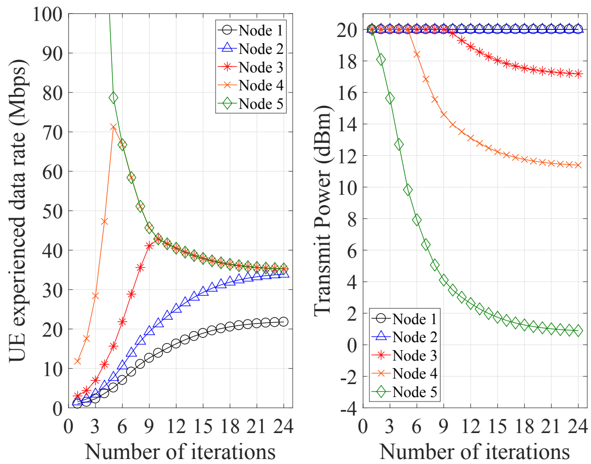

Fig. 3: User experienced data rate and transmit power versus number of iterations with single-hop transmission

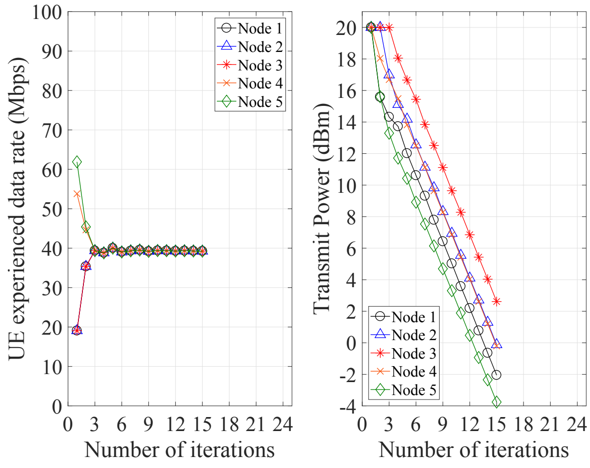

Fig. 4: User experienced data rate and transmit power versus number of iterations with multihop transmission

Also, as the iteration proceeds, the transmit power of node 5, 4 and 3 decreased to mitigate their interference. Here, the UE experienced data rate cannot converge to the same value. The iteration stops due to the difference between t and $t-1$ is less than the minimum offset, e.g., 1 Kbps.

5.2. *Performance of Adaptive CST and CTPC*

Figure 4 shows UE experienced data rate and transmit power versus number of iterations with multihop transmission. Multihop is because the adaptive CST is dynamic control the network topology, which means the packets from node 1 to node 6 cannot be directly delivered. Through the CST algorithm, the nodes can only communicate with their neighbor nodes. Here, the ϵ of each link is different. There is only one flow shared the link$_{12}$, and 5 flows shared the $link_{56}$. There is a gap of UE experienced data rate among each node at first. After the control by proposed CTPC algorithm, the UE experienced data rate of all nodes are converged to around 40 Mbps. Also, as the iteration proceeds, the transmit power of all nodes decreased dramatically to mitigate their interference. Here, it can be noticed that the proposed adaptive CST and CTPC scheme can prevent crosstalk, and multihop fashion can dramatically increase the user experienced data rate and decrease the total transmit power.

5.3. *Performance of Energy Efficiency*

Figure 5 shows energy efficiency versus number of iterations. The black triangle line is results of CTPC, which means fixing CST value. The red square line is results of adaptive CST and CTPC. Before the iterations of “8”, there is no much difference between them. That is because all of the two fashions are worked under the proposed CTPC scheme. However, for single-hop transmission, the node 1 and node 2 are far away the destination node. Thus, the have to maintain their transmit power to achieve higher UE experienced data rate (see Fig. 3). For multihop transmission, after 3 times

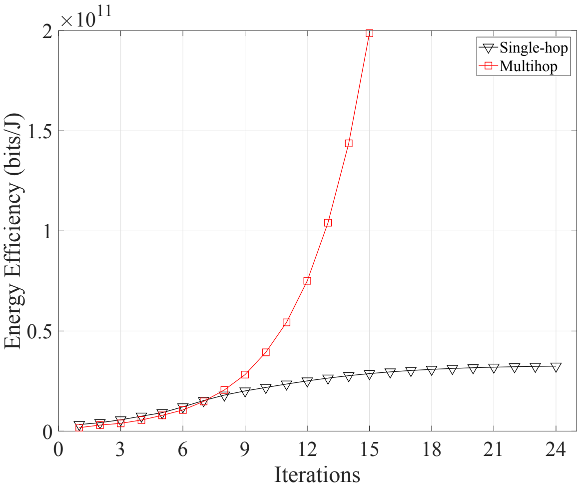

Fig. 5: Energy efficiency versus Number of iterations

iterations, the nodes already converge to the balance. Due to the dense environment, the noise is too less (changed with temperature). Thus, the $SINR$ is similar to SIR. When CTPC find the balance point, all of the nodes can decrease their transmit power together without influence on UE experienced data rate. However, if interference level is near to the noise level, balance would be broken.

5.4. *Influence of Consensus Coefficient*

Figure 6 shows the number of iterations versus consensus coefficient. For ultra dense environment, adjustment of the consensus coefficient can accelerate the convergence to achieve high efficiency. For single-hop, due to the great gap of UE experienced data rate, consensus coefficient should be less than 1. If the value of consensus coefficient is greater than 1, the gap among nodes cannot be eliminated, thus, the UE experienced data rate cannot converge to the same target value. Oppositely, the value should greater than 1 for multihop transmission, due to the gap of UE experienced data rate among nodes is not substantial. Thus, the increased consensus coefficient can accelerate the convergence. Similarly, if the value of consensus coefficient is smaller than 1, the UE experienced data rate cannot converge to the same target value.

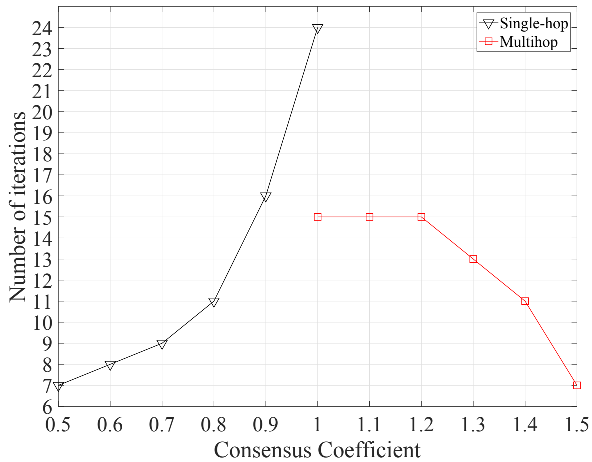

Fig. 6: Number of iterations versus consensus coefficient

6. Concluding Remarks

In this paper, to minimize the energy consumption and maximize the average UE experienced data rate (end-to-end throughput with multihop fashion), the consensus transmit power control scheme is proposed for ultra-dense networks. To validate the effectiveness of proposed CTPC scheme, the adaptive carrier sense threshold is proposed on the trade-off between UE experienced data rate and network energy efficiency. Numerical simulation results reveal that the proposed adaptive CST and CTPC scheme can improve UE experienced data rate and energy efficiency dramatically. Moreover, parameter of consensus coefficient can reduce the number of iterations to increase efficiency of proposed scheme.

Further research work will be conducted to investigate the performance of proposed scheme with more complicated scenarios (i.e., more random nodes or dynamic nodes in the scenarios).

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