Environmental Aware Hierarchical Ad Hoc Network with Multiple Frequency Bands using Weighted Laplacian Matrix

Toshiyuki Shizuoka and Takeo Fujii
Advanced Wireless & Communication Research Center (AWCC)
The University of Electro-Communications, 1-5-1, Chofugaoka, Chofu city, Tokyo, 182-8585 Japan
E-mail: {shizuoka, fujii}@awcc.uec.ac.jp

***Abstract*—Wireless ad hoc networks have attracted high attention to adapt to multi-hop networks such as wireless mesh network, sensor networks, vehicle-to-vehicle (V2V) networks, and so on. While it has the feature of self-configuring and infrastructure-less, researchers mainly use only one frequency band for a system. In our prior study, we proposed an adaptive spectrum band allocation for topology control and data transmission. Due to its lower attenuation rate, the lower-frequency band is allocated for topology control. On the other hand, we allocated higher-frequency band for data transmission because high-frequency bands can transmit data more rapidly. However, this routing method only considers connectivity between nodes. Thus this method not considers about throughput or stability between nodes. In this paper, we propose a throughput-aware and stability-aware distributed routing scheme for ad hoc network using multiple frequency bands. In this routing method, we use the weighted Laplacian matrix for each node's topology control. Signal-to-Noise Ratio (SNR) is used for the weighted value of the Laplacian matrix. By using weighted Laplacian matrix, we introduce that our method can choose an optimized route by the selected priority. From a number of computer simulations, the improvement of Packet Delivery Ratio (PDR) and throughput, and the reduction of average interference area are confirmed.**

I. Introduction

As the development of the Internet of Things (IoT) [1] and Machine to Machine (M2M) communication [2], wireless communication is not limited to human-only communications. As these communications start, the traffic of wireless communication is considered to increase explosively. In this environment, how to treat such traffic in limited frequency resource to provide robust wireless networks and satisfy users' demand is essential issue [3]. Wireless ad hoc networks have attracted high attention because it can generate dynamic links according to the surrounding environment. Up to now, many researchers and companies assumed to use wireless ad hoc network in 2.4 GHz Industry-Science-Medical (ISM) bands because such bands can use freely without any permission. However, 2.4 GHz ISM bands are already crowded at all times by wireless LANs, microwave ovens, and so on. From the viewpoint of users, on the other hand, the requirement of the system is different according to the service. For instance, voice applications need stable, low latency communication because voice communication needs real-time communication. However, voice communication does not require a high data rate channel because it uses only a low data rate. Meanwhile, video streaming services need high data rate channel because the data traffic of such services is massive compared to other services. However, such a service does not need stable or low latency communication because it downloads data at high speed when connecting, then downloaded data are held at the buffer. That is why the application adaptive routing scheme is preferable to systems. Except for 2.4 GHz bands, there are some unlicensed bands (frequency bands that can use without any license) in each country. In Japan, for example, 920 MHz is used for Radio Frequency Identification (RFID) or sensor networks, and 5 GHz is used for wireless LANs. Besides, there are a large number of white spaces (i.e., frequencies that are allocated to some services but not used under specific times or areas) are exist. Especially, TV white spaces (TVWS) are typical one [4]. To use such frequency efficiently, some researchers examined about wireless ad hoc network in multiple frequency bands. As the first example, in [5], Tamaki *et, al.* proposed the method to use a band that has shorter delay time by checking congestion of each frequency. In [6], Abbagnale *et, al.* proposed a concept of *Cognitive Radio* adapted to wireless ad hoc network. However, these methods use the same channel for routing and data transmission. Therefore, these systems remain not adapted to the user or application's requirement. In our prior work [7], we proposed the method of band selection for wireless ad hoc networks that corresponds to multi-frequency and user's frequency requirement by using the Laplacian matrix and the Imperfect Algebraic Connectivity (IAC). However, its method only detects each edge exists or not. Thus, the Received Signal Strength Indicator (RSSI) of each link is not considered. To this end, this paper contains some contributions. First, we proposed a method of the weighted topology-recognition scheme in each frequency and channel. In our scheme, we use weighted Laplacian matrix for topology control. Our method uses a different frequency channel for topology control and data transmission, respectively. Each node has a different Laplacian matrix in each frequency. Second, we proposed a method of band selection for wireless ad hoc networks that corresponds to multi-frequency and user's requirements. We remark that this is the weighted Signal-to-Noise power Ratio (SNR)-aware-decentralized routing scheme for wireless ad hoc network. Each component of the Laplacian matrix is weighted by SNR. We select routing priority by setting a threshold. *Algebraic Connectivity*, the second smallest eigenvalue of the Laplacian matrix, is used to compare the connectivity of each channel and frequency. Thus, it can generate a robust network to avoid disconnection. By using our proposed method, it causes a small amount of interference area to other systems. From numerical simulations, we indicate our method to achieve PDR-aware or Throughput-aware routing in addition to decreasing surrounding interference area by our proposed method.

The rest of this paper is organized as follows. Section II explains the weighted Laplacian matrix in graph theory, including weighted adjacency matrix and algebraic connectivity. Section III presents a generalized system model. Section IV presents a number of numerical simulations. The paper concludes in section V.

II. Weighted Laplacian Matrix and Algebraic Connectivity

A. Weighted Laplacian Matrix

Let $G(N, E)$ be a graph, where N is the set of nodes, and E is the set of edges. In graph theory, the connectivity of a graph is represented by the Laplacian matrix $\mathbf{L}$. This matrix is derived from two matrices, the adjacency matrix, and the diagonal matrix. The adjacency matrix is a $(N \times N)$ binary matrix represented the connectivity between nodes by 1 (the edge between nodes exists) or 0 (otherwise). We assume that there are no loops in a graph, and diagonal entries of the adjacency matrix are all 0. Adjacency matrix is weighted if any of its edges (i, j) is associated to a number $w_{i,j} > 0$. The weighted adjacency matrix is denoted as $\mathbf{W}$. Diagonal matrix, denoted as $\mathbf{D}$, is a matrix that has only diagonal components. Laplacian matrix, denoted as $\mathbf{L}$, is calculated by weighted adjacency matrix and diagonal matrix,

$$\mathbf{L} \equiv \mathbf{D} - \mathbf{W}. \tag{1}$$

Weighted Laplacian matrix is symmetric and all its row and column sums are equal to 0. Thus, components of weighted Laplacian matrix can be written as below.

$$\mathbf{L_{i,j}} = \begin{cases} \sum_{j=1}^{n} w_{i,j} & \text{if } i = j, \\ -w_{i,j} & \text{if } i \text{ and } j \text{ are adjacent,} \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

where $w_{i,j}$ is the weights of the edge between i and j. The eigen spectrum of $\mathbf{L}$ is defined as the set of its eigen values, denoted as λ that can be ordered in ascending order $(\lambda_1 \leq \lambda_2 \leq \ldots \leq \lambda_N)$. The eigenvalues of the weighted Laplacian matrix represent the connectivity of the graph [8]–[10]. The second smallest eigenvalue of Laplacian matrix, denoted as λ_2, is called *Algebraic Connectivity*. It is described in the next subsection.

B. Algebraic Connectivity

Theorem of Algebraic Connectivity is written by Mohar [8].

Theorem 1 [8]: the smallest eigenvalue of the Laplacian matrix of the graph G is equal to 0 (i.e. $\lambda_1 = 0$) and the number of eigenvalues equal to 0 is the number of connected components of G. Consequently, $\lambda_2 = 0$ iff G is disconnected; λ_2 is generally called *Algebraic Connectivity*.

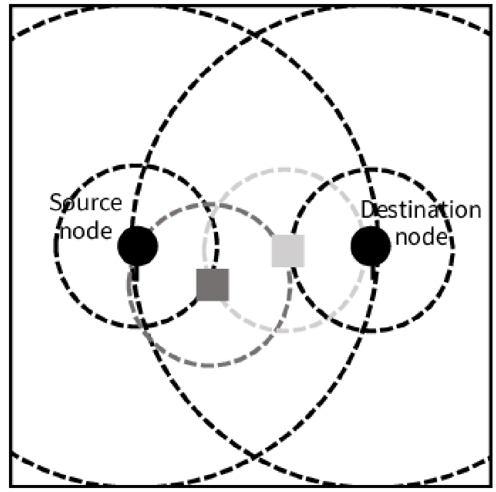

Fig. 1. Multiband hierarchical ad hoc network.
Each circle is coverage area.

In [11], the authors showed the algebraic connectivity λ_2 indicates the robustness of the graph.

C. Imperfect Algebraic Connectivity

In our prior work [7], we defined the *Imperfect Algebraic Connectivity* (IAC). The algebraic connectivity judges the connectivity to all nodes, whereas the imperfect algebraic connectivity assesses the robustness between the source node and the destination node. A value of IAC changes due to the number of hops between the source node and the destination node. We used IAC to select the channel that has a plural route for considering the robustness of the channel.

III. System Model

We consider a multihop ad hoc network with M nodes and N frequencies. We assume that there are four channels in each frequency. Transmission becomes a success if the receiver's Signal-to-Noise Ratio (SNR) is bigger than the threshold. Otherwise, we assume that transmission is failed. The system model is described in Fig. 1. A bigger circle means lower-frequency channel's coverage, meanwhile smaller circle means higher-frequency channel's coverage. For simplicity, a bigger circle of relay nodes are erased. In each channel $c \in C$ of each frequency $f \in N$, each node $i \in M$ have the $(M \times M)$ sizes weighted Laplacian matrix $L(i, f, c)$. The source node constructs a low-frequency control channel, and a high-frequency data transmit channel from the results of the Laplacian matrix. After the route generating step, the source node transmits packets to the destination node. In a route generation stage, we only consider the propagation loss. The propagation loss is different among the used frequency bands. In the packet sending stage, fading is multiplied in addition to the propagation loss. Route generating stage can split into five steps (A − E). Each step is described below.

A. Recognition of Adjacent Nodes

At first, each node $i \in M$ broadcasts HELLO message to other nodes in each channel $c \in C$ of each frequency $f \in N$. The purpose of this message is to register weights on each edge. Weights are calculated by approximation formula. In our method, we used the results of Average PDR per SNR threshold in our prior work [7]. We approximated this results by deciding two points. SNR = 10 [dB] is defined as weight 0.6. SNR = 15 [dB] is defined as weight 1. From these two points, we use the linear approximation. The result of the calculation is registered in each node's holding Laplacian matrix $L(i, f, c)$. As defined in Equation (2), the (i, j) component of the Laplacian matrix registered $-w_{i,j}$ iff node i and node j are adjacent and connect each other. In this paper, if node i can connect to node j, then we assume that node j can connect to node i. That is called, *Undirected Graph* in graph theory. Thus, if $L_{i,j} = -w_{i,j}$, then $L_{j,i} = -w_{j,i} = -w_{i,j}$. After that, the sum of the value of the weights in the same row of the Laplacian matrix is registered to the diagonal components. Due to the propagation loss, the coverage area of each HELLO message is different in each frequency. Hence, components of each Laplacian matrix is different even if the same node makes it. Note that, each node can get information only about the adjacent nodes in this step. It means that other components of Laplacian matrix (connectivity information created by other nodes) are not included yet. Therefore Laplacian matrix is not completed now.

B. Selecting the Control Channel

Next, the source node $\mathrm{M}_{\mathrm{sender}}$ selects the control frequency f_{control} and control channel c_{control}. $\mathrm{M}_{\mathrm{sender}}$ examines the $N \times C$ numbers of Laplacian matrix that it has. In series of Laplacian matrix, the highest frequencies one that can communicate to all other nodes (i.e., all component of the source node's row is not 0 without diagonal one) is selected as f_{control}. Note that the source node checks the connectivity between the source node and other nodes in this step, so it can select even though each Laplacian matrix is an incomplete one. After selecting the control channel, the source node broadcasts the information of the control channel to all other nodes through the selected channel c_{control} in f_{control}.

C. Sharing Each Weighted Laplacian Matrix

In this step, each node $i \in M$ broadcasts all own Laplacian matrices $L(i, f, c)$ of each channel $c \in C$ in each frequency $f \in N$. This information is sent through the control channel c_{control} in f_{control} decided at the previous step. As a result, all nodes in the graph will derive the *Common Laplacian Matrix* $L'(i, f, c)$ that summarizes each node's component of the Laplacian matrix.

D. Generation of Route

After getting the common Laplacian matrix, the source node finds the route to the destination node in each channel $c \in C$ of each frequency $f \in N$, using the common Laplacian matrix $L'(i, f, c)$. In our proposed method, unlike in the case of the previous most famous route discovery method, Ad-hoc On-demand Distance Vector (AODV) [12], it does not need to send *route request* packets. In our proposed method, the source node finds the shortest route using the common weighted Laplacian matrix. If the weight of an edge is lower than the weight threshold, we regard this edge as disconnected. What the algorithm of route generates in the proposed method is shown below.

Algorithm 1 Generation of route in Weighted Laplacian Matrix

```
s ← source node
d ← destination node
P ← total node number
A ← false
if L(s, f, c)_{s,d} = −w_{s,d} then
    if w_{s,d} > Weight threshold then
        A ← true
        break
    end if
end if
for x = 0 to P do
    if L(s, f, c)_{s,x} = −w_{s,x} then
        if w_{s,x} > Weight threshold then
            if L(s, f, c)_{x,d} = −1 then
                if w_{x,d} > Weight threshold then
                    A ← true
                else if
                    for y = 0 to P do L(s, f, c)_{x,y} = −w_{x,y} then
                        if w_{x,y} > Weight threshold then
                            x = y
                        end if
                    end for
                end if
            end if
        end if
    end if
end for
return A
```

E. Selecting the Data Channel

Finally, the source node decides the data channel c_{data} in f_{data}. Each candidate frequency is needed to exceed the IAC threshold, besides, to succeed route generating. The data transmit channel c_{data} is selected from the highest frequency from candidate frequencies. After deciding the c_{data}, the source node broadcasts the information to all other nodes via c_{control}.

F. Interference Area

Our proposed method aims to decrease surrounding interference area as possible to prevent interference with other systems operated on the same channel. To evaluate the interference of the system to others, *Quasi-Monte Carlo Method* [13] is used to compute the size of the interference area. We assumed that there is a vast area outside of the simulation area. In vast area, *the points* are placed at intervals of 1 [m]. First, each node makes own interference zone. The definition of interference zone is the circle (represents node's coverage) made by each node. Each node calculates the distance d in which the received power at a distance is -95 [dBm], then makes the circle of radius d. Then, the point in the interference zone is checked. After that, count up the square blocks made by the interfered points. The sum of blocks is approximately equal to the interference area.

IV. Numerical Results

To evaluate the performance of the proposed method, we show the results of computer simulations. Simulation parameters are shown in Table I. Simulations were carried out from four points of views, (1)Success rate of routing, (2)Average packet delivery ratio (PDR), (3)Average throughput and (4)Average interference area. In each simulation, we prepare five different frequency bands. Our proposed method uses two frequency bands. One frequency is used for routing and topology control, and the other is used for data transmission. We consider three types of square areas, with a side length of 300, 400, 500 [m]. We assumed that the source node and the destination node is fixed at the center of these simulation areas with $x/2$ [m] apart from each other. Other nodes are uniformly distributed. In this paper, we only consider the propagation loss when the generation of routes. In contrast, the propagation loss and the fading are considered in the packet delivering stage. The shadowing is not considered in this paper. The propagation loss attenuation factor is set as three. The noise level of each node is set at -95 [dBm] and the threshold of SNR for packet delivery without error is defined as 10 [dB]. Thus, if the nodes' received SNR is more than 10 [dB], we evaluate that the packet is successfully transmitted. Packets are generated at Poisson process with the arrival rate λ.

A. Success Rate of Routing

First, we show the success rate of routing as shown in Fig. 3. In this simulation, same as our prior work, we compare the success rate of routing among AODV and the proposed method for each frequency. The figure confirms that the success rate of the routing of AODV is reduced in proportion to frequency. At a high frequency, the propagation loss is larger compared to a low frequency. Thus, the possible distance of transmission becomes small. In our proposed method, the success rate of routing is always 100%. It is because our scheme aims to connect at a higher frequency as much as possible, but if route generating is failed, the system then changed to a lower frequency. Therefore, the proposed system can generate the route altogether.

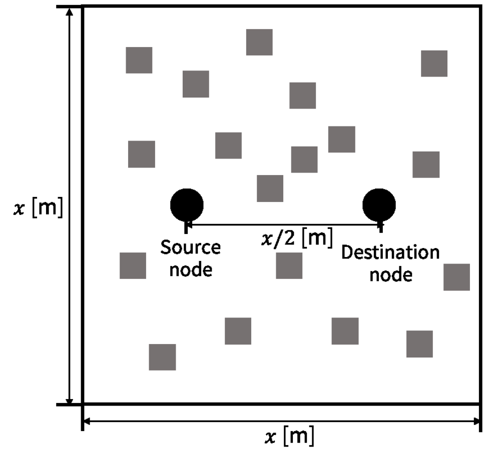

Fig. 2. Simulation area.
x is 300, 400, or 500.

B. Average PDR

Next, we derive the packet delivery ratio by changing the weights threshold of each node and the value of arrival rates as shown in Figs. 4 and 5. This simulation was carried out at 300 [m] square area. The PDR is measured when the route generates is succeeded. In this paper, the PDR is calculated by the equation below.

$$\mathrm{PDR} = \frac{\text{Number of packets arrived at destination node}}{\text{Number of packets sent at source node}} \tag{3}$$

TABLE I
Simulation Parameters

Method	AODV	Proposed
Freqency	200, 400, 920 [MHz], 2.4, 5 [GHz]	
Selectivity	Select 1 channel	Select 2 channels
Area	300 [m] $\times$ 300 [m] 400 [m] $\times$ 400 [m] 500 [m] $\times$ 500 [m]	
Vast Area	2000 [m] $\times$ 2000 [m]	
Number of Nodes	20	
Transmit Power	10 [dBm]	
Noise level	-95 [dBm]	
Desired SNR	10 [dB]	
Pathloss Coefficient	3	
Fading	Rayleigh fading	
Protocol	CSMA/CA	
Data Rate	50 [kbps] (200, 400 [MHz]) 100 [kbps] (920 [MHz]) 54 [Mbps] (2.4, 5 [GHz])	
Packet size	127 [byte] (200, 400, 920 [MHz]) 1500 [byte] (2.4, 5 [GHz])	
ACK Wait Time	220 [ms] (200, 400, 920 [MHz]) 16 [us] (2.4, 5 [GHz])	
Attempt	1000	
Time	10000000 [us]	

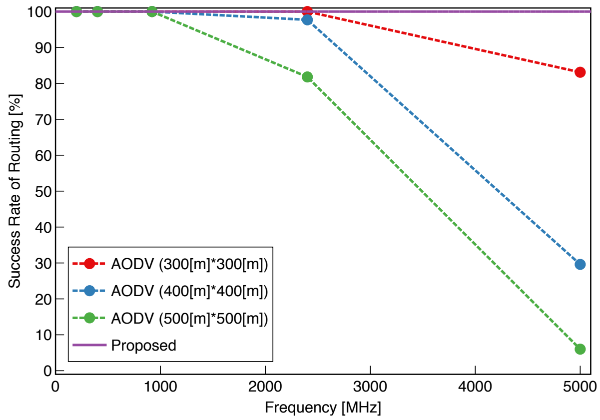

Fig. 3. Success Rate of Routing.

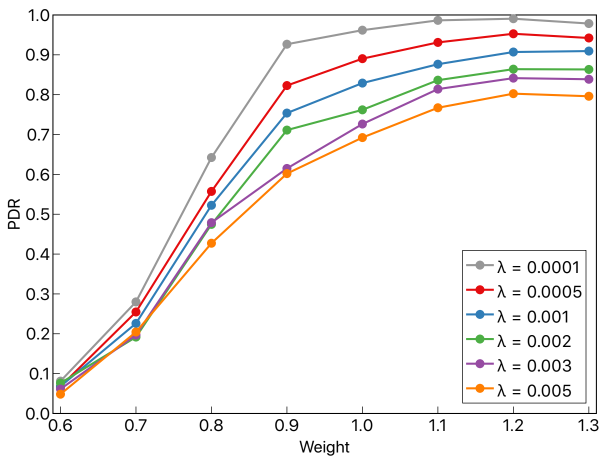

Fig. 4. Average PDR of proposed method (Weight changed).

In the primal simulation, the figure indicates that the PDR is proportion to weight in each arrival rate. If the user sets the high weight value, our proposed method chooses a route that tolerant for fading. The fading margin of these routes is bigger than a smaller weight's one. Also, the system tends to choose a lower frequency as the weight increases. In the second simulation, the PDR is also proportional to packet arrival rates. In bigger arrival rates, the PDR is lower than smaller arrival rates one. It is because relay nodes tend to store more packets to their buffer. In this simulation, we used the CSMA/CA packet sending system. Thus, at our simulation time finishing, many packets remain kept in relay nodes' buffer.

C. Throughput

Next, we derive the throughput by changing the weights threshold of each node and the value of arrival rates as shown in Figs. 6 and 7. This simulation was carried out at 300 [m] square area. The throughput measured only when the route generation is succeeded. In this paper, the throughput is calculated by the equation below.

$$T_h = \frac{(\text{Packets arrived at destination}) * (\text{Packet size})}{\text{Simulation time}} \quad (4)$$

In the primal simulation, the figure indicates that the throughput is decreased in proportion to the weight. It is because our proposed method tends to use a lower frequency in a higher weight threshold. Although lower weights tend to get high throughput, the PDR of these systems tends to lower than a high weight one. There is a tradeoff between the PDR and the throughput. In the following simulation, we show that there is a limit on the throughput in each weight. If the arrival rate is high, a large number of packets are arrived at the source node compared to a low arrival rate's one. However, the number of packets pass the route in a specific time is limited. If we select a high weight threshold, the system tends to select a lower frequency. The maximum speed defined at each frequency is different, so if the system selects a low-frequency, we gain a lower throughput.

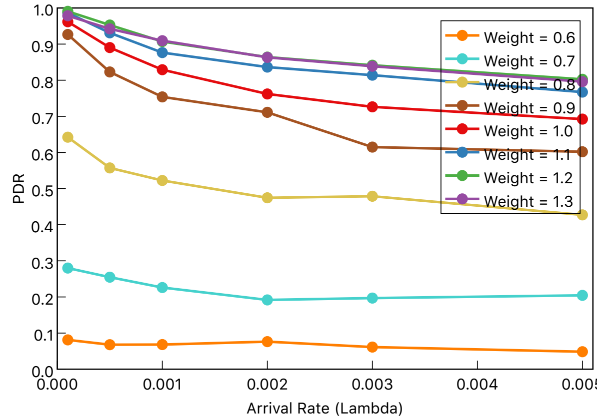

Fig. 5. Average PDR of proposed method (Lambda changed).

D. Average Interference Area

Next, we show the average interference area by (1) changing the weight threshold of each node as shown in Fig. 8 and (2)changing the packet arrival rate as shown in Fig. 9. This simulation was carried out at 300 [m] square area. In both results, the average interference area means the data transmitting channel's one. It is because the control channel does not send many packets; meanwhile, the many packets are sent in data transmitting channel so it may affect more to other systems in the environment. In both simulations, the figure implies that the average interference is proportional to the weight. It is because the transmission area becomes wide as the selected frequency becomes low. Plus, the average interference area does not depend on the packet arrival rate.

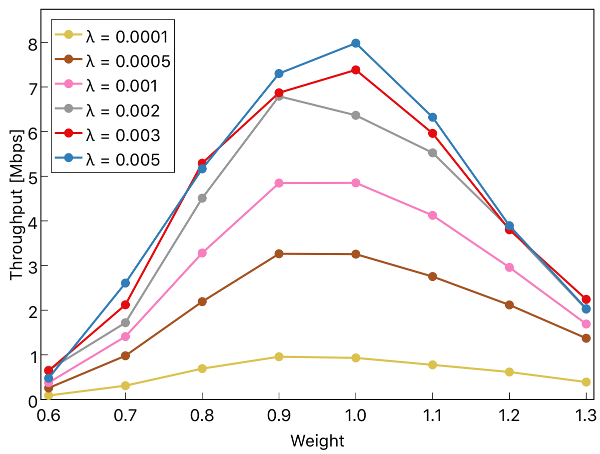

Fig. 6. Average Throughput of proposed method (Weight changed).

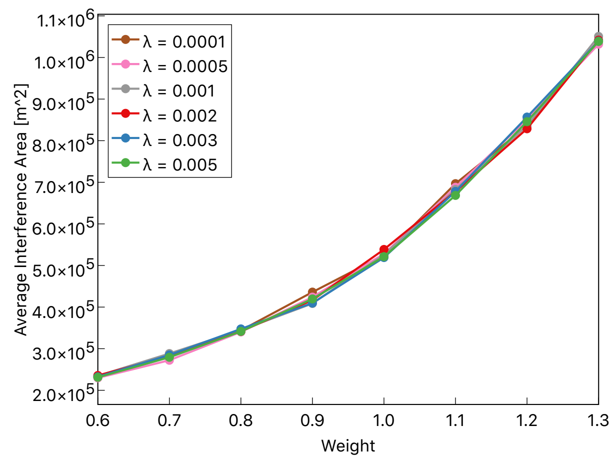

Fig. 8. Average Interference Area of proposed method (Weight changed).

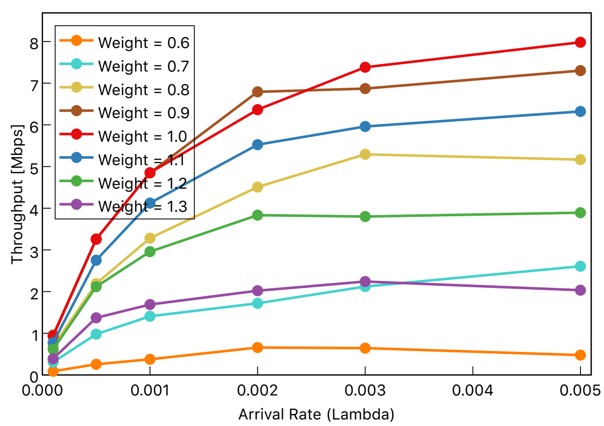

Fig. 7. Average Throughput of proposed method (Lambda changed).

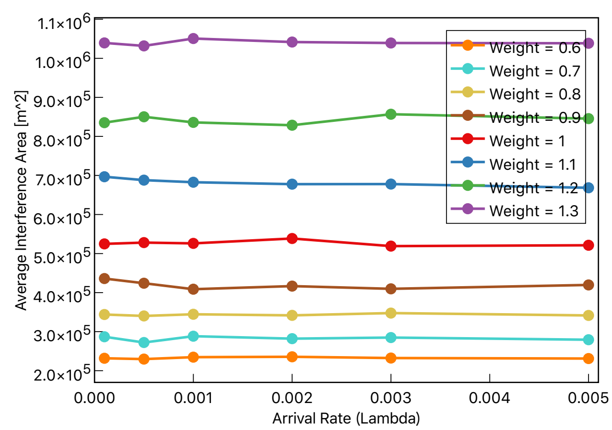

Fig. 9. Average Interference Area of proposed method (Lambda changed).

V. Conclusion

In this paper, the multiband hierarchical ad hoc network scheme that is adapted to multi-systems is proposed. In this method, the weighted Laplacian matrix and the algebraic connectivity are used to control the topology and select the control/data transmitting channel. By using the computer simulations, we can confirm that the proposed method can select the throughput-aware or the PDR-aware routing by choosing the weight threshold by each user. If we want high-speed transmission, we should select a lower weight. On the other hand, we should select a higher weight if we want to send more accurately. However, there is a tradeoff between the PDR and the throughput. If we want to gain both high throughput and PDR, we should carefully check the relationship between the throughput and the PDR, then need to decide the compromise.

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