Group Based Multi-beams Subchannel Assignment for mmWave Internet of Things Networks

Zhongjiang Yan[1,2], Mao Yang[1], Bo Li[1], Yusheng Liang[1], Xiaoya Zuo[1]

[1] School of Electronics and Information, Northwestern Polytechnical University, China
[2] Science and Technology on Communication Networks Laboratory, China
{zhjyan, yangmao, libo.npu, zuoxy}@nwpu.edu.cn, liangys@mail.nwpu.edu.cn

Abstract

Wireless millimeter wave (mmWave) communication technology is promising to meet the low size, low weight and high data rate requirements in body area, Internet of Things (IoTs) networks. To combat the high path loss of mmWave channel, large scale array is employed to form several directional and narrow shape beams to serve multiple users. However, although the beams are narrow overlapping area may exist between multiple directional beams. This paper studies the resource allocation problem for a multi-beams communication system, which is proved to be NP-hard. This paper proposes a group based multi-beams subchannel assignment algorithm based on orthogonal frequency division multiple access (OFDMA). The beam spatial reuse gain is exploited for the groups of nodes deployed in difference coverage area of these beams, named as non-overlapped groups. And the multiple user diversity gain is exploited for the groups of nodes covered simultaneously by several beams, named as overlapped groups. Simulations results show that the throughput of the proposed algorithm outperforms the heuristic algorithm which only exploits the beam spatial reuse gain or the multiple user diversity gain.

Keywords: Internet of things, mmWave, Multi-beams, Beam spatial reuse gain, Multiple user diversity gain

1 Introduction

In Internet of Things (IoTs) networks, multiple photo and video cameras may be adopted, which are working at different spectral range (visible, near infrared, far infrared) and covering different fields of view. They can also exploit arrays of radio or light detection and ranging (Radar or Lidar) sensors to detect the presence of targets, of their speeds, distance and direction [1]. Even the access of distributed nodes in IoT towards a centralized cloud storage or processing center requires high data rate connections. Such high speed sensing nodes with data rates of Gbps in IoTs appear in many applications [1-2], such as surveillance of home or office scenarios, healthcare and wellness applications in body area networks.

Such kind of sensing nodes require low size and low weight, and fully integrated mmWave (millimeter wave) wireless transceivers can be exploited by using a complementary metal oxide semiconductor (CMOS) silicon-on-insulator (SOI) technology radio frequency (RF) [1]. Considering the network densification of IoTs, mmWave band is a viable method to form stable and high performance links to support advanced IoT services [3].

Fundamental differences between the mmWave communications and existing other communication systems exist, in terms of high propagation loss, directivity, and sensitivity to blockage. These characteristics of mmWave communications pose several challenges to fully exploit the potential of mmWave communications. To combat the high path loss of mmWave, the large scale array is employed to form several directional and narrow shape beams to serve the multiple users. However, there may also exist overlapping area between multi-beams. How to design an efficient resource allocation algorithm for such a multi-beams communication system is a significant and challenging problem.

Due to the high transmission rate of each beam in the mmWave systems, multi-user transmission is desired in mmWave IoTs networks, and the mmWave channel can be modelled as a frequency selective steering channel [3-4]. Multicarrier transmission technique, such as orthogonal frequency division multiple (OFDM), has been well established due to its advantages, mainly its robustness in multipath fading channels and the adaptively in resource allocation. Particularly, when multi-user access is desired OFDMA can be applied. Thus the multi-beams resource allocation problem can be transformed as a multi-beams subchannel assignment problem.

In the literature, most of the related works on MIMO-OFDM (multiple input and multiple output) resource allocation are on digital beamforming, such as [5-7] and the references therein. In Ref. [5], Adhikary

*Corresponding Author: Zhongjiang Yan; Email: zhjyan@nwpu.edu.cn
DOI: 10.3966/160792642019052003022

et al. consider to use joint spatial division and multiplexing method to mmWave channels, where clusters of multi-path components are used to serve several users. A conflict graph based method is proposed to select users and allocate the angular. In Ref. [6], Sun et al. investigate the downlink massive MU-MIMO (multiple user MIMO) transmission with multiple antennas at each user, and a beam domain channel model is proposed. By selecting users with non-overlapping beams, the MU-MIMO channels are decomposed into multiple single user MIMO channel links. In Ref. [7], Huang et al. consider to use coordinated or switched beamforming to serve the sensing nodes' demand while avoiding interference across sectors, where the beam patterns among the base stations are scheduled. For the mmWave resource allocation problems, most of the related works study the problems in the wireless personal area networks or WLAN. For example, In Ref. [8], Sandra et al. consider the time spatial resource allocation problem to serve a mixed set of multimedia applications. A channel time allocation partial swarm optimization algorithm is proposed with the consideration of the challenge of the blockage of the mmWave signal. We have studied how to concurrently schedule multiple mmWave links in one time slot in [9] with acceptance interference level between each other directional links. A heuristic clique based scheduling algorithm is proposed, where the directional links which can co-exist in the same slot is formulated as a clique of the conflict graph, and the maximal clique of the modelled graph is found.

To the best knowledge of the authors, this paper is the first to study how to design a multi-beams subchannel assignment algorithm, to exploit both the beam spatial reuse gain and the subchannel multiple user diversity gain. Suppose beam b_1 and b_2 share the same frequency, pointing to different directions. User n_1 and n_2 are covered by b_1 and b_2, respectively. Then user n_1 and n_2 can share the same subchannel of b_1 and b_2 at the same time. This is referred as the beam spatial reuse gain in this paper. For a given subchannel, different users may have different data rate on it, and when the user with highest data rate is selected then this selection bring a gain which is defined as the subchannel diversity gain. The main contributions are three folds.

- The multi-beams subchannel assignment problem is formulated as a non-linear integer programming problem. It targets at how to assign which beam's which subchannel(s) to which sensing node.
- The challenges to optimally solve the formulated problem are analyzed. And the formulated multi-beams subchannel assignment problem is proved to be an NP-hard problem by inducting to the classical multiple knapsack problem (MKP), which is NP-hard [22].
- To combat the complexity of finding the optimal solution, a group based multi-beams subchannel assignment algorithm is proposed, to exploit both the beam spatial reuse gain and the subchannel multi-user diversity gain.
- Simulation results evaluate the performance of the proposed algorithm, and reveal the relationships of the beam spatial reuse gain and subchannel multi-user diversity gain, with the sensing node numbers and the downlink traffic load of each sensing node, respectively.

Related works are presented in Section 2. The system model are detailed in Section 3. Section 4 formulates the multi-beams subchannel assignment problem as a non-linear integer programming problem, which is proved to be an NP-hard problem. To counter the high computation complex, Section 5 details the proposed group based multi-beams subchannel assignment algorithm. The performance of the proposed algorithm is evaluated in Section 6. Section 7 concludes this paper.

2 Related Works

New opportunities has been brought forth by the emergence of Internet of Things (IoT), which seamlessly integrates the physical world using computing, sensing, and wireless networks, transforming it into a cyber-physical system. In Ref. [10], Li et al. review the evolution of IoT wireless networks for low rate and real time applications, and analyses three standards (WirelessHART, ISA100.11a and WIA-PA) and future trends for industrial wireless networks based on IEEE 802.15.4. Ma et al. review the background and state of the art of Health IoT in Ref. [11], and four typical application scenarios are introduced, including the medical industry, health monitoring, exercise promotion and mental support.

Khan et al. survey the enabling technologies for effective deployment of IoT systems from a communication networking perspective in Ref. [12]. Networking is one of the key enabling technologies for the effective deployment of IoTs. A cost effective network architecture is required to meet the challenges how to support the large area of coverage and diverse QoS (Quality of Service), reliability, spectrum requirements. A low cost heterogeneous network using short range radio standards of IEEE 802.15.4/Zigbee, IEEE 802.11/WLAN is proposed in Ref. [12] to support large number of IoT devices for various applications. In Ref. [13], Agrawal and Sharma discuss the 5G mmWave communication system how to provide seamless user experience by accommodating large number of devices in IoT environment with a Gbps data rate with the consideration of Big-Data.

In Ref. [14], Chiang argues that it is limited to just design architecture without performance concerns.

Chiang proposes a prediction-based scheme for data stream with time constraint over IoT. A performance driven model to IoT real-time delivery is proposed and a novel methodology for deploying real-time data stream based on prediction mechanism in IoT environment is presented. Experimental evaluation of the proposed scheme shows that advantage in overall system utility over the existing approaches even with workload fluctuations. In Ref. [15], Chen et al. propose an improved cloud computing architecture for IoT, where the things as a service (TaaS) are employed on the cloud computing layer to form the virtual network model. In Ref. [16], Chen et al. develop a high quality communication frameworks for IoT data test-bed based on LTE communication systems. The NetFPGA and OpenFlow platforms are employed to emulate the test-bed framework, which is expected to offer the sensitiveness control over IoT communication.

The realistic channel capacity and bit rate analyses are presented from the perspective of IoT application deployments in Ref. [3]. And in Ref. [17], Heydari overviews the recent advances in the development of silicon-based mm-wave/THz imaging sensors for near-field IoT applications. To meet the demand of IoT and its appications for small and low power nodes, Freidl et al. implement a fully functional MMID system in the E-band both for the base station and the user sides, and the performance is presented in a system context in Ref. [18]. Saponara et al. present the design of 60GHz transceiver key blocks to ensure several Gbps data rate and up to 10m connection distances in Ref. [1], which allow for the implementation of low cost nodes for IoT systems. Such IoT specifications are suitable for home/office scenarios, for the body area networks for healthcare and wellness, and for the applications of on-board vehicles.

In Ref. [19], Kong et al. study how to explore the mmWave communications to meet the exponential increase of traffic data in autonomous vehicles. By combining the advantages of the IoTs and cloud computing, the proposed vehicular mmWave system supports vehicles sharing the surrounding environment and recognizing objects via the cloud in real time, which may be multi-gigabit. To be secure, in Ref. [20] Agrawal and Sharma propose to interleave the transmitted data in the software defined system in 5G millimeter wave (mmWave) communication system. The IoT receiver de-interleaves the received interleaved data and the interleaved parameters. Refs. [5-7] discuss how to allocate the digital beamforming resource of the MIMO-OFDM system. Ref. [8] considers the time spatial resource allocations problem, and Ref. [9] considers how to schedule multiple directional mmWave links without interference with each other.

However, the resource allocation problem in mmWave IoT network is unsolved when there exists overlapping area between multi-beams, which motivates our work.

3 System Models

Suppose there are two kinds of nodes in the mmWave IoT network, i.e., an access point (AP) and several sensing nodes. And the AP node forms B beams with fixed pointing directions fully covering a given area, where there are N sensing nodes randomly distributed. The sensing nodes can be the photo and video cameras requiring high data rate in the mmWave IoT networks. Each sensing node associates with one beam according to its received SINR. All of the B beams are working on the same frequency channel in OFDMA mode, which is composed of K subchannels.

In the following, we use n, b, k to denote a specific sensing node, beam and subchannel, respectively. Let the binary matrix $\boldsymbol{A}=[a_{b,n}]_{B\times N}$ denote the association relationships between the sensing nodes and the beams, where $a_{b,n}=1$ meaning that the sensing node n is associated with beam b. In this paper, we assume each sensing node can only associate with only one beam, i.e., $\sum_{b=1}^{B} a_{b,n} \le 1$. Furthermore, each beam can only assign its subchannels to the sensing nodes associated with it. Let B_i^j denote the jth set of any i beams out of B, where $1 \le j \le C(B,i)=\dfrac{B!}{i!(B-i)!}$, and $1 \le i \le B$. And let $N_{B_i^j}$ denote the set of sensing nodes covered by all of the beams in B_i^j .

The path loss of mmWave is given as

$$PL[dB]=\alpha+10\beta\log_{10}(d)+X_\sigma,$$

where d is the distance between the transmitter and the receiver, α is the intercept in dB, β is the slope, and X_σ is a zero mean Gaussian random variable with a standard deviation σ in dB. To decrease the large path loss impact, beamforming is employed by the antenna array, where the beams can point to different directions by changing the current of arrays. In this paper, the rectangular plane array is employed which are arranged in a rectangular grid unit in the XOY plane [21]. Beam b's transmitter antenna gain at sensing node n can be computed as

$$G_t(b,n)=[S_{norm}(b,n)]^2 G_{t_{\max}},$$

where $S_{norm}(b,n)$ is normalized array radiation factor received by sensing node n from beam b, and $G_{t_{\max}}$ is the maximum transmitter antenna gain of beam b.

Sensing node n's received power from beam b can be calculated as

$$P_r(b,n)[dBm] = P_t[dBm] + G_t(b,n)[dBi] + G_r[dBi] - PL[dB],$$

where P_r and P_t are the received and transmitted power, respectively, and G_r is the receiver antenna gain at the sensing node *n*. In this paper, we assume that the sensing node equip with an omnidirectional antenna and $G_r = 0dB$, same as [21]. At a given time slot, by taking the small-scale Rayleigh fading into account, the received signal power at subchannel *k* can be written as

$$P_r(b,n,k)[mw] = \frac{P_r(b,n)[mw]}{K} \times Y_\delta,$$

where Y_δ is a Rayleigh distributed random variable with parameter δ. Then, the received signal to interference plus noise ratio (SINR) from beam *b* for sensing node *n* in subchannel *k* can be calculated as

$$SINR_r(b,n,k) = \frac{P_r(b,n,k)}{\sum_{\substack{b'=1\\ b'\neq b}}^{B}\sum_{\substack{n'=1\\ n'\neq n}}^{N} P_r(b',n',k) + P_N}.$$

$\sum_{\substack{b'=1\\ b'\neq b}}^{B}\sum_{\substack{n'=1\\ n'\neq n}}^{N} P_r(b',n',k) + P_N$ is the total interference power at the subchannel *k*, and P_N is the noise power. Thus, the data rate of sensing node *n* in subchannel *k* of beam *b* can be calculated with the Shannon formula as

$$r_{b,k,n} = W_k \log(1 + SINR(b,n,k)).$$

where W is the bandwidth of the subchanel *k*.

4 Problem Formulation and Analysis

Since the mmWave IoT networks are expected to be designed for data applications with high and flexible data rates especially in the downlink, in this paper the investigations are concentrated on downlink transmission. The AP holds the data transmission requests of each node. We note that the uplink transmission problem can also be solved by the proposed algorithm, where the data transmission requirements of the sensing nodes can be gathered by the AP node.

Supposed that the AP holds the sensing nodes' downlink traffic and want to transmit them to the sensing nodes with the maximum network throughput. Let $R = \{R_n, 1 \le n \le N\}$ denote the downlink traffic rate requirement set of the sensing nodes, where the unit of R_n is bits per second (bps). The objective of the proposed multi-beams subchannel assignment problem is to maximize the total throughput of the network, by assignment the beams' subchannels to the sensing nodes. Such that, the proposed multi-beams subchannel assignment problem can be formulated as follows.

$$\max \sum_{n=1}^{N} \min\Big(\big(\sum_{b=1}^{B}\sum_{k=1}^{K} a_{b,n}x_{k,n}r_{b,k,n}\big), R_n\Big)$$

$$s.t. \quad \forall k,i,j, \sum_{n\in N}^{N}\sum_{b\in B_i^j}^{B} a_{b,n}x_{k,n} \le 1,$$

$$\forall n, \quad \sum_{b=1}^{B}\sum_{k=1}^{K} a_{b,n}x_{k,n} \le K,$$

$$\forall n,k \;\; x_{k,n} = 0 \; or \; 1.$$

In the above formulated problem, the objective of the formulated problem is to maximize the sum of the total users' assigned data rate, i.e., achieving the maximum network throughput. Note that each user's achieved data rate is the minimum of each user's assigned data rate and its required downlink data rate. Furthermore, the physical meaning of $x_{k,n} = 1$ is that subchannel *k* is assigned to node *n*, otherwise $x_{k,n} = 0$.

The physical meanings of the constraints are illustrated as follows. Firstly, for any subchannel *k*, it can only be assigned to at most one sensing node, within the given sensing node set $N_{B_i^j}$ covered by all of the beams in B_i^j, to avoid the co-subchannel interference between sensing nodes. The reason is presented as follows. Taking Figure 1 as an example, suppose sensing node s_2 associates with Beam 1, and sensing node s_3 associates with Beam 2. Thus this constraints means that if subchanel 1 of Beam 1 is assigned to sensing node s_2, the subchannel 1 of Beam 2 can not be assigned to sensing node s_3. Otherwise, co-subchannel interference will be caused. Similarly, when subchannel 1 of Beam 1 is assigned to sensing node s_2 it can not be assigned to sensing node s_1 again, though sensing node s_1 and sensing node s_2 are both covered by Beam 1. Thus this constraint holds for any k,i and *j*. Secondly, for any node *n*, the total number of the assigned subchanels should not be larger than *K*. The reason is also to avoid co-subchannel interference, since there are at most *K* subchannels.

It can be seen that the formulated problem is a non-linear integer programming problem. The main challenge to optimally solve this formulated problem is to meet the first constraint. It consists of several coupled relationships which complicate the formulated problem. The first coupled relationship is the association relationship between the sensing node and the beams, i.e., $a_{b,n}$. The second coupled relationship is the subchannel assignement relationship between the subchannel and the sensing node, i.e., $x_{k,n}$. The last but not the least coupled relationship is the covered relationship between the sensing nodes and the beams. For example, any two sensing nodes covered by the same beams, can not share the same subchannel, even

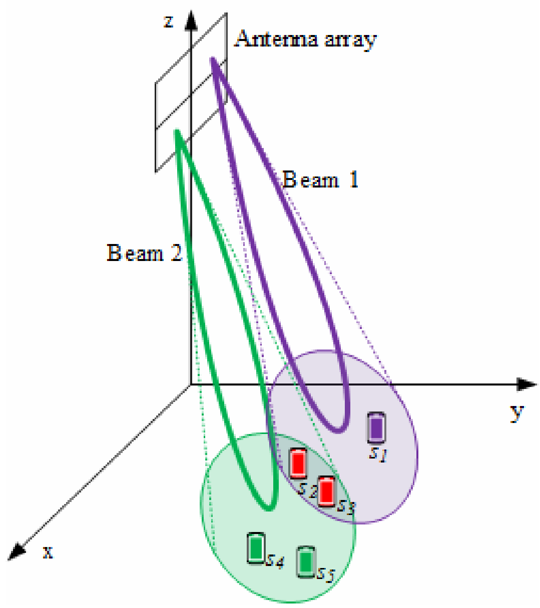

Figure 1. System model

though these two nodes are assigned the same subchannel of different beams, i,e., $\sum_{n\in N}^{N}\sum_{b\in B_i^j}^{B} a_{b,n}x_{k,n} \le 1$.

Theorem 1 shows that the formulated problem is an NP-hard problem.

***Theorem* 1:** The proposed multi-beams subchannel assignment problem is an NP hard problem.

Proof: The basic idea is to show that an instance of the proposed multi-beams subchannel assignment problem is a Multiple Knapsack Problem (MKP), which is NP-hard [22]. Such that the proposed multi-beams subchannel assignment problem is NP-hard.

Firstly, the MKP problem can be formulated as follows, with a little abuse of variable notations. Suppose that there are n items and m knapsacks, and the profit and weight of each item vary according to the knapsack for which they are assigned. Let $p_{i,j}$ and $w_{i,j}$ denote the profit and weight if item j is assigned to knapack i. The objective of the MKP is to maximize the total profit with the capacity constraint of each knapsack m, i.e., c_i, by varying the item assignments. Therefore, the MKP can be formulated as

$$\begin{aligned} &\max \sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}x_{ij} \\ &s.t. \quad \forall i \quad \sum_{j=1}^{N} w_{ij}x_{ij} \le c_i, \\ &\qquad \forall j, \quad \sum_{b=1}^{B} x_{i,j} \le 1, \\ &\qquad \forall i,j \quad x_{ij} = 0 \; or \; 1. \end{aligned}$$

Secondly, we show that an instance of the proposed multi-beams subchannel assignment problem is NP-hard. The basic idea is to regard the subchannels as the items, and to regard the sensing nodes as the knapsacks in MKP. Such that there are K items and N knapsacks in the proposed problem. Let an instance of the proposed problem be assumed as follows.

Suppose that there is only one beam, i.e., $B=1$, and all of the N sensing nodes are associated with this beam, i.e., $a_{1,n}=1$ for any n. Let the downlink transmission requirement of each node n is infinity, i.e., $R_n = \infty$. Such that the objective of the proposed problem can be derived as

$$\sum_{n=1}^{N}\min\Big(\big(\sum_{b=1}^{B}\sum_{k=1}^{K} a_{b,n}x_{k,n}r_{b,k,n}\big), R_n\Big) = \sum_{n=1}^{N}\sum_{k=1}^{K} x_{k,n}r_{1,k,n},$$

We note that this instance is a particular case of the propsed multi-beams subchannel assignment problem, which is actually a single beam subchannel assignment problem.

Next, the profit and the weight of each subchannel k is given as follows. Let the weight of subchannel k if assgined to sensing node n is the number of subchannel k, i.e., $w_{k,n}=1$. And the profit of the subchannel k if assgined to sensing node n is the expcted data rate of subchannel k, i.e., $r_{1,k,n}$. Such that the constranits of the proposed problem can be derived as

$$\sum_{n\in N}^{N}\sum_{b\in B_i^j}^{B} a_{b,n}x_{k,n} = \sum_{n=1}^{N} x_{k,n} \le 1,$$

and

$$\sum_{b=1}^{B}\sum_{k=1}^{K} a_{b,n}x_{k,n} = \sum_{k=1}^{K} x_{k,n} = \sum_{k=1}^{K} w_{b,n}x_{k,n} \le K$$

where K can be regarded as the capacity of the sensing node, i.e., no mored K subchannels can be assigned to sensing node n.

Thus we can re-formulate the proposed multi-beams subchannel assignment problem as follows.

$$\begin{aligned} &\max \sum_{n=1}^{N}\sum_{k=1}^{K} k_{k,n}r_{1,k,n} \\ &s.t. \quad \forall i \quad \sum_{n=1}^{N} x_{k,n} \le 1, \\ &\qquad \forall n, \quad \sum_{k=1}^{K} w_{b,n}x_{k,n} \le K, \\ &\qquad \forall n,k \quad x_{k,n} = 0 \; or \; 1. \end{aligned}$$

Therefore, it can be seen this single beam subchannel assignment problem is an MKP, which is NP-hard. Thus the proposed multiple beam assignment problem is NP-hard. This complete the proof.

Since the NP-hard problem can not be optimally solved within polynomial time, next we focus on designing a group based multi-beams subchannel assignment algorithm algorithm to solve the proposed problem in the following section.

5 Group Based Multi-beams Subchannel Assignment Algorithm

In this paper, a sensing node group based multi-beams subchannel assignment algorithm is proposed. The basic idea is to divide the sensing nodes into groups firstly according to the beams' overlapped coverage areas or non-overlapped coverage areas. Then, the subchannels are assigned to the sensing nodes to exploit the beam spatial reuse gain and the subchannel multi-user diversity gain.

Next, the method of dividing the sensing nodes into groups is presented in Section 5.1, and the proposed group based multi-beams subchannel assignment algorithm is given in Section 5.2.

5.1 Dividing the Sensing Nodes into Groups

The terms of *non-overlapped areas of beams* and *overlapped areas of beams* are illustrated as follows. Taking Figure 1 as an example, sensing node s_2 and sensing node s_3 are located in the overlapped area of Beam 1 and Beam 2, and sensing node s_1 is located in the non-overlapped area of Beam 1, and sensing node s_4 and sensing node s_5 are located in the non-overlapped area of Beam 2. Therefore, when there are 2 beams the total sensing nodes can be divided into 3 sensing node groups. Therefore, the non-overlapped area of beam, or non-overlapped group, is a set of sensing nodes which is only covered by only one beam. While the overlapped area of beams, or overlapped group, is a set of sensing nodes which is simultaneously covered by several beams.

We note that the beam spatial reuse gain can be achieved by assigning the subchannel to the sensing node/sensing nodes located in the non-overlapped areas. For example, when a given subchannel k is assigned to sensing node s_1, the same subchannel k can also be assigned to sensing node s_4 or sensing node s_5. That is because the sensing node s_1 is covered by Beam 1 which does not cover the sensing node s_4 or sensing node s_5, such that the same subchannel k of Beam 2 can also be assigned to sensing node s_4 or sensing node s_5. In this case, the beam spatial reuse gain can be achieved by assigning the same subchannel k (of diffenret beams) to the sensing nodes located in the non-overlapped areas.

While the subchannel multi-user diversity gain is achieved by assigning the subchannel to the sensing node which has the highest data rate. For example, sensing node s_2 and sensing node s_3 are both covered by Beam 1 and Beam 2. To avoid co-subchannel interference, if the subchannel k of Beam 1 is assigned then that of Beam 2 can not be assigned. Therefore, there may exist 4 pairs of relationships between the two beams and the two sensing nodes for any subchannel k, i.e., the two-tuples (Beam1, sensing node s_2), (Beam1, sensing node s_3), (Beam2, sensing node s_2) and (Beam2, sensing node s_3). Each of these four two-tuples corresponds to an expected data rate, i.e., $r_{1,k,2}$, $r_{1,k,3}$, $r_{2,k,2}$ and $r_{2,k,3}$. Therefore, to obtain the multi-user diversity gain and to achive the maximum total throughput, the subchannel k can be assigned to the sensing node whose expected data rate is the largest one.

In the practical mmWave IoT networks, the expected data rate of each subchannel of beams, i.e., $r_{b,n,k}$, can be used to divide the sensing nodes into groups. In this paper, if $\max_{1\le k\le K} r_{b,n,k} \ge \gamma$, then sensing node n is said to be covered by beam b, where γ is the lowest data rate. The physical meaning is that if the data rate of beam b's highest data rate of the subchannels is larger than γ, then at least one of the subchannels of beam b can be assigned to sensing node n.

5.2 The Proposed Algorithm

To jointly exploit both of the beam spatial reuse gain and subchannel multi-user diversity gain, the group based multi-beams subchannel assignment algorithm is proposed, and the pseudo-code of the proposed algorithm is given in Algorithm 1.

The basic idea of the proposed algorithm is to sequentially assign the subchannels to the sensing nodes. For each assignment of subchannel k, there are mainly three parts constituting Algo. 1, which are attempting assignment of non-overlapped groups from lines 4 to line 11 to exploit the beam spatial reuse gain, attempting assignment of overlapped groups from line 12 to line 19 to exploit the multiple user diversity gain, and comparing and decision making of the attempting from line 20 to line 29. Before going into the details of the proposed algorithm, we would like to recall that the beam spatial reuse gain can be exploited by assigning the same subchannel k to different sensing nodes located in different non-overlapped groups. And the multiple user diversity gain can be exploited by assigning one subchannel k to one sensing node whose data rate is the largest. The details of Algo. 1 are presented as follows.

There are four types of input variables which include the association relationship matrix of the sensing nodes and the beams, i.e., $\boldsymbol{A}$, the data rate matrix of the sensing nodes at each subchannel of each beam, i.e., R, the set of downlink traffic requirements of the sensing nodes, i.e., R, and the sensing node groups $\{N_B \mid \forall B' \subseteq B\}$ of the non-overlapped ones and the overlapped ones. The output is the assignment binary variable matrix $\boldsymbol{X}$.

Algorithm 1: Group based Multiple Beams Subchannel Assignments Algorithm

Input: $\mathbf{A} = [a_{b,n}]_{B\times N}$; $\mathbf{R} = [r_{b,k,n}]_{B\times K\times N}$;
$\mathcal{R} = \{R_n | 1 \le n \le N\}$; $\{\mathcal{N}_{\mathcal{B}'} | \forall \mathcal{B}' \subseteq \mathcal{B}\}$, where
$\mathcal{B} = \{b_i | 1 \le i \le B, b_i \text{ is a beam}\}$.

Output: $\mathbf{X} = [x_{k,n}]_{K\times N}$

1 $\mathcal{K} = \{1, 2, \cdots, K\}$, $\mathcal{N} = \{1, 2, \cdots, N\}$,
$\mathbf{X} = [x_{k,n}]_{K\times N} = zeros(K, N)$;
2 **while** $\mathcal{K} \neq \emptyset$ *and* $\mathcal{N} \neq \emptyset$ **do**
3   randomly select a k from $\mathcal{K}$, $\mathcal{K} = \mathcal{K} - \{k\}$;
4   $r_{ng} = 0$, $\mathcal{N}_{ng} = \emptyset$;
5   **for** $b = 1 : B$ **do**
6     $r_{max} = 0$, $n_{max} = -1$;
7   **for** $\forall n \in \mathcal{N}_{\{b\}}$ **do**
8   **if** $r_{max} < (a_{b,n} r_{b,k,n})$ **then**
9         $r_{max} = r_{b,k,n}$, $n_{max} = n$;
10   **if** $n_{max} \neq -1$ **then**
11       $r_{ng} = r_{ng} + r_{max}$, $\mathcal{N}_{ng} = \mathcal{N}_{ng} + \{n_{max}\}$;
12   $r_{og} = 0$, $n_{og} = -1$;
13   **for** $\forall \mathcal{B}' \subseteq \mathcal{B}$, *where* $|\mathcal{B}'| \ge 2$ **do**
14     $r_{max} = 0$, $n_{max} = -1$;
15   **for** $\forall n \in (\mathcal{N}_{\mathcal{B}'} \cap \mathcal{N})$ **do**
16   **if** $r_{max} < (a_{b,n} r_{b,k,n})$ **then**
17         $r_{max} = r_{b,k,n}$, $n_{max} = n$;
18   **if** $n_{max} \neq -1$ *and* $r_{og} < r_{max}$ **then**
19       $r_{og} = r_{max}$, $n_{og} = n_{max}$;
20   **if** $r_{ng} > r_{og}$ **then**
21   **for** $\forall n \in \mathcal{N}_{ng}$ **do**
22       $x_{k,n} = 1$, $R_n = R_n - r_{b,k,n}$;
23   **if** $R_n \le 0$ **then**
24         $\mathcal{N} = \mathcal{N} - \{n\}$;
25   **else**
26   **if** $r_{og} > 0$ **then**
27       $x_{k,n_{og}} = 1, , R_n = R_n - r_{b,k,n_{og}}$;
28   **if** $R_n \le 0$ **then**
29         $\mathcal{N} = \mathcal{N} - \{n_{og}\}$;
30 **return X**;

In line 1, the temporary variables, i.e., the set of the subchannels *K* and the set of the sensing nods *N*, and the output variable ***X*** are initialized. Here, *K* is used to denote the subchannels waiting to be assigned, and *N* is used to denote the sensing nodes whose data transmission requirements has not been met. When a given subchannel is assigned to the sensing nodes, this subchannel will be removed from *K*. And a sensing node will be removed from *N* when its requirement has been met. Thus in line 2, if both *N* and *K* are not empty set, it means that there are left subchannels which can be assigned to the sensing node to meet the requirements of the sensing node, and maximize the total network throughput further. Otherwise, there may be no subchannels left, or all of the sensing nodes' requirement are met, then stop the assignment and return the assignment results ***X*** in line 30.

In line 3, to avoid deep shadowing effect of the subchannels, the subchannel is randomly selected in each loop. To exploit both the beam spatial reuse gain and the subchannel multi-user diversity gain, each subchannel *k*'s two data rates are computed by attempting to assignment the subchannel *k* to the non-overlapped groups and the overlapped groups, from lines 4 to line 11 and from 12 to line 19, respectively.

From lines 4 to line 11, subchannel *k* is attempted to be assigned to the non-overlapped sensing node groups. Firstly, in line 4 the temporary variables are initialized where r_{ng} is the total data rate, and N_{ng} is the assigned sensing node set. For each non-overlapped group of beam *b*, i.e., node set $N_{\{b\}}$, in line 6 the temporary variables $r_{\max}$ and $n_{\max}$ are initialized to record the maiximum data rate and its corresponding node. The nodes whose requirement have not been met are checked one by one, i.e., the node in $N_{\{b\}} \cap N$ in line 7, by finding the maximal dara rate node in line 8-9. Note that the minimum *n* is 1, thus if $n_{\max} \neq -1$ (the initialization value of $n_{\max}$ in line 6) then one sensing node with the maximal data rate is found. Thus the final temporary assignment results is updated by taking this assignment into account in line 11. That is if subchannel *k* is assigned to the non-overlapped groups then the total achieved data rate is r_{ng}, and the assigned sensing nodes are included in N_{ng}.

From lines 12 to line 19, subchannel *k* is attempted to be assigned to the overlapped sensing node groups. Different from the non-overlapped one, subchannel *k*'s data rate is the maximum of each overlapped sensing node group's maximum data rate. In line 12, the temporary variables are initialized where r_{og} is the expected data rate, and n_{og} is the assigned sensing node. Then for each overlapped group, i.e., node set $N_{B'}$, in line 14 the temporary variables $r_{\max}$ and $n_{\max}$ are re-initialized to record the assignment results. Similarly, the nodes whose requirement have not been met are checked one by one, i.e., the node in $N_{B'} \cap N$ in line 15, by finding the maximal dara rate node in line 16-17. When a maximum data rate node is found then update the assignment result in line 18-19, where the achived data rate by assgining subchannel *k* to the overlapped groups is r_{og}, and the assigned sensing node is n_{og}.

From line 20-29, the assignment decision making is done by comapring which assignment achieves the larger data rate, i.e., $r_{ng} > r_{og}$ or not, in line 20. If $r_{ng} > r_{og}$ then subchannel *k* is assigned to the nodes in non-overlapped groups, and the data transmission requirements of the nodes are updated. Otherwise it is assigned to the nodes in overlapped groups.

6 Performance Evaluation

To evaluate the performance of the proposed algorithm, we compare it with an intuitive strategy, the basic idea of which is given as follows.

We note that the main challenge comes from the co-subchannel interference in the formulated problem, particularly the coupled interference relationships between the simultaneously covered nodes by several beams and subchannels of these beams. Thus, an intuitive strategy is to assign the subchannels to the nodes which is covered by several beams. After that the left subchannels can be assigned to the nodes which is covered by only one beam. That is in this heuristic method, the subchannel multi-user diversity gain is exploited firstly, and then the beam spatial reuse gain is exploited.

Simulation parameters are given as follows. Suppose that there exists a rectangle antenna array equipped on the AP, with height of 10 m, where the number of the antennas is set as 32×32. There are 4 beams formed according to [21], the maximum transmitter antenna gain of which is set as 16dBi. The transmission power of each beam is set as 22 dBm. The channel bandwidth is set as 500MHz, with the center frequency 28GHz, which is divided into 32 subchannels in OFDM mode. In each subchannel the noise power can be calculated as $P_N = 6.425 \times 10^{-11}$ mW. The channel model parameters are set as $\alpha = 45.3$, $\beta = 2.9$, $\delta = 0.04$. The height of BS antenna arrays is 10m, and the height of sensing node antenna is 0m. The radius of a sector is 50m with angle 60°. Within this sector, many nodes are uniformly distributed, the receiving antenna gain of each node is set as 0 dBi and can received the signal omnidirectional. The beam pointing position of each beam are set as follows.

Beam 1 and Beam 2 are set to cover the edge of the sector, where the pointing position are in polar coordinates and are set as (0.45×50m, 60° – Hpbw)/2) and (0.45×50m, 60° – Hpbw)/2), where Hpbw is the half power of all of the beam width. Beam 3 is set to cover the center part between Beam 1 and Beam 2, and it is pointing to (0.45×50m, 0). And Beam 4 is set to cover the nearest part with the pointing position (0.15×50m, 0). In this method, we note that the beam pointing position changes with the beam's Hpbw to maximize the beam covering areas of the sector. The problem of how to determine the beams' pointing position to minimize the overlapped areas, or to maximize the covered areas will be the future work of this paper.

To find the relationships between Hpbw and the nodes ratio covered by the beam, Monte Carlo method is employed, where 5000 nodes are assumed to be deployed in the sector. Hpbw is changed from 5° to 32°, and the nodes which are not covered by any beams, covered by one, two, three and four beams are calculated. Here, a node is covered meaning that it is located within one beam's Hpbw, i.e., the normalized array radiation factor received by sensing node n from beam b, $[S_{norm}(b,n)]^2 > 0.5$.. Figure 2 shows that with the increase of the beam's Hpbw the ratio that the nodes not be covered decreases monotonously. However, the nodes ratio which are covered only by one beams increases firstly and then decreases after it reaches its maximum. Importantly, we note that due to the irregularly the beam covering shape in the sector, it can be found there exists some nodes are covered by 2 beams when there are still not covered nodes. This implies that the proposed problem that there exist overlapped area between the beams are actually significant to be solved.

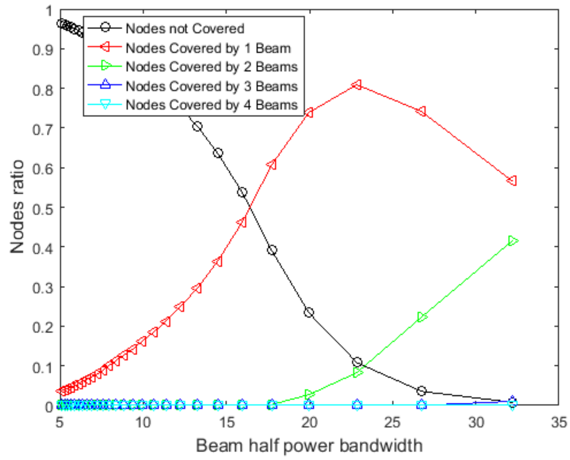

Figure 2. Nodes covered ratio versus the changing of beam's Hpbw

However, we would like to point that although the beam's Hpbw disclose the relationships between the nodes ratios at some level, but the information of beam's Hpbw can not be used to allocate resource to the users directionally. That is because that the beam's Hpbw is not the users' achieved data rate, which is actually related with the ratio of the received signal to interference and noise, i.e., SINR.

Figure 3 shows the effected differences between the beam's Hpbw and data rate on nodes covered ratio. We note that the rightmost stacked bars are the nodes ratios when applying the data rate information. Here a node is said to be not covered if its received data rate is zero, i.e., its received SINR is too small. And it is said to be covered by multiple beams if its SINR under multiple beams are larger than 0. While the others are the results when the normalized beam array radiation factor β information is applied. Taking the stacked bar of $\beta = 0.3$ for example, a node is said to be covered by a beam if its received β from that beam is larger than 0.3. Therefore, the main difference comes from that SINR or data rate takes the interference information from other beams into account, but β only considers the received normalized beam array radiation factor, i.e., the beam gain, ignores the interference. Thus, in the following simulation we use the data rate to distinguish the overlapped node groups and the non-overlapped node groups.

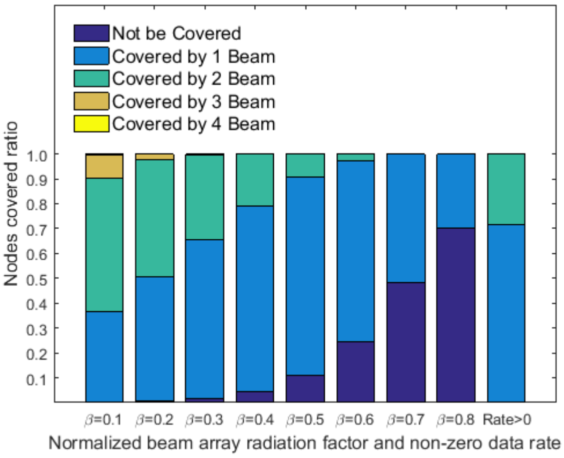

Figure 3. Nodes covered ratio comparison between the normalized beam array radiation and non-zero data rate when Hpbw = 22.8539°

The simulation results are demonstrated in Figure 4 and Figure 5. In Figure 4, the requirement of each sensing node, R_n, increases from 50Mbps to 350Mbps with a step of 50, and then increases from 350Mbps to 950Mbps with a step of 100. And for each setting of R_n, the scenarios of sensing node number with 30, 60 and 90 are simulated. For the proposed method, the network throughput increases as R_n increases. While for the heuristic method, the networks throughput first increases and then decreases as R_n increases. Furthermore, it can be seen that there is a peak rate achieved by both the proposed method and the heuristic method. This can be explained as follows. When R_n is small, with the heuristic method the requirement of the sensing nodes located in the overlapped area can be satisfied and a few of subchannels can be left, which can be used by the sensing nodes located in the non-overlapped area. However with the increase of R_n, the number of the left subchannel goes to zero, which made the network throughput decreases. It can be seen that the lowest network throughput of the heuristic method is near 2.7Gbps, which is almost equivalent to (32×86.79 Mbps), where 86.79Mbps is the highest data rate achieved by one subchannel. In other words, the subchannel multi-user diversity gain is high when R_n is small, while when it is large the gain is low. This is also the reason that why there is a pulse with the proposed method when R_n is small.

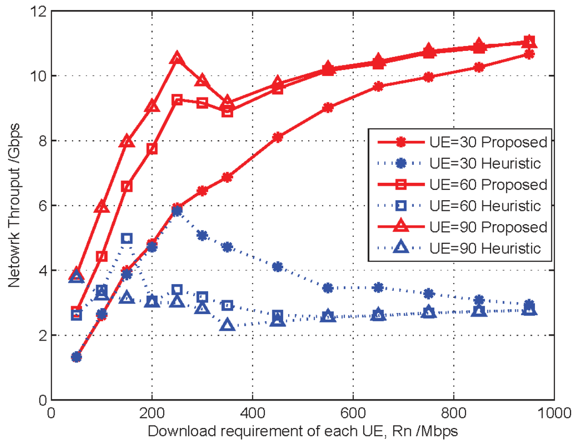

Figure 4. Network throughput with various R_n

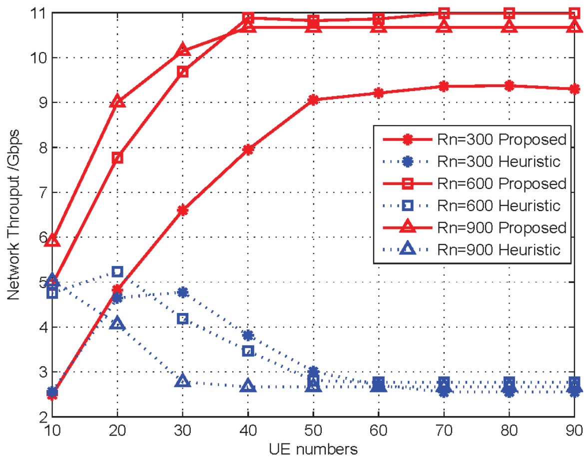

Figure 5. Network throughput with various sensing node numbers

In Figure 5, the number of sensing nodes increases from 10 to 90 with a step of 10, under different download requirements of each sensing node. It can be found that the cures are similar with Figure 2. And it can be concluded that when the sensing node number is small the multi-user diversity gain is high, while as the increase of the sensing node number the multi-user diversity gain decrease.

7 Conclusion

Beamforming of the mmWave communication technology is a promising technology to enable the IoTs network, to provide high data rate connections between the sensing node and the centralized data or processing center. Although large scale array is employed and narrow beams can be formed, the coverage area of different beams of the large scale array may be overlapped. Thus the problem of how to serve the sensing nodes located in the overlapped area needs to be solved.

This paper proposes a group based multi-beams subchannel assignment for mmWave networks. The proposed problem is formulated as an integer programming problem. To combat the complexity, a group based subchannel algorithm is proposed, to explore both the beam spatial reuse gain and the subchannel multi-user diversity gain. Simulation results evaluate the performance of the proposed algorithm. And it shows that the beam spatial reuse gain will increase with the increase of the download requirement of each sensing node and the sensing node numbers. However, the subchannel multi-user diversity gain will increase with the increase of the download requirement of each sensing node and the sensing node number, when they are small. However, it will decrease with the increase of the download requirement of each sensing node and the sensing node number, when they are large.

Further characterizations of the beam spatial gain and the subchannel multi-user diversity gain will be studied in the future.

Acknowledgments

This work was supported in part by the National Natural Science Foundations of CHINA (Grant No. 61771392, No. 61771390, No. 61501373, and No. 61271279), the Science and Technology on Communication Networks Laboratory Open Projects (Grant No. KX172600027), the National Science and Technology Major Project (Grant No. 2015ZX0300 2006-004 and 2016ZX03001018-004), and the Fundamental Research Funds for the Central Universities (Grant No. 3102017ZY018).

References

[1] S. Saponara, B. Neri, mm-Wave Integrated Wireless Transceivers: Enabling Technology for High Bandwidth Connections in IoT, *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, Milan, Italy, 2015, pp. 149-153.

[2] T. Yilmaz, G. Gokkoca, O. B. Akan, *Internet of Things (IoT) in 5G Mobile Technologies*, Springer International Publishing, 2016.

[3] T. Yilmaz, O. B. Akan, On the Use of the Millimeter Wave and Low Terahertz Bands for Internet of Things, *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, Milan, Italy, 2015, pp. 177–180.

[4] Z. Xiao, X.-G. Xia, D. Jin, N. Ge, Iterative Eigenvalue Decomposition and Multipath-Grouping Tx/Rx Joint Beamformings for Millimeter-Wave Communications, *IEEE Transactions on Wireless Communications*, Vol. 14, No. 3, pp. 1595-1607, March, 2015.

[5] A. Adhikary, E. A. Safadi, M. K. Samimi, R. Wang, G. Caire, T. S. Rappaport, A. F. Molisch, Joint Spatial Division and Multiplexing for mm-Wave Channels, *IEEE Journal on Selected Areas in Communications*, Vol. 32, No. 6, pp. 1239-1255, June, 2014.

[6] C. Sun, X. Gao, S. Jin, M. Matthaiou, Z. Ding, C. Xiao, Beam Division Multiple Access Transmission for Massive MIMO Communications, *IEEE Transaction on Communications*, Vol. 63, No. 6, pp. 2170-2184, June, 2015.

[7] Z.-E. Huang, J.-Y. Pan, Coordinative Switch Beamforming Scheduler for Guaranteed Service with Service Area Subsectorization in Next Generation Cellular Network, *IEEE Wireless Communications and Networking Conference (WCNC 2015)*, New Orleans, LA, 2015, pp. 1000-1005.

[8] S.-H. Sandra, G.-P. Emiliano, Multimedia Resource Allocation in mmWave 5G Networks, *IEEE Communications Magazine*, Vol. 53, No. 1, pp. 240-247, January 2015.

[9] Z. Yan, B. Li, X. Zuo, M. Yang, A Heuristic Clique Based STDMA Scheduling Algorithm for Spatial Concurrent Transmission in mmWave Networks, *2015 IEEE Wireless Communications and Networking Conference (WCNC)*, New Orleans, LA, 2015, pp. 1036-1041.

[10] Z. Li, Z. Chen, J. Zhang, J. Zhu, N. N. Xiong, The Evolution of IoT Wireless Networks for Low-Rate and Real-Time Applications, *Journal of Internet Technology*, Vol. 18, No. 1, pp. 175-188, January, 2017.

[11] Y.-J. Ma, Y. Zhang, O. M. Dung, R. Li, D.-Q. Zhang, Health Internet of Things: Recent Applications and Outlook, *Journal of Internet Technology*, Vol. 16, No. 2, pp. 351-362, March, 2015.

[12] J. Y. Khan, D. Chen, O. Hulin, Enabling Technologies for Effective Deployment of Internet of Things (IoT) Systems, *Australian Journal of Telecommunications and the Digital Economy*, Vol. 2, No. 4, pp. 65.1-65.22, December, 2014.

[13] S. K. Agrawal, K. Sharma, 5G Millimeter Wave (mmwave) Communications, *2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom)*, New Delhi, India, 2016, pp. 3630-3634.

[14] D.-J. Chiang, Real-Time Data Delivering Based on Prediction Scheme over Internet of Things, *Journal of Internet Technology*, Vol. 18, No. 2, pp. 395-405, March, 2017.

[15] X.-J. Chen, B.-D. Chen, X.-M. Jiang, X.-B. Chen, W.-H. Cai, Improved Cloud Computing Architecture for the Internet of Things, *Journal of Internet Technology*, Vol. 17, No. 4, pp. 683-693, July, 2016.

[16] J.-L. Chen, H.-C. Hsieh, Y. T. Larosa, Integrated LTE Test-Bed Framework Evaluating EPC Compliance for IoT QoS Architecture, *Journal of Internet Technology*, Vol. 14, No. 2, pp. 171-179, March, 2013.

[17] P. Heydari, Invited: Integrated Millimeter-wave/terahertz Sensor Systems for Near-field IoT, *2016 53nd ACM/EDAC/IEEE Design Automation Conference (DAC)*, Austin, TX, 2016, pp. 1-6.

[18] P. F. Freidl, M. E. Gadringer, D. Amschl, W. Bcsch, mm-Wave RFID for IoT Applications, *2017 Integrated Nonlinear Microwave and Millimetre-wave Circuits Workshop (INMMiC)*, Graz, Austria, 2017, pp. 1-3.

[19] L. Kong, M. K. Khan, F. Wu, G. Chen, P. Zeng, Millimeter-Wave Wireless Communications for IoT-Cloud Supported

Autonomous Vehicles: Overview, Design, and Challenges, *IEEE Communications Magazine*, Vol. 55, No. 1, pp. 62-68, January, 2017.

[20] S. K. Agrawal, K. Sharma, Software Defined Internet of Things (IoT) in 5G Millimeter Wave (mmWave) Communication System, *International Journal of Advance Reseach in Science and Engineering*, Vol. 6, No, 7, pp. 185-192, July, 2017.

[21] Q. Xue, B. Li, X. Zuo, Z. Yan, M. Yang, Cell Capacity for 5G Cellular Network with Inter-Beam Interference, *2016 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC)*, Hong Kong, China, 2016, pp. 1-6.

[22] S. Martello, P. Toth, *Knapsack Problems: Algorithms and Computer Implementations*, John Wiley & Sons, Inc. 1990.

Biographies

Zhongjiang Yan received the B.E. and Ph.D. degree from Xidian University, Xi'an, China, in 2006 and 2011, respectively. Now he is currently an Associate Professor of Northwestern Polytechnical University, Xi'an, China. His research interests include protocols design and their FPGA implement of the networking protocol of the wireless networks.

Mao Yang received the B.S. and M.S. degrees both from Xidian University, China, and received his Ph.D. degree from Tsinghua University, China, in 2014. He is currently an Associate Professor of Northwestern Polytechnical University, China. His research interests include future mobile and wireless networking protocol and wireless resource management.

Bo Li received the B.S., M.S. and Ph.D degrees from Xidian University, Xian, China, in 1994, 1996 and 2002, respectively. He is currently with the School of Electronics and Information Engineering, Northwestern Polytechnical University, Xian, China, as a Full-Time Professor. His current research interests include broadband wireless mobile networks.

Yusheng Liang received the B.E. degree from Northwestern Polytechnical University, China, in 2015, where he is currently a master student. His research interests are in the area of wireless networking and communications, including mmWave networks, non-orthogonal multiple access for 5G and directional Ad hoc networking.

Xiaoya Zuo received the B.Sc., M.Sc., and Ph.D. degrees from Northwestern Polytechnical University, Xi'an, China, in 2005, 2008, and 2011, respectively, where he is currently an associate professor His research interests include broadband wireless communications, ultra-wideband communications, millimeter wave communication systems, and multiple-input multiple-output communication systems.