Directional Link Scheduling for Real-time Data Processing in Smart Manufacturing System

W. Na, Y. Lee, N.-N. Dao, D.-N. Vu, M. Arooj, and S. Cho

***Abstract*—Internet of Things (IoT) technology has accelerated various industries through digital transformation. In an edge computing-based smart factory, a significant number of IoT devices generate large volumes of real-time data. This big data requires efficient routing among Edge Gateways (EGs) and an Edge Server (ES) for real-time data processing. Existing industrial wireless communication systems provide relatively low data rates and network capacity for real-time sensor data and control information over a wireless channel. This calls for the use of the very large bandwidth available at the mmWave spectrum for real-time data transmission. Existing data routing techniques for the mmWave band are based on traditional mobile ad hoc routing techniques and do not reduce the transmission delay for real-time sensory data in smart manufacturing systems. Therefore, to alleviate the real-time data processing requirement, we propose a new directional routing and link scheduling algorithm based on Maximum Weight Independent Set (MWIS). The proposed algorithm solves complicated MWIS problems efficiently and computes backhaul link scheduling results in a relatively short time by lowering the deafness problem among EGs. For transmission fairness, we used a Jain's fairness index method with numerical analysis of the transmission fairness constraint. We measured the efficiency of our proposed scheme in terms of throughput, delay, packet loss rate, and transmission fairness. Our simulation results show that the proposed scheme outperforms existing mmWave routing techniques. Moreover, we investigated the performance difference between the proposed algorithm and the optimal solution.**

***Index Terms*—mmWave band, backhaul routing, smart manufacturing system, directional antenna, link scheduling**

I. Introduction

NEW business requirements and an emerging set of autonomous technologies, such as Internet of Things (IoT), are shifting manufacturing companies' legacy environment towards smart manufacturing [1]. In a smart manufacturing system, various IoT based Manufacturing Equipment (ME) generate, process, and exchange large-scale sensory information and control data over the industrial IoT network with context awareness [2]–[4]. This accumulated data requires a larger bandwidth and efficiently reconfigurable routing protocols to link the networked IoT devices for real-time processing [5].

Currently, there are a number of standards for wireless industrial communications, such as WirelessHart, ZigBee, ISA 100, and WiFi. The existing industrial wireless systems provide relatively low data rates for sensor information and traffic control [6]. This type of technology can be used in the last mile of a wireless sensor network, especially for mobile manufacturing equipment in a smart manufacturing system. Although wireline counterparts generally support higher rates, they typically suffer from prohibitive wiring costs in large manufacturing sites.

TABLE I
THE COMBINATION TERMINOLOGIES USED IN THIS PAPER

Terminologies	Meaning
Directional Link	Link over which directional antenna is used
Directional Communication	Communication using directional antenna
Directional Routing	Routing through the directional links

As a solution to this problem, massive amounts of bandwidth, available at the mmWave 60 GHz spectrum, can open the way for large-scale data capacity and high data rate capabilities as a wireless backhaul in smart manufacturing. At the mmWave band around 60 GHz, gigabit-per-second transmissions are known to be achievable owing to the huge available bandwidth [7]–[10]. Due to the high signal attenuation in the mmWave band, directional antennas (with high antenna gain) are mainly used in this band, as they allow a better spatial reuse while lowering the chances of interference.

In EdgeX Foundry based smart manufacturing (see Fig. 1), Edge Gateways (EGs) aggregate local IoT traffic, which can then be routed over directionally connected links (*directional links*) between EGs and between an EG and an Edge Server (ES) [11]. As shown in Fig. 1, an EdgeX Foundry layer architecture comprises of 4 service layers, and each service layer is composed of several embedded micro-services modules. In particular, the scheduling microservice in the supporting services layer performs backhaul routing, whereas the mmWave microservice in the device services layer can be utilized to support communication using directional antenna (*directional communication*) over an industrial IoT network. The locally aggregated real-time traffic requires an efficient scheduling algorithm for backhaul links in order to reduce the total average end-to-end transmission delay. Moreover, routing with the use of a directional antenna improves network throughput and consumes the minimum total energy [12].

A large variety of routing protocols based on directional antennas (*directional routing*) have been reported in the literature [13]–[22], [26]. They can be traditionally classified into (1) *proactive* or (2) *reactive* approaches. The former establishes routing paths in a local routing table to reduce the routing delay [13], [21], [26]. The latter tries to find a routing path when needed [14]–[20], [22]. However, both of

W. Na, Y. Lee, N.-N. Dao, D.-N. Vu, M. Arooj, and S. Cho are with the School of Computer Science and Engineering, Chung-Ang University, South Korea; Correspondence should be addressed to Sungrae Cho; srcho@cau.ac.kr.

This research was partly supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIT) (No. 2018-0-00889, A study on core technology of 5G mobile communication using millimeter wave band) and the Chung-Ang University Young Scientist Scholarship (CAYSS) Program.

the above techniques are limited by end-to-end transmission delay, since they are based on traditional mobile ad hoc routing (MANET) and do not effectively rectify the *deafness problem*. The deafness problem occurs when a node does not answer a communication request frame addressed to it and consequently the originator transmits more request frames, thus increasing the contention window [27]. The limitations are exacerbated in a smart manufacturing system since real-time control information or sensory data can be lost or does not arrive in time at the destination EG. Therefore, a technique to improve real-time data delivery is necessary for smart manufacturing systems.

In this paper, we have proposed a new directional routing link scheduling algorithm for smart mobile edge in a smart manufacturing system based on Maximum Weight Independent Set (MWIS). This algorithm is designed to explicitly reduce transmission delay by lowering the chances of deafness problem among EGs by using a conflict/deafness graph. In a smart manufacturing system, all the EGs operate under the control of an ES. Therefore, in our scheme, the ES maintains a conflict-deafness graph and determines whether the directional links among the EGs interfere with one another or create a deafness problem when scheduled simultaneously. The link scheduling results are computed by the ES and are delivered to all the EGs via a control channel[1]. The proposed algorithm solves a complicated MWIS problem in real-time by considering EGs in the order of their maximum number of independent sets and assigning time slots to the links with maximum traffic loads. Considering the characteristics of both large-scale real-time backhaul traffic and mmWave technology, the use of a directional antenna reduces radio interference among EGs and improves packet throughput greatly. In the scheduling process, our algorithm discovers and assigns time slots that maximizes spatial reuse among the links. However, links with a poor channel condition are not scheduled in this policy, and therefore, some links may not be scheduled. To guarantee fair scheduling, once directional links are scheduled, the algorithm measures the fairness constraint between links in order to ensure fair sharing of transmission resources among the EGs. The transmission fairness is ensured using Jain's fairness index, which eventually maximizes the end-to-end throughput while minimizing the energy consumption. The effectiveness of our proposed algorithm was measured by evaluating performance metrics that include throughput, delay, packet loss rate, and transmission fairness. The simulation results show that the proposed scheme outperformed existing mmWave routing schemes; however, it gave sub-optimal results when compared to the optimal solution.

The remainder of this paper is organized as follows: Section II summarizes related works on directional routing protocols. Section III explains the system model for our proposed scheme, and Section IV presents the details of our proposed link scheduling algorithm based on transmission fairness in relation to the centralized approach. In Section V, we describe the performance of the proposed directional routing scheme. Finally, we conclude our work in Section VI and discuss future work.

II. Related Work

Scheduling and directional routing techniques for ad hoc networks have been addressed as a major research problem. Traditionally, these routing techniques have been classified into two categories: (1) *proactive* routing schemes and (2) *reactive (on-demand)* routing schemes. The former establishes a routing path in a local routing table to reduce the routing delay. On the other hand, the latter comprises of a node that attempts to find a routing path when required.

Gharavai *et al.* [14] proposed a Directional Dynamic Source Routing (DDSR)-based multipath routing protocol for mobile wireless ad hoc networks. This protocol is based on Dynamic Source Routing (DSR), which is a source-initiated on-demand routing protocol [15], and uses existing ad hoc routing protocols to set up routes. They consider some metrics, such as hop count, overlap count, and number of joint nodes, to select multiple routes. In this paper, it was important to minimize the overlap count between the source and destination, because the proposed protocol was able to select multipath routes, which could minimize the overlap count.

T. Ueda *et al.* [26] proposed a slightly revised version of zone-disjoint path routing [17], or priority-based Quality of Service (QoS) routing. When data communication occurs along one path and it does not interfere with other data communication paths, the path can be called a *zone disjoint*. This protocol avoids coupling between routes used by high and low priority traffic by reserving a high priority zone of communication. Low priority flows will try to avoid this zone by selecting routes that are maximally zone-disjoint with respect to the high priority reserved zone and will consequently reduce the contention between high and low priority flows in that reserved zone. However, this does not ensure that the low priority flows will be able to avoid the high priority zone completely.

B. Cheng *et al.* [13] proposed an orthogonal rendezvous routing protocol for a Wireless Mesh Network. This protocol has increased scalability and reduced geographic information issues. In this scheme, each node has a local sense of direction. A pair of orthogonal lines from each node will intersect at two points at a minimum. Rendezvous points can be formed to forward a packet. To achieve this, they need both a proactive element and a reactive element. The proactive element constructs the rendezvous-to-destination path. Each node then sends announcement packets to its neighbors in all four orthogonal directions. When the neighbors receive announcement packets, they put them into a routing table as a destination-next-hop pair and forward that packet out in the opposite direction from which it was received. The reactive element builds the source-to-rendezvous path. In order to build the path from a source to a rendezvous node on-demand, a reactive element is needed. When the routing request packet arrives at a rendezvous node, the node replies with that packet. When the source node receives the reply packet, it generates a destination-next hop routing entry. After making a destination-next- hop routing entry, the source node can forward a packet.

Y. Dai *et al*. [29] proposed a novel routing protocol based on the traditional source routing protocol in a cognitive radio network with directional antennas. To resolve the channel availability problem, they use boundary nodes, which are located at the boundary of the Primary User (PU) that has a higher priority or legacy rights on the usage of a specific channel. The protocol's scheme chooses the route with the minimum weighted length, which is measured by using counts. The number of channels on a link can show that the that link is inside the PU area. However, when boundaries are not detected, it can significantly affect the weighted length calculations of different routes. To overcome

[1]We assume that an omni-directional underlay control channel that uses some of the spectrum of data channel, thus there is no deafness problem in control channel [28]

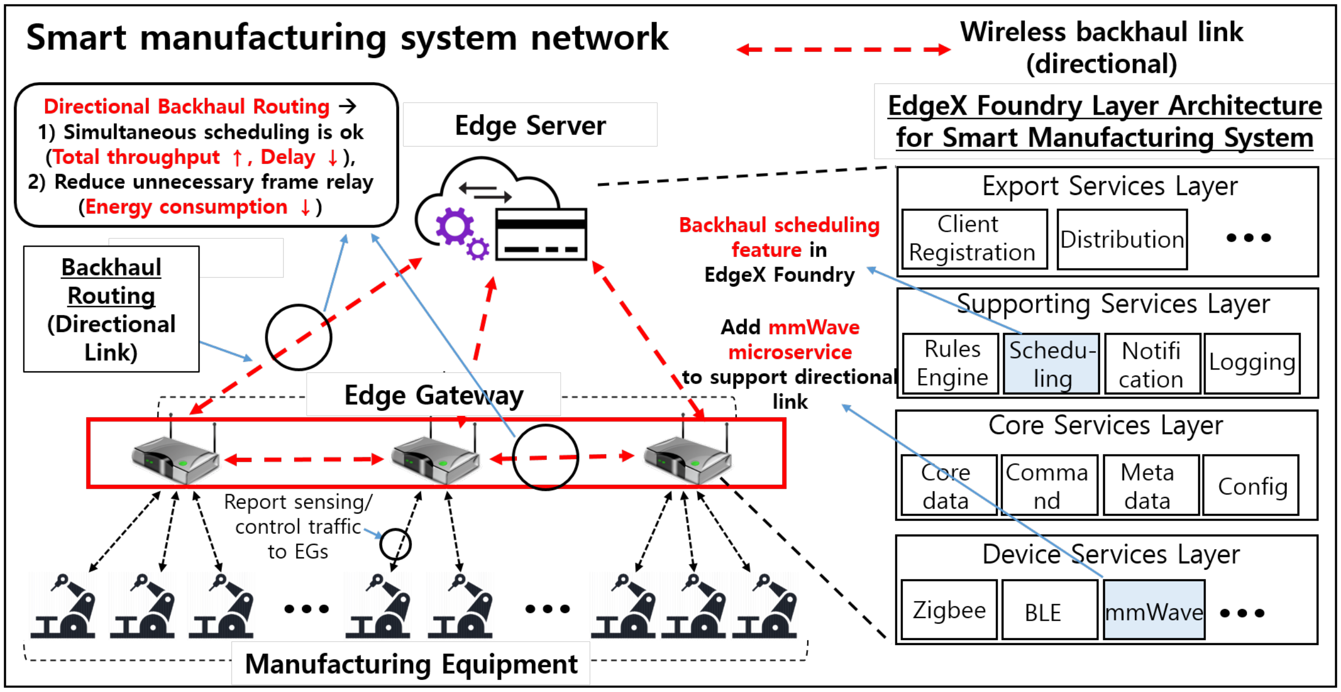

Fig. 1. mmWave based smart manufacturing system network based on EdgeX Foundry [11]

the missing boundary detection problem, this paper proposes the virtual boundary node scheme, which slightly increases the communication cost. Several papers have proposed the link scheduling scheme to resolve the problems of interference and transmission delays in multi-hop routing using directional antenna. In [30], the authors proposed transmission scheduling for multi-hop transmission in 60 GHz wireless networks. A Multi-hop Concurrent Transmission (MHCT) is capable of improving time slot utilization.

In [31], the authors proposed a link scheduling scheme to address the issues of blockage and interference in 60 GHz ad hoc networks. To consider both single-hop and multi-hop cases, the authors proposed scheduling algorithms that include a greedy algorithm and a column generation-based algorithm to resolve Binary Integer Programming (BIP) problems.

Recently, there were some research works that adopted mmWave backhaul network in 5G networks [18]–[23], [31]. They focus on link and channel scheduling to maximize spatial reuse, minimize the interference among relay nodes, and optimize flow control by adjusting the data rate. However, there is a limitation that the transmission delay between the end-to-end nodes is high since their technologies are simply aimed at optimizing link scheduling between one-hop links. Therefore, they are not applicable for multi-hop smart manufacturing system where real-time backhaul traffic requires efficient data delivery among backhaul IoT devices. In addition, it may result in high energy consumption at a specific EG, because traffic is concentrated at a link with a good channel environment.

Owing to the merits of mmWave and directional routing, the backhaul routing scheme for smart manufacturing networks, which is proposed in this paper, has the following advantages:

- The proposed scheme provides sub-optimal link scheduling results in real time based on complex MWIS problem.
- The proposed scheme reduces the energy load consumed by EGs, thus ensuring transmission fairness between them.
- The proposed scheme minimizes the end-to-end transmission delay by assigning weights to heavy traffic links. As a result, the edge obtains a high priority by being allocated to a time slot.

III. Preliminary Assumptions and System Model

In this section, we introduce preliminary assumptions and our system model. Additionally, an interference model and the concept of the conflict-deafness graph are discussed.

A. *Wireless backhaul networks system models*

In the proposed scheme, we consider that our wireless backhaul system model supports multi-hop communication among EGs, ES, and a backhaul network in a smart manufacturing environment. We also assume that all the EGs and the ES are equipped with switched beam directional antennas. An ME communicates to an EG by transmitting a communication request frame to the EG, which is located near the ME. Each EG collects the wireless backhaul traffic from MEs and forwards this traffic to the ES utilizing its directional antenna. As the backhaul traffic reaches the ES, it forwards this traffic to the core network. We further assume that the wireless backhaul network supports multi-hop communication between EGs. Therefore, each EG can build a mesh topology and perform multi-hop communication with other EGs except the ES. As shown in Fig. 1, each ME is associated to an EG. All EGs are also linked to their neighboring EG. The ES is connected to the cloud network via wired backhaul and forwards the backhaul traffic to the EGs by utilizing its directional antenna.

Commonly, directional antennas are classified into two types based on the technique they employ: switched beam antenna [24], and phase array antenna [25]. In this paper, we chose to use a switched beam antenna, which has been adopted widely in various researches as a wireless backhaul

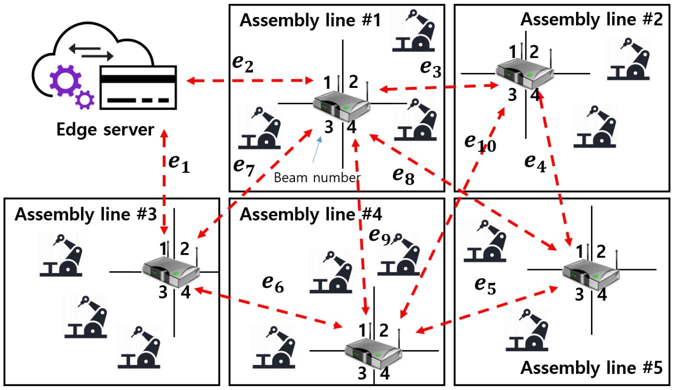

Fig. 2. Example of smart manufacturing system backhaul network

TABLE II
EXAMPLE OF CONFLICT AND DEAFNESS GRAPHS INTEGRATION

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}
e_1	-1	1	0	0	0	1	1	0	0	0
e_2	1	-1	1	0	0	0	1	1	1	0
e_3	0	1	-1	1	0	0	1	1	1	1
e_4	0	0	1	-1	1	0	0	1	0	1
e_5	0	0	0	1	-1	1	0	1	1	1
e_6	1	0	0	0	1	-1	1	0	1	0
e_7	1	1	1	0	0	1	-1	1	1	0
e_8	0	1	1	1	1	0	0	-1	1	1
e_9	0	1	1	0	1	1	1	1	-1	1
e_{10}	0	0	1	1	1	1	0	1	1	-1

network. We assume that all the EGs consist of the same number of antenna beams, denoted by M. All the beams are non-overlapping in order to cover all directions and have the same transmission coverage area and transmitted power. However, when an EG transmits wireless traffic, only one beam operates at that time to direct the transmitted traffic to the intended recipient while the other beams are blocked due to the utilization of a single channel. The recipient EG that receives the wireless backhaul traffic adjusts its directional beam towards the EG that has requested to communicate.

In order to transmit wireless backhaul traffic, an EG requires information about its neighboring EGs including the beam ID, beam direction, and channel weight. Information about the neighboring EGs is periodically collected through a cooperation channel (e.g., ISM bands) via a hello message and the obtained information is saved in the EG's beam table [34].

We modeled our wireless backhaul network by a directed graph $\mathcal{G} = (\mathbf{N}, \mathcal{E})$, where $\mathbf{N}$ represents the set of all EGs and $\mathcal{E}$ is the set of all directional edges. The wireless backhaul network consists of a set $\mathbf{F}$ of data flows and a set $\mathbf{K}$ of orthogonal channels. When an EG (n_1) sends wireless backhaul traffic to another EG (n_2), it is denoted by a directed edge $e = (n_1, n_2)$ in $\mathcal{G}$. The set of EGs is represented by $\mathbf{N} = \{n_1, n_2, ..., n_\alpha\}$, where α denotes the number of EGs in a wireless backhaul, and each n_i have some edges, denoted by e. The set of edges is represented by $\mathcal{E} = \{e_1, e_2, ..., e_\beta\}$, where β denotes the number of edges on the wireless backhaul. We also defined $N(n)$ as a set of neighboring nodes of node n, which are located within the transmission range of node n.

In addition, we were able to derive the channel capacity r_e of edge e as follows [35], [36]:

$$r_e = W \log_2(1 + \frac{P_T G_T G_R (\frac{\lambda}{4\pi d})^2}{N_0 W + I}), \tag{1}$$

where W is the channel bandwidth of the wireless backhaul, N_0 is the noise power spectral density, I is the wireless backhaul interference, P_T is the EG's transmitted power, and G_T and G_R are the directional beam gains of the transmitter EG and receiver EG, respectively, λ is the wavelength of the directional beam, ~~4π reflects that the directional antenna has four sectors,~~ and d denotes the distance between the transmitter EG and receiver EG.

B. Interference model

In our proposed scheme, the ES and all the EGs are equipped with directional antennas. As shown in Fig. 2, there is an ES along with five EGs, denoted by n_0 through n_i, respectively. The sets $\mathbf{N} = \{n_1, n_2, ..., n_5\}$ and $\mathcal{E} = \{e_1, e_2, ..., e_{10}\}$ demonstrate the number of EGs (α) being five and the number of edges (β) being ten. The EGs are equipped with a directional antenna that consists of four indexes. If n_1 wants to send traffic to n_5, n_2 and n_4 cannot communicate because its target beam is blocked. However, when n_1 sends wireless backhaul traffic to n_5, one of the other EGs can attempt to communicate through e_1 and e_6. Consequently, some EGs can simultaneously transmit traffic using the directional antenna while all the beams are not blocked. For example, e_1 and e_4 can simultaneously execute their communication without interference. As the EG and its edge depend on a near beam environment, beam and channel scheduling is necessary for fair communication.

C. Conflict/deafness Graphs

In the proposed scheme, all of the EGs in the wireless backhaul are fixed and periodically exchange their own information using a hello message to build a mesh network topology. The hello messages include information such as EG location, data rate, and beam index, and they are delivered through an omni-directional antenna. After receiving the latest hello message, an EG updates itself with the provided information. The ES can obtain information of all the EGs because all the EGs send wireless backhaul traffic to the ES in order to to access the core network. Therefore, the ES maintains a conflict/deafness graph that determines whether different links interfere/deafness to each other. As shown in Table II, some of the edges cannot be scheduled simultaneously. For example, when e_6, which is connected between n_3 and n_4, is scheduled, e_1 or e_4 can be scheduled at the same time. However, e_2 cannot be scheduled simultaneously with any other edges because e_2 causes interference to the other EGs, except for e_8 and e_{10}. This conflict graph ($\mathbf{C}$) is defined as

$$c_i^j = \begin{cases} 1, & \text{if } e_i \text{ and } e_j \text{ cannot be scheduled simultaneously,} \\ 0, & \text{if } e_i \text{ and } e_j \text{ can be scheduled simultaneously,} \\ -1, & \text{otherwise.} \end{cases} \tag{2}$$

Similar to the conflict graph, the ES maintains a deafness graph, which determines whether the deafness problem arises when different links are scheduled simultaneously. The deafness graph ($\mathbf{F}$) is defined as

$$f_i^j = \begin{cases} 1, & \text{if the deafness problem occurs,} \\ 0, & \text{if the deafness problem does not occur,} \\ -1, & \text{otherwise.} \end{cases} \tag{3}$$

IV. Link scheduling algorithm based on transmission fairness

In this section, we formulate the objective function for wireless backhaul networks in the form of an MWIS problem and propose our link scheduling algorithm to solve the MWIS problem.

A. Problem formulation

In the proposed scheme, we assume that the ES is responsible for scheduling the wireless backhaul network links because it has information of all the EGs and all the EGs communicate with one another under the control of the ES [32]. Preferentially, we denoted the set of edges' weights by $\mathcal{W} = \{w_1, w_2, ..., w_\beta\}$, where β is the number of edges on a wireless backhaul. Then, the weight of edge e at the time slot t, $w_e(t)$, is given by

$$w_e(t) = r_e(t) \cdot Q_e(t), \tag{4}$$

where $Q_e(t)$ is the sum of the backlog size at edge e, and $r_e(t)$ denotes the achievable rate of link e at time slot t defined by (1). The definition of weights is associated with the instantaneous queue backlog sizes that vary over time t. Therefore, this definition is different from that of the transmission throughput, which is by definition a time-averaged quantity. The queue backlog size at edge e, evolves according to

$$Q_e(t) = \max[0, Q_e(t) - \mu_e(t)] + \lambda_e(t), \tag{5}$$

where $\mu_e(t)$ and $\lambda_e(t)$ denote the number of bits leaving the queue of e and the number of bits added to the queue of e, respectively.

Additionally, we assume that all time slots $t \in \mathbf{T}$ that occupy a channel have the same length, where $\mathbf{T}$ is the set of time slots. Conceptually, the objective of our proposed scheduling algorithm is to find the set of links, channel, data rate, and routing flow that maximize the sum of weights over all possible independent sets. Therefore, the objective function was designed to find a set of links that maximizes the weight as follows:

$$\text{maximize} \sum_{f \in \mathbf{F}} \sum_{k \in \mathbf{K}} \sum_{t \in \mathbf{T}} w_e^k(t) \cdot t_e^k, \tag{6}$$

where t_e^k is an indicator variable and it can be expressed in two cases

$$t_e^k = \begin{cases} 1, & \text{if } e_i \text{ can be scheduled on time slot } t, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

However, the problem of finding a link set that simply maximizes the weight is not feasible in a smart manufacturing system; therefore, we can consider the following constraints: deafness management, collision management, and flow conservation.

The following are the constraints for backhaul routing:

1) Flow conservation constraint: Each flow f is transmitted at a particular data rate on link e during timeslot t along multiple paths from a source node, $s(f)$, to a destination node $d(f)$.We denote a directional link from node n to node m as $\underset{mn}{\rightarrow}$. Then, the following flow conservation constraint is given by:

$$\sum_{m \in N(n)} d^f_{\underset{nm}{\rightarrow}} - \sum_{m \in N(n)} d^f_{\underset{mn}{\rightarrow}} = \begin{cases} d_f, \text{if } n = s(f); \\ -d_f, \text{if } n = d(f); \\ 0, \text{ otherwise;} \end{cases} \tag{8}$$

where d_f denotes the average data rate of flow f.

2) Link capacity constraint: Since the average data rate over each directional link cannot exceed the average capacity over the directional link, we have the following constraint:

$$\sum_{f \in \mathbf{F}} d^f_{\underset{nm}{\rightarrow}} \leq \frac{\sum_{k \in \mathbf{K}} \sum_{t \in \mathbf{T}} t^k_{\underset{nm}{\rightarrow}} \cdot r^k_{\underset{nm}{\rightarrow}}}{T} \tag{9}$$

3) Channel match constraint: The two nodes n and m must communicate over the same channel. Therefore, we define $a^k_{\underset{nm}{\rightarrow}}$ as a channel assignment indicator that indicates whether channel k is assigned to the directional link $\underset{nm}{\rightarrow}$ or not, i.e.,

$$a^k_{\underset{nm}{\rightarrow}} = \begin{cases} 1, & \text{if channel } k \text{ is assigned to link } \underset{nm}{\rightarrow}, \\ 0, & \text{otherwise.} \end{cases} \tag{10}$$

From (10), we were able to derive

$$a^k_{\underset{nm}{\rightarrow}} = a^k_{\underset{mn}{\rightarrow}}, \forall n \in \mathbf{N}, m \in \mathbf{N}, \forall k \in \mathbf{K}. \tag{11}$$

4) Channel constraint: In the case of multiple allocations of different pairs of directional links over the same channel, multiple channels can be assigned to the link. However, if the same channel is assigned to more than two pairs of directional antennas onto a single link, interference occurs between transmissions from other pairs of directional antennas. To solve this problem, different orthogonal channels should be assigned to the pairs of directional antennas allocated onto the same link. Therefore, the number of channels assigned to a directional link must be equal to the number of pairs of directional antennas allocated to the directional link.

$$\sum_{m \in N(n)} \sum_{k \in \mathbf{K}} a^k_{\underset{nm}{\rightarrow}} \leq M, \forall n \in \mathbf{N}, \forall m \in \mathbf{N}, \forall k \in \mathbf{K}, \tag{12}$$

where M denotes the number of antennas.

In addition, if a node n either transmits data to node m through its outgoing directional link on channel k or receives data from node m through its incoming directional link on channel k, then channel k should be allocated to link $\underset{nm}{\rightarrow}$. Hence, we define the following constraint:

$$a^k_{\underset{nm}{\rightarrow}} \geq \frac{\sum_{t \in \mathbf{T}} \left(t^k_{\underset{nm}{\rightarrow}} + t^k_{\underset{mn}{\rightarrow}} \right)}{T}, \forall n \in \mathbf{N}, \forall m \in \mathbf{N}, \forall k \in \mathbf{K}. \tag{13}$$

5) Transmission interference constraint: A node cannot receive data simultaneously through multiple incoming directional links on the same channel. Therefore, in order to avoid collision/deafness among transmission nodes and ensure a feasible link scheduling scheme, we define the following feasible scheduling constraint:

Algorithm 1 Proposed link scheduling algorithm

Input: G, $\mathcal{W} = \{w_i, \dots, w_\beta\}, c_i^j, f_i^j, \tau$
Input: $\mathbf{N}_n \leftarrow$ A set of neighboring EGs for all the EGs
Output: Scheduling result (set of time slot)
1: $\mathcal{N}_s \leftarrow$ A set of the selected EGs during link scheduling;
2: $\mathcal{N}_e^i \leftarrow$ A set of links which is not scheduled for EG i;
3: Initialize $\mathbf{N}$ for all EGs;
4: **while** There are EGs which are not scheduled in $\mathcal{N}$ **do**
5:     $\mathcal{N}_s \leftarrow$ Find the EG i which has a maximum in $\mathbf{N}_n$;
6:     **if** $|\mathcal{N}_s| \geq 2$ **then**
7:         $|\mathcal{N}_e^i| \leftarrow$ Calculate the number of links for EG i;
8:         $\mathcal{N}_s \leftarrow$ Find the EG i which has a minimum $\mathcal{N}_e^i$;
9:         **if** The size of $\mathcal{N}_s \geq 2$ **then**
10:             $i \leftarrow$ Select EG i randomly in $\mathcal{N}_s$;
11:         **end if**
12:     **end if**
13:     $E_i \leftarrow$ Initialize the links of EG i;
14:     **while** There are links which are not scheduled in E_i **do**
15:         $e \leftarrow$ Find the link which has the largest weight in E_i;
16:         **if** e is already scheduled **then**
17:             $E_i \leftarrow E_i - e$;
18:         **else**
19:             Schedule e to the empty time slot satisfying (22);
20:             $E_i \leftarrow E_i - e$;
21:         **end if**
22:     **end while**
23:     $\mathcal{N} \leftarrow \mathcal{N} - \mathcal{N}_i$;
24:     **if** constraint (27) is not satisfied **then**
25:         Find the link which has the lowest weight in $\mathcal{E}$ and schedule it to the empty time slot satisfying (22);
26:         Go to line 24;
27:     **end if**
28: **end while**

$$t_e^k + \sum_{e \in N(e)} t_e^k \leq 1, \tag{14}$$

where $N(e)$ denotes the set of neighboring edges for e. If $c_e^{e'} + f_e^{e'} \geq 1$, e' is included in $N(e)$.

6) Transmission fairness constraint: Each node consumes energy whenever it receives/transmits data. In a smart manufacturing environment, the amount of remaining energy in each EG is important for efficient communication and to send real-time data back and forth. Therefore, a fairness constraint ascertains a chance for every EG to transmit evenly and equalizes energy consumption among EGs fairly [33]. We used the Jain's Fairness Index to set the following constraint:

$$\frac{\left(\sum_{t \in \mathbf{T}} \sum_{e \in \mathbf{E}} w_e^k(t) \cdot t_e^k\right)^2}{\beta \cdot \sum_{t \in \mathbf{T}} \sum_{e \in \mathbf{E}} \left(w_e^k(t) \cdot t_e^k\right)^2} \geq \tau, \forall t \in \mathbf{T}, \tag{15}$$

where τ denotes fairness threshold.

7) Objective Function: From (8) to (15), we can design an objective function, the details of which are provided in Appendix.

B. Centralized Link Scheduling Problem

The objective function (16) is complex and requires a considerable amount of time to be solved, using various solvers. Therefore, to reduce the scale of the problem, we assumed a single channel environment and the amount of data transmitted in a time slot cannot exceed the channel capacity. Thus, we were able to eliminate flow conservation, link capacity, and channel match constraints and obtain a reduced objective function as a pure MWIS problem. For solving an MWIS problem, various heuristic and approximation algorithms have been proposed, since MWIS is a well known Non-deterministic Polynomial-time hardness (NP-hard) problem. In this section, we describe our proposed heuristic algorithm. In the proposed scheme, scheduling links are computed in real time by the ES and delivered to all EGs via a control channel. In addition, each EG reports its queue backlog size to the ES at regular intervals through the control channel. In this paper, we assume an underlay control channel that uses some of the frequencies of each channel [28].

Algorithm 1 shows the pseudo code of our proposed routing scheme. First, the EG with the largest number of neighbor EGs is found (*line 5*). If there are more than two EGs found, the algorithm selects the EG with a lower number of connected links of EGs; otherwise, it selects the EG randomly (*lines 6 - 11*). The edge with the highest weight connected to the selected EG is scheduled first and all the edges are assigned a time slot in this way (*lines 14 - 22*). When all the edges of the selected EG are scheduled, the corresponding EG is removed from the candidates list and the process continues until the edges of all the EGs are scheduled. In particular, in the process of scheduling other edges, the algorithm finds the time slot that maximizes spatial reuse and allocates it. Once all edges are scheduled, we measure the fairness between EGs using Jain's fairness index. If constraint (27) is not satisfied, we find the edge with the lowest weight and continue scheduling (*lines 24 - 27*). The proposed heuristic algorithm handles complicated MWIS problems efficiently and provides backhaul routing link scheduling results in a short amount of time. This is well suited for a smart manufacturing network system to process commands and to monitor the state of the ME in real time.

To assess the performance of the heuristic algorithm in terms of complexity, the computational complexity of each phase was analyzed as follows: For the phase of scheduling, target EG searching is used in this study, and it requires $\mathbf{N}$ comparisons for the finding target EG that has the maximum number of neighboring nodes. However, in the worst case, $\mathbf{N}$ nodes can have the same number of neighboring nodes. Therefore, it requires additional $\mathbf{N}$ comparisons for *lines 6 - 10*, and the scheduling algorithm is quadratic with regard to the size of $\mathbf{N}$. Finally, the entire algorithm takes the computational complexity as $O(\mathbf{N}^2)$.

V. Performance Evaluation

In this section, we discuss the simulation results to verify our link scheduling algorithm based on a greedy approach. The proposed algorithm was implemented by using an OPNET simulator. In our simulation, we focused on the result of the aggregate network throughput, delay, packet loss rate, and fairness. In order to perform the simulation, we assumed that the wireless backhaul network topology was built according to Fig. 2. The detailed configuration of the simulation parameters is shown in Table III. In addition, we have used the simulation parameters in [37] in terms of path loss model, radiation

TABLE III
SIMULATION PARAMETERS FOR DIRECTIONAL ROUTING

Parameters	Value
Number of Edge Gateways	5 - 100 (with Point Poisson Process)
Number of Links	10 - 200
Number of Beams	4
Backhaul Trrafic Load	1000Mbps/GW (Exponential Distribution)
Channel Bandwidth	1.76 GHz
Time Slot Duration	10 μs
Area Dimension	100 m x 100 m
Tx Power	10 dBm
Tx/Rx Antenna Gain	19 dBi

pattern, and modulation. Moreover, in our simulation we assumed that all the EGs have already obtained their routing information and set the scheduling delay to 10 ms. In addition, the routing information was implemented by a matrix in our simulator.

To measure the effectiveness of the proposed scheme, we evaluated the following performance metrics.

- **Total Backhaul Network Throughput (Gbps):** Total data traffic transferred successfully from all EGs to the ES divided by time,
- **Average Delay (msec):** Average delay time between source and destination,
- **Packet Loss Rate (%):** The number of lost packets divided by the total number of transferred packet, and
- **Jain's Fairness Index [38]:** The square of the average of x_i divided by the average of x_i^2, where N denotes the number of EGs and x_i is the number of times that EG i (or gateway i) has been assigned time slots (15).

$$J(x_1, x_2, \cdots, x_N) = \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N \sum_{i=1}^{n} x_i^2}.$$

Fig. 3 shows the graph of backhaul network throughput versus normalized traffic load. For example, a traffic load of two means that the incoming traffic requires an aggregate rate at each EG in the backhaul system to have twice the average capacity of a single link. The throughput of all the employed schemes grew rapidly with an increase in traffic load. In particular, the brute-force approach had the highest increase amongst all the schemes; it achieved more than 27% of that achieved by the proposed scheme ($\tau = 0.9$) at a heavy traffic load. However, the brute-force approach is not scalable when a large number of nodes are deployed. The DSR-based backhaul routing scheme showed the lowest performance due to the overhead required for setting the routing path. Although the Spatial Division Multiple Access (SDMA) based resource management scheme for 5G [23] optimizes the link scheduling, the aggregate throughput is lower than that of our proposed scheme. This is because, SDMA based resource management scheme optimizes the link scheduling that only considers the one-hop link. Thus, the frame may be lost at the intermediate GW and the end-to-end delay may increase. Interestingly, we found that the best performance of our proposed algorithm was at higher τ. This means that the fairness of transmission between high links increases end-to-end throughput.

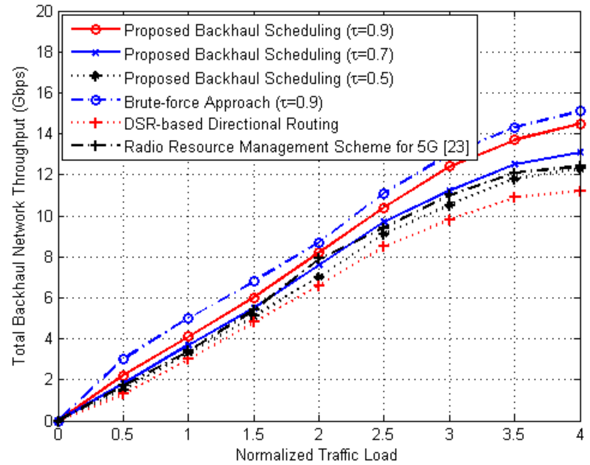

Fig. 3. Backhaul network throughput versus normalized traffic load

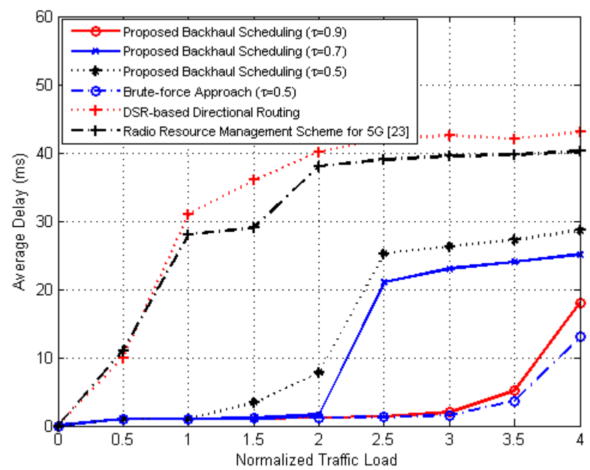

Fig. 4. Average delay versus normalized traffic load

In Fig. 4, the average delay of the proposed scheme and the DSR-based scheme increases rapidly at traffic loads of 2 and 0.5, respectively. We conducted further explorations of the delay performance at higher traffic loads and found that the delay of the proposed scheme ($\tau = 0.9$) increased slowly when the traffic load was 3.5. In the proposed schemes with low fairness constraint ($\tau = 0.5$ and $\tau = 0.7$), the average delay increases when the traffic load = 2. This is because of unbalanced link scheduling, which causes packets to be discarded. In the DSR-based scheme, the node suffers from signaling overhead as it must find the routing path. As a result, the network delay increases. In addition, since the radio resource management scheme for 5G performs link scheduling for one hop, a bottleneck occurs in the intermediate GW, thereby exhibiting a high delay.

The trend of the curves of the packet loss rate performance, shown in Fig. 5, is similar to that of the delay performance. It should be noted that the proposed scheme ($\tau = 0.9$) achieved

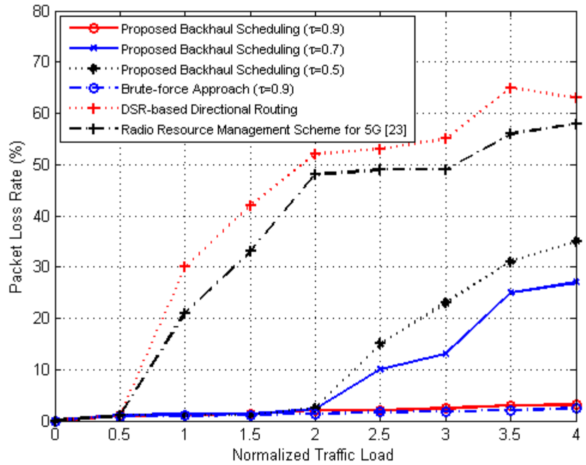

Fig. 5. Packet loss rate versus normalized traffic load

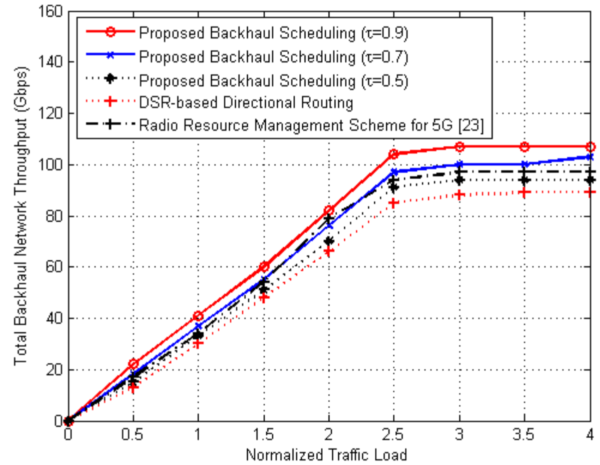

Fig. 6. Backhaul network throughput versus normalized traffic load in large scale networks

TABLE IV
JAIN'S FAIRNESS INDEX (TRAFFIC LOAD = 5; EG = 5; ES = 1)

Scheme	Fairness Index
Proposed Backhaul Scheduling ($\tau = 0.9$)	0.8932
Proposed Backhaul Scheduling ($\tau = 0.7$)	0.7315
Proposed Backhaul Scheduling ($\tau = 0.5$)	0.6624
DSR-based Routing	0.4142
Brute-force Approach	0.9341
Radio Resource Management Scheme [23]	0.4684

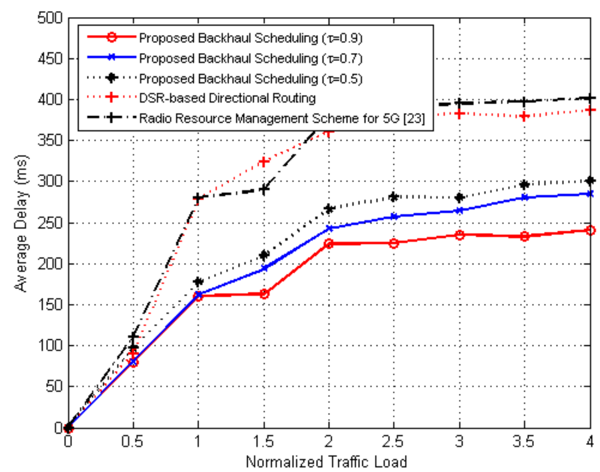

Fig. 7. Average delay versus normalized traffic load in large scale networks

almost zero packet loss even at a heavy traffic load of four, whereas more than 63% and 30% of packets were discarded for the DSR-based scheme and the proposed schemes with low fairness constraint ($\tau = 0.5$ and $\tau = 0.7$), respectively.

Table IV shows the Jain's fairness index when the traffic load is 5. As can be seen from the table, all of the proposed schemes almost satisfy the requirement of the fairness constraint. The brute-force approach achieves the highest score of 0.9341. This result means that the optimal value for τ is 0.9341 in this scenario.

Fig. 6 and Fig.7 show the throughput and delay results when 100 GWs are deployed on a 1 km x 1 km topology (more stressful environment), respectively. As shown in the figure, the network throughput is similar to that of the previous result, and it can be confirmed that the throughput is saturated as the traffic increases for all of the schemes In the case of delay, it can be confirmed that it has increased overall. However, we observed that delay of the proposed scheme is within 300 msec, which is the target end-to-end delay time proposed by EdgeX Foundry [11]. Therefore, the proposed scheme is suitable for real-time data processing in smart manufacturing systems.

VI. Conclusion and Future Work

In an edge computing based smart manufacturing system, various IoT devices generate, process and exchange large volumes of real-time sensory information and control data over an industrial IoT network. This real-time large-scale data needs to be efficiently routed over a smart industrial IoT network in order to be processed at the destination in real-time. In this paper, we have proposed a directional routing link scheduling scheme that efficiently schedules backhaul traffic over directional links established between EGs. The proposed directional routing scheme is based on the MWIS principle and tries to reduce transmission delay and energy consumption through transmission fairness among EGs. The proposed algorithm calculates sub-optimal link scheduling results in real time and reduces the end-to-end delay by ensuring transmission fairness and throughput among the directional links. Simulation results showed that our proposed scheme outperformed existing mmWave routing schemes in terms of throughput, delay, packet loss rate, and transmission fairness. However, the algorithm gave sub-optimal results in a small-scale smart manufacturing system (less than 10 EGs). As the network grows, the results are still questionable. Therefore, in our future research, we intend to validate our proposed solution in a real industrial environment, analyze how many devices are acceptable in smart manufacturing system, and obtain an optimal link scheduling algorithm by applying the message passing technique, which can solve the MWIS problem effectively in a short time. In addition, since the proposed method is operated in a centralized manner, its scalability is low. Therefore, we intend to design a routing protocol that operates in a fully distributed manner by applying the concept of game theory.

References

[1] F. Shrouf, J. Fadi, J. Ordieres, and G. Miragliotta, "Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm," *in Proc. of International Conference on Industrial Engineering and Engineering Management (IEEM)*, pp. 697-701, 2014.

[2] I. Bisio, A. Sciarrone, and S. Zappatore, "A new asset tracking architecture integrating RFID, Bluetooth Low Energy tags and ad hoc smartphone applications," *Pervasive and Mobile Computing*, vol. 31, pp. 79-93, 2016.

[3] K. Suto, H. Nishiyama, N. Kato, and C. W. Huang, "An energy-efficient and delay-aware wireless computing system for industrial wireless sensor networks," *IEEE Access*, vol. 3, pp. 1026-1035, 2015.

[4] I. Bisio, F. Lavagetto, A. Sciarrone, T. Penner, and M. Guirguis, "Contextawareness over transient cloud in D2D networks: energy performance analysis and evaluation," *Transactions on Emerging Telecommunications Technologies*, vol. 28, no. 2, 2017.

[5] X. Ding, Y. Tian, and Y. Yu, "A real-time big data gathering algorithm based on indoor wireless sensor networks for risk analysis of industrial operations," *IEEE transactions on industrial informatics*, vol.12, no. 3, pp. 1232-1242, 2016.

[6] M. Cheffena, "Industrial wireless communications over the millimeter wave spectrum: opportunities and challenges," *IEEE Communications Magazine*, vol.54, no. 9, pp. 66-72, September 2016.

[7] W. Feng, Y. Li, D. Jin, L. Su, and S. Chen, "Millimetre-Wave Backhaul for 5G Networks: Challenges and Solutions," *Sensors*, doi:10.3390/s16060892, 2016.

[8] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter Wave Beamforming for Wireless Backhaul and Access in Small Cell Networks," *IEEE Trans. Communications*, vol. 61 no. 10, pp. 4391-4403, 2013.

[9] Z. Gao, L. Dai, D. Mi, Z. Wang, M. A. Imran, and M. Z. Shakir, "MmWave massive-MIMO-based wireless backhaul for the 5G ultra-dense network," *IEEE Wireless Communications*, vol. 22 no. 5, pp. 13-21, 2015.

[10] C. Dehos, J. L. Gonzlez, A. De Domenico, D. Ktenas, and L. Dussopt, "Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems?," *IEEE Communications Magazine*, vol. 52 no. 9, pp. 88-95, 2014.

[11] "About EdgeX Foundry", *EdgeX Foundry*, 2018. [Online] Available: https://www.edgexfoundry.org/about/. [Accessed: 25- Nov- 2017].

[12] I. L. Cherif, L. Zitoune, and V. Vque, "Joint optimization of energy consumption and throughput of directional WMNs," *in Proc. of InCommunications (ICC), 2017 IEEE International Conference on,* pp. 1-6, May 2017.

[13] B. Cheng, M. Yuksel, and S. Kalyanaraman, "Orthogonal Rendezvous Routing Protocol for Wireless Mesh Networks," *IEEE/ACM Transactions on Networking*, vol. 17, no. 2, pp. 542-555, 2009.

[14] H. Gharavi and B. Hu, "Directional Antenna for Multipath Ad Hoc Routing," *in Proc. of IEEE CCNC*, pp. 1-5, 2009.

[15] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad-Hoc Wireless Networks," *in Proc. of Mobile Computing*, pp.153-181, 1996.

[16] A. Nasipuri, J. Mandava, H. Manchala, and R.E. Hiromoto, "On-Demand Routing Using Directional Antennas in Mobile Ad Hoc Networks," *in Proc. of International Conference on Computer Communications and Networks*, pp. 535-541, 2000.

[17] S. Roy, D. Saha, S. Bandyopadhyay, T. Ueda, and S. Tanaka, "A Network-Aware MAC and Routing Protocol for Effective Load Balancing in Ad Hoc Wireless Networks with Directional Antenna," *in Proc. of ACM MobiHoc*, pp. 88-97, 2003.

[18] H.-T. Roh and J.-W. Lee. "Channel assignment, link scheduling, routing, and rate control for multi-channel wireless mesh networks with directional antennas," *Journal of Communications and Networks* vol. 18 no. 6 pp. 884-891, 2016.

[19] T. Noguchi, and T. Kobayashi, "Adaptive Location-Aware Routing with Directional Antennas in mobile adhoc networks," *in Proc. of IEEE In Computing, Networking and Communications (ICNC),* pp. 1006-1011, 2017.

[20] Y. Zeng, , K. Xiang, , D. Li, and A. V. Vasilakos, "Directional routing and scheduling for green vehicular delay tolerant networks," *Wireless networks*, vol. 19, no. 2, pp. 161-173, 2013.

[21] R. S. Raw, D. K. Lobiyal, S. Das, and S. Kumar, "Analytical evaluation of directional-location aided routing protocol for VANETs," *Wireless Personal Communications*, vol. 82 no. 3, pp.1877-1891, 2015.

[22] A. Jain, and B. R.Reddy, "Ant Colony Optimization Based Orthogonal Directional ProactiveReactive Routing Protocol for Wireless Sensor Networks," *Wireless Personal Communications*, vol. 85, no.1, pp.179-205, 2015.

[23] Y. Li, E. Pateromichelakis, N. Vucic, J. Luo, W. Xu, and G. Caire, "Radio resource management considerations for 5G millimeter wave backhaul and access networks," *IEEE Communications Magazine*, vol. 55, no. 6, pp. 86-92, 2017.

[24] H. Wang, Z. Zhang, Y. Li, and M. F. Iskander, "A switched beam antenna with shaped radiation pattern and interleaving array architecture," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 7, pp. 2914-2921, 2015.

[25] M. Nikfalazar, C. Kohler, A. Wiens, A. Mehmood, M. Sohrabi, H. Maune, J. R. Binder and R. Jakoby, "Beam steering phased array antenna with fully printed phase shifters based on low-temperature sintered BST-composite thick films," *IEEE Microwave and Wireless Components Letters*, vol. 26, no. 1, pp. 70-72, 2016.

[26] T. Ueda, S. Tanaka, S. Roy, D. Saha, and S. Bandyopadhyay, "A Priority-based QoS Routing Protocol with Zone Reservation and Adaptive Call Blocking for Mobile Ad Hoc Networks with Directional Antenna," *in Proc. of IEEE GlobeCom*, pp. 50-55, 2004.

[27] W. Na, L. Park and S. Cho, "Deafness-aware MAC protocol for directional antennas in wireless ad hoc networks," *Ad Hoc Networks*, vol. 24, pp.121-134, 2015.

[28] W. Na, J. Yoon, S. Cho, D. W. Griffith and N. Golmie, "Centralized Co-operative Directional Spectrum Sensing for Cognitive Radio Networks," *IEEE Transactions on Mobile Computing*, vol. PP, no. 99, pp. 1-1, 2017.

[29] Y. Dai, J. Wu, and Y. Zhao, "Boundary Helps: Reliable Route Selection With Directional Antennas in Cognitive Radio Networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 9, 2015.

[30] J. Qiao, L. Cai, X. S. Shen, and J. W. Mark, "Enabling Multi-Hop Concurrent Transmissions in 60 GHz Wireless Personal Area Networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 11, 2011.

[31] Z. He, S. Mao, and T. T. Rappaport, "On Link Scheduling Under Blockage and Interference in 60-GHz Ad Hoc Networks," *IEEE Access* vol. 3, 2015.

[32] J. Kim, G. Caire, and A. F. Molisch, "Quality-aware streaming and scheduling for device-to-device video delivery," *IEEE/ACM Transactions on Networking* vol. 24, no. 4, pp. 2319-2331, 2016.

[33] A. B. Sediq, R. H. Gohary, H. Yanikomeroglu, "Optimal tradeoff between efficiency and Jain's fairness index in resource allocation," *IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC*, pp. 577-583, 2012.

[34] L. Park, J. Yu, C.-G. Lee, and S. Cho, "BTRB: Beam Table-based Reliable Broadcast for Directional Antennas," *IEICE Transactions on Communications*, vol. E95-B, no. 10, pp. 3307-3311, 2012.

[35] J. Qiao, L. Cai, and X. Shen. "Enabling multi-hop concurrent transmissions in 60 GHz wireless personal area networks." *Wireless Communications, IEEE Transactions*, vol. 10, no. 11, pp.3824-3833, 2011.

[36] A. I. Sulyman, A. Alwarafy, G. R. MacCartney, T. S. Rappaport, and A. Alsanie, "Directional radio propagation path loss models for millimeter-wave wireless networks in the 28-, 60-, and 73-GHz bands," *IEEE Transactions on Wireless Communications*, vol. 15, no. 10, pp. 6939-6947, 2016.

[37] J. Kim, S.-C. Kwon, and G. Choi, "Performance of Video Streaming in Infrastructure-to-Vehicle Telematic Platforms With 60-GHz Radiation and IEEE 802.11ad Baseband," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 10111110115, 2016.

[38] R. Jain, A. Durresi, and G. Babic, "Throughput fairness index: An explanation," Tech. rep., Department of CIS, The Ohio State University, pp. 99-0045, 1999.

Appendix

A. Objective Function

Our objective function is given by

$$\text{maximize} \sum_{k \in \mathbf{K}} \sum_{i \in \mathbf{T}} w_e^k(t) \cdot t_e^k, \tag{16}$$

subject to

$$\sum_{m \in N(n)} d_{\underset{nm}{\rightarrow}} - \sum_{m \in N(n)} d_{\underset{mn}{\rightarrow}} = \begin{cases} d_s, \text{if } n = s(f); \\ -d_s, \text{if } n = d(f); \\ 0, \text{ otherwise}; \end{cases} \tag{17}$$

$$\sum_{f\in\mathbf{F}} d^f_{\underset{nm}{\rightarrow}} \leq \frac{\sum_{k\in\mathbf{K}}\sum_{t\in\mathbf{T}} t^k_{\underset{nm}{\rightarrow}} \cdot r^k_{\underset{nm}{\rightarrow}}}{T}, \forall n, m \in \mathbf{N}, \quad (18)$$

$$a^k_{\underset{nm}{\rightarrow}} \geq \frac{\sum_{t\in\mathbf{T}}\left(t^k_{\underset{nm}{\rightarrow}} + t^k_{\underset{mn}{\rightarrow}}\right)}{T}, \forall n \in \mathbf{N}, \forall m \in \mathbf{N}, \forall k \in \mathbf{K}, \quad (19)$$

$$a^k_{\underset{nm}{\rightarrow}} = a^k_{\underset{mn}{\rightarrow}}, \forall n \in \mathbf{N}, m \in \mathbf{N}, \forall k \in \mathbf{K}, \quad (20)$$

$$\sum_{m\in N(n)}\sum_{k\in\mathbf{K}} a^k_{\underset{nm}{\rightarrow}} \leq M, \forall n \in \mathbf{N}, \forall m \in \mathbf{N}, \forall k \in \mathbf{K}, \quad (21)$$

$$t^k_e + \sum_{e\in N(e)} t^k_e \leq 1, \forall e \in \mathcal{E}, \forall k \in \mathbf{K}, \forall t \in \mathbf{T}, \quad (22)$$

$$d_f \geq 0, \forall f \in \mathbf{F}, \quad (23)$$

$$d^f_{\underset{nm}{\rightarrow}} \geq 0, \forall n \in \mathbf{N}, \forall m \in N(n), \forall f \in \mathbf{F}, t^k_{\underset{nm}{\rightarrow}} \in \{0, 1\}, \quad (24)$$

$$\forall n \in \mathbf{N}, \forall m \in N(n), \forall k \in \mathbf{K}, \quad (25)$$

$$a^k_{\underset{nm}{\rightarrow}} \in \{0, 1\}, \forall n \in \mathbf{N}, \forall m \in N(n), \forall k \in \mathbf{K}, \quad (26)$$

$$\frac{\left(\sum_{t\in\mathbf{T}}\sum_{e\in\mathbf{E}} w^k_e(t) \cdot t^k_e\right)^2}{\beta \cdot \sum_{t\in\mathbf{T}}\sum_{e\in\mathbf{E}}\left(w^k_e(t) \cdot t^k_e\right)^2} \geq \tau, \forall t \in \mathbf{T}. \quad (27)$$