Joint Power and Channel Allocation for Multimedia Content Delivery using Millimeter Wave in Smart Home Networks

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***Abstract*—Millimeter wave (mm-wave) communication has been considered as a promising technology for providing short range, high speed data service in wireless networks. In this paper, we apply the mm-wave technology for multimedia content distribution among different wireless devices in smart home networks. We study the resource allocation problem and propose a new multi-channel medium access control (MAC) protocol considering mm-wave channelization and various types of multimedia services. We define a set of utility functions for battery-constrained devices considering different types of services in smart home networks. We formulate a joint power and channel allocation problem to maximize the aggregate network utility, which is a non-convex mixed integer programming problem. We transform the problem into a series of convex mixed integer programming problems and develop an efficient algorithm to find the solution. Simulation results show that the proposed MAC protocol has superior performance compared to the existing single-carrier MAC protocol in IEEE 802.15.3c standard.**

I. Introduction

Smart home networks enhance the in-home network performance and user experience [1], [2]. With the popularity of smart devices such as smart phones, tablets, and laptops, multimedia content delivery (e.g., video streaming and sharing) is becoming the major source of data traffic in smart home networks. Typically, multimedia content delivery is delay sensitive and requires high data rate, which consumes more energy than other low data rate services. However, many portable devices in smart home networks are battery-powered and have a limited lifetime when performing multimedia content delivery. Therefore, to improve the performance of multimedia content delivery in smart home networks, it is important to design efficient resource management schemes (such as channel allocation and power control) to achieve high data rate with low energy consumption.

Recently, millimeter-wave (mm-wave) band technology has been studied for wireless personal area networks (WPANs) and is shown to be able to provide over one gigabits per second (Gbps) data rate in a short range [3]. High data rate and small interference range make mm-wave communication a very promising technology for multimedia smart home networks. A medium access control (MAC) protocol for mm-wave communication has been standardized for WPAN – IEEE 802.15.3c, which is designed for high data rate applications such as content downloading and real time streaming [4]. Researchers have been working on designing resource allocation schemes considering the spatial reuse in WPANs [5]. However, the current protocol does not explore the diversity of mm-wave channelization and energy efficiency of the devices. To further improve users' experience for multimedia content delivery in smart home networks, it is necessary to design an energy efficient resource allocation protocol for applications with different quality of service (QoS) requirements.

In this paper, we consider a scenario where multiple user pairs deliver multimedia content in smart home networks. The wireless devices require different types of services with various QoS constraints. We consider multi-channel mm-wave communication and study the resource allocation problem. The main contributions of this paper are as follows:

- We propose a multi-channel MAC protocol based on the IEEE 802.15.3c standard which enables multiple channel time allocations (CTAs) to be assigned to different user pairs at a given time and substantially improves the throughput and aggregate network utility.
- We propose utility functions for battery-constrained multimedia devices, and formulate the channel and power allocation problem as a non-convex mixed integer programming problem aiming at maximizing the aggregate network utility. We transform the problem into a series of convex mixed integer programming problems, and design a greedy algorithm to solve the transformed problems, which is more efficient than the standard generalized Benders decomposition (GBD) method.
- Simulation results show that the proposed MAC protocol achieves higher aggregate network utility than the IEEE 802.15.3c protocol in multimedia smart home networks.

The rest of this paper is organized as follows. In Section II, we describe the system model and propose the multi-channel MAC protocol. In Section III, we formulate the network utility maximization problem. An efficient algorithm is proposed in Section IV. Simulation results are presented in Section V, and conclusions are drawn in Section VI.

II. System Model

We consider a smart home network with a set of battery-constrained devices such as laptop computers, tablets, and wireless game controllers, randomly deployed in a living space

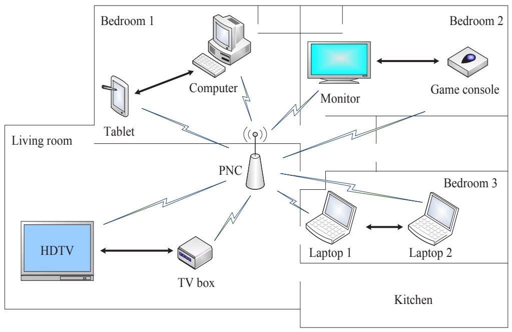

Fig. 1. An example of smart home network in a 3-bedroom apartment.

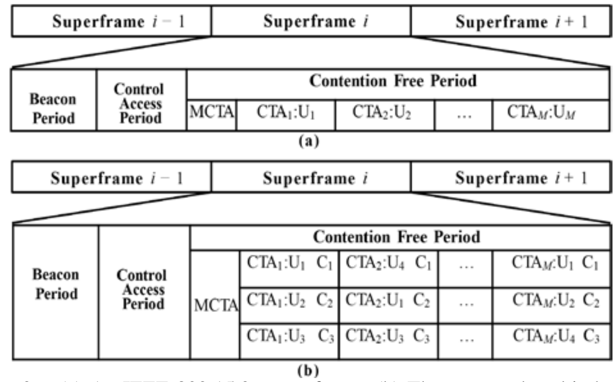

Fig. 2. (a) An IEEE 802.15.3c superframe. (b) The proposed multi-channel superframe with three channels enabled simultaneously.

(e.g., an apartment). We consider the devices are delivering multimedia content in pairs. We denote $\mathcal{Q}$ as the set of all links, where each link represents a transmitting user pair. According to the IEEE 802.15.3c standard, wireless devices can autonomously form a piconet. One device is selected as the piconet coordinator (PNC) as shown in Fig. 1.

A. Channel Model

We consider mm-wave transmission in the physical layer, which operates at the frequency band from 57 GHz to 64 GHz. There are three channels (C_1, C_2, C_3) in this range for American channelization according to the IEEE 802.15.3c standard. Each channel has a bandwidth of 2160 MHz. We adopt the wireless channel model in the IEEE 802.15.3c WPAN standard [6], which is proposed specifically for mm-wave communication. We consider the impact of path loss and shadowing. In an indoor environment (e.g., inside an office building or a residential house), the channel gain for link $i \in \mathcal{Q}$ can be represented as $h_i = L(d_i) + X_\sigma$, where d_i is the distance between the source device and the destination device of link i, $L(\cdot)$ is the path loss function with respect to the distance, and X_σ is a zero-mean Gaussian random variable that models the shadowing effect.

According to the IEEE 802.15.3c standard, the path loss function $L(d_i)$ can generally be modeled as follows [6]

$$L(d_i) = \begin{cases} L_{FS}(d_i), & d_i \leq d_{BP}, \\ L_{FS}(d_{BP}) + n10\log_{10}(\frac{d_i}{d_{BP}}), & d_i > d_{BP}, \end{cases} \quad (1)$$

where n and d_{BP} are constants depending on the environment. The term $L_{FS}(\cdot)$ is the path loss function for free space transmission. We notice that the path loss $L(d_i)$ is frequency dependent. That is, the parameter n and $L_{FS}(d_{BP})$ may vary with respect to the carrier frequency. The frequency dependence is considered in our proposed MAC. The list of parameters for different channels can be found in [6].

We use p_i to represent the transmission power of the transmitting device of link $i \in \mathcal{Q}$. The achievable data rate for this link is

$$R_i = \eta B \log_2\left(1 + \frac{p_i h_i}{N_0}\right), \quad (2)$$

where B is the bandwidth, $\eta \in [0, 1]$ is the efficiency of the transceiver design, and N_0 is the noise power.

B. Multi-channel MAC for Smart Home Networks

In the considered smart home network, the home gateway acts as the PNC. The existing MAC in the IEEE 802.15.3c standard is based on a superframe structure as shown in Fig. 2 (a). Each superframe begins with a beacon period for network synchronization and control message broadcast. After the beacon period, devices send requests to PNC during the contention access period (CAP). The remaining time of the superframe is the contention free period, which consists the management channel time allocation (MCTA) and multiple channel time allocation (CTA) slots for data transmission. In the standard, during the contention free period, each CTA slot is allocated to one transmission pair exclusively using the time division multiple access (TDMA) scheme as shown in Fig. 2 (a). However, this MAC protocol is originally designed for ultra-wideband communication. The non-overlapping channels in mm-wave band are not efficiently utilized using this protocol.

In this paper, we consider the following practical modification for the 802.15.3c MAC: As shown in Fig. 2 (b), during the contention free period, all three mm-wave channels (C_1, C_2, C_3) are enabled and allocated to different transmission pairs by the PNC according to a certain criterion. This modification is practical and only requires minor changes to the MCTA time periods: the PNC needs to broadcast the channel allocation decisions and user pair IDs during MCTA. For the case of Fig. 2 (b), we fully exploit the three channels in the mm-wave band without any co-channel interference.

For each communication pair, considering the overhead (i.e., beacon and MCTA) and the number of allocated CTA slots, the effective throughput is proportional to the capacity of the assigned channel. We define $\mathcal{M}$ as the set of CTA slots in each superframe, and $\mathcal{C}$ as the set of available mm-wave channels. We further define $p_i^{m,c}$ as the transmission power at the transmitting device of link i and $h_i^{m,c}$ as the corresponding channel gain of the link on channel c in CTA slot m. The effective throughput r_i for link i can be modeled as

$$r_i = \frac{\eta B L_{CTA}}{L_{SF}} \sum_{m\in\mathcal{M}} \sum_{c\in\mathcal{C}} \log_2\left(1 + \frac{p_i^{m,c} h_i^{m,c}}{N_0}\right), \quad (3)$$

where L_{SF} is the length of the superframe. $p_i^{m,c} \in [0, p_i^{\max}]$ where $p_i^{\max}$ is the maximum power allowed for the transmitting device of link i. We define $\boldsymbol{p}_i$ as the power allocation decision for the transmitting device of link i, where $\boldsymbol{p}_i = (p_i^{1,1}, \cdots, p_i^{1,|\mathcal{C}|}, p_i^{2,1}, \cdots, p_i^{2,|\mathcal{C}|}, \cdots, p_i^{|\mathcal{M}|,|\mathcal{C}|})$. Under the proposed multi-channel MAC protocol, to find the optimal resource allocation at the PNC is equivalent to finding the optimal $\boldsymbol{p}_i$ for each link i under certain optimization objective, since the value of $p_i^{m,c}$ implies whether the CTA slot m on channel c is allocated ($p_i^{m,c} > 0$) or not ($p_i^{m,c} = 0$). In this paper, we aim to maximize the aggregate network utility, which is discussed in the following subsection.

C. Utility Functions

In the remaining part of the paper, we use the terms *link* and *user* interchangeably. We define utility functions to characterize the users' experience in sharing different types of multimedia content. We consider typical applications and usage scenarios proposed by the IEEE 802.15.3c standardization group as follows [7]: **S1**) Uncompressed video streaming: HDTV signal transmission with adaptive modulation coding, which requires a data rate from 0.95 Gbps to 3.8 Gbps; **S2**) Workstation desktop and conference ad-hoc: for signal transmission between computer devices or in an ad-hoc network. The data rate required for this scenario is 1.54 Gbps–5.87 Gbps; **S3**) Kiosk file downloading: video and music downloading on portable devices. No minimum data is required for this scenario. We define $\mathcal{S}_1$, $\mathcal{S}_2$, $\mathcal{S}_3$ as the sets of links that use service S1, S2 and S3, respectively. For link $i \in \mathcal{Q}$, we define the utility function of the corresponding user pair as

$$U_i(\boldsymbol{p}_i) = w_i^r U_i^r(r_i(\boldsymbol{p}_i)) + w_i^p U_i^p(\boldsymbol{p}_i), \tag{4}$$

where $U_i^r(r_i(\boldsymbol{p}_i))$ characterizes users' satisfaction about the effective throughput $r_i(\boldsymbol{p}_i)$, $U_i^p(\boldsymbol{p}_i)$ is a function representing the energy consumption, w_i^r and w_i^p are weighting factors that balance the utility about throughput and energy consumption. This utility function is suitable for characterizing users' experience when both throughput and energy are major concerns, i.e., running video streaming on battery-constrained devices.

We propose a general function $U_i^r(\cdot)$ for different service scenarios in the IEEE 802.15.3c standard as follows

$$U_i^r(\boldsymbol{p}_i) = \begin{cases} 0, & r_i(\boldsymbol{p}_i) < r_i^{\min}, \\ \Phi_i(r_i(\boldsymbol{p}_i)), & r_i(\boldsymbol{p}_i) \geq r_i^{\min}, \end{cases} \tag{5}$$

where $\Phi_i(\cdot)$ represents the satisfaction in regard to the effective throughput $r_i(\boldsymbol{p}_i)$, which is defined in (3), and $r_i^{\min}$ is the minimum data rate required by link i. This function implies that when the effective throughput is less than the minimum requirement, users are not satisfied at all (function value is 0). For the service in scenarios S1 and S2 (such as video streaming or conference ad-hoc) which requires a minimum data rate ($r_i^{\min} > 0, i \in \mathcal{S}_1 \bigcup \mathcal{S}_2$), we use a quasi-concave function to characterize the users' satisfaction with respect to the effective throughput. That is,

$$\Phi_i(r_i) = K_{1i} \ln(1 + K_{2i} \log_2(1 + (r_i - r_i^{\min}))), \tag{6}$$

where coefficients K_{1i} and K_{2i} are the application dependent parameters. It can be seen that a user's satisfaction increases quickly at the beginning when the minimum data rate is achieved and then the marginal increment becomes smaller as the data rate becomes higher. This satisfaction function is widely used for delay sensitive applications [8].

For the service in scenario S3 (such as file downloading) which does not have a minimum rate requirement ($r_i^{\min} = 0, i \in \mathcal{S}_3$), we use a linear function $\Phi_i(r_i) = K_{3i} r_i$, where K_{3i} is a user dependent parameter. Note that in this scenario, we also have $U_i^r(\boldsymbol{p}_i) = \Phi_i(r_i(\boldsymbol{p}_i))$.

Since high energy consumption reduces battery lifetime, the user's utility decreases with respect to the transmission power when using the battery-constrained devices. We use a linear function to model the relation between average transmission power per CTA slot and users' experience [9]. We define

$$U_i^p(\boldsymbol{p}_i) = -\frac{L_{CTA}}{L_{SF} L_i} \sum_{m \in \mathcal{M}} \sum_{c \in \mathcal{C}} p_i^{m,c}, \tag{7}$$

where L_i is a number that characterizes the battery's capacity of the transmitting device of link i.

III. Problem Formulation

In the proposed multi-channel MAC in Section II-B, we regard each CTA slot in a given channel as a resource block (RB). The PNC is responsible for allocating the RBs to all links according the proposed MAC to optimize the network performance. In this paper, we consider the aggregate network utility as a performance criterion. However, the utility of each transmission pair is not only related to the amount of RBs allocated to them, but also depends on the transmission power of the transmitting device. Therefore, to find the optimal resource allocation decisions at the PNC and the transmission devices, we formulate a joint power and channel allocation problem as follows. We define $x_i^{m,c} \in \{0,1\}, m \in \mathcal{M}, c \in \mathcal{C}$ as an indicator whether CTA slot m in channel c is allocated to link i and $\boldsymbol{x}_i = (x_i^{1,1}, \cdots, x_i^{1,|\mathcal{C}|}, x_i^{2,1}, \cdots, x_i^{2,|\mathcal{C}|}, \cdots, x_i^{|\mathcal{M}|,|\mathcal{C}|})$. We further define $\boldsymbol{p}$ as the set of the transmit power decision and $\boldsymbol{x}$ as the set of channel allocation decision for all the user pairs, where $\boldsymbol{p} = \{\boldsymbol{p}_1, \boldsymbol{p}_2, \cdots, \boldsymbol{p}_i, \cdots, \boldsymbol{p}_{|\mathcal{Q}|}\}$ and $\boldsymbol{x} = \{\boldsymbol{x}_1, \boldsymbol{x}_2, \cdots, \boldsymbol{x}_i, \cdots, \boldsymbol{x}_{|\mathcal{Q}|}\}$. Then, the utility maximization problem can be formulated as

$$\underset{\boldsymbol{x},\boldsymbol{p}}{\text{maximize}} \;\; U_\Sigma \triangleq \sum_{i \in \mathcal{Q}} U_i(\boldsymbol{p}_i) \tag{8a}$$

$$\text{subject to} \;\; 0 \leq p_i^{m,c} \leq x_i^{m,c} p_i^{\max}, \; \forall\, i \in \mathcal{Q}, m \in \mathcal{M}, c \in \mathcal{C}, \tag{8b}$$

$$\sum_{c \in \mathcal{C}} x_i^{m,c} = 1, \quad \forall\, i \in \mathcal{Q}, m \in \mathcal{M}, \tag{8c}$$

$$\sum_{i \in \mathcal{Q}} x_i^{m,c} = 1, \quad \forall\, c \in \mathcal{C}, m \in \mathcal{M}, \tag{8d}$$

$$x_i^{m,c} \in \{0,1\}, \quad \forall\, i \in \mathcal{Q}, m \in \mathcal{M}, c \in \mathcal{C}, \tag{8e}$$

where constraint (8b) guarantees that the power consumed by link i is no greater than $p_i^{\max}$, constraint (8c) indicates that each link can only utilize one channel during a time slot, and constraint (8d) implies that one RB cannot be allocated to multiple links (to avoid co-channel interference). Note that the objective function (8a) is not concave in general, since users requesting services in S1 and S2 have quasi-concave utility functions, as discussed in Section II-C. Moreover, the RB allocation variables are binary. Thus, problem (8) is a non-convex mixed integer programming problem, which is in general hard to solve. In the following subsection, we transform the problem into a series of subproblems with concave objective function. Such transformation is based on the following lemma.

Lemma 1. *When the optimum solution* $(\boldsymbol{x}^*, \boldsymbol{p}^*)$ *of problem (8) is achieved, for link* $i \in \mathcal{S}_1 \bigcup \mathcal{S}_2$, *we have either* $r_i(\boldsymbol{p}_i^*) \geq r_i^{\min}$ *or* $r_i(\boldsymbol{p}_i^*) = 0$.

Proof: Assume that $0 < r_i(\boldsymbol{p}_i^*) < r_i^{\min}$ for any link $i \in \mathcal{S}_1 \bigcup \mathcal{S}_2$. Then, $\boldsymbol{p}_i^*$ is not an all-zero set since the rate is non-zero. According to the utility function in Section II-C, we have $U_i(\boldsymbol{p}_i^*) = w_i^r U_i^r(\boldsymbol{p}_i^*) + w_i^p U_i^p(\boldsymbol{p}_i^*) = -w_i^p \frac{L_{CTA}}{L_{SF} L_i} \sum\limits_{m \in \mathcal{M}} \sum\limits_{c \in \mathcal{C}} p_i^{m,c*} < U_i(\mathbf{0}) = 0$, which contradicts that $\boldsymbol{p}_i^*$ is the optimal solution. Since we always have $r_i(\boldsymbol{p}_i) \geq 0$, the optimal solution $\boldsymbol{p}_i^*$ must be either $r_i(\boldsymbol{p}_i^*) \geq r_i^{\min}$ or $r_i(\boldsymbol{p}_i^*) = 0$. This completes the proof. ∎

Lemma 1 implies that to optimize the network utility, the PNC either does not allocate any RB to a link in $\mathcal{S}_1 \cup \mathcal{S}_2$, or it allocates sufficient RBs to guarantee the minimum data rate required for that link. Therefore, if the PNC decides to allocate RBs to a link $i \in \mathcal{S}_1 \bigcup \mathcal{S}_2$, the quasi-concave satisfaction function $U_i^r(\cdot)$ can be replaced by the concave function $\Phi_i(\cdot)$ and an additional constraint $r_i(\boldsymbol{p}_i) \geq r_i^{\min}$. Based on this observation, we can solve problem (8) as follows. We define $\mathcal{T}$ as the subset of links which requires a minimum data rate and is allocated RBs by the PNC. For each $\mathcal{T} \subseteq \mathcal{S}_1 \bigcup \mathcal{S}_2$, we can find the optimal network utility, denoted as $V^*(\mathcal{T})$, assuming the PNC only allocates RBs to links in $\mathcal{Q}^{\mathcal{T}} = \mathcal{T} \bigcup \mathcal{S}_3$. The problem is as follows

$$\underset{\boldsymbol{x},\boldsymbol{p}}{\text{maximize}}\ V(\mathcal{T}) \triangleq \sum_{i \in \mathcal{Q}^{\mathcal{T}}} \left(w_i^r \Phi_i \left(r_i(\boldsymbol{p}_i) \right) + w_i^p U_i^p(\boldsymbol{p}_i) \right) \quad (9a)$$

$$\text{subject to } 0 \leq p_i^{m,c} \leq x_i^{m,c} p_i^{\max}, \forall\, i \in \mathcal{Q}^{\mathcal{T}}, m \in \mathcal{M}, c \in \mathcal{C}, \quad (9b)$$

$$\sum_{c \in \mathcal{C}} x_i^{m,c} = 1, \quad \forall\, i \in \mathcal{Q}^{\mathcal{T}}, m \in \mathcal{M}, \quad (9c)$$

$$\sum_{i \in \mathcal{Q}^{\mathcal{T}}} x_i^{m,c} = 1, \ \forall\, c \in \mathcal{C}, m \in \mathcal{M}, \quad (9d)$$

$$x_i^{m,c} \in \{0, 1\}, \quad \forall\, i \in \mathcal{Q}^{\mathcal{T}}, m \in \mathcal{M}, c \in \mathcal{C}, \quad (9e)$$

$$r_i(\boldsymbol{p}_i) \geq r_i^{\min}, \quad \forall\, i \in \mathcal{T}, \quad (9f)$$

$$x_i^{m,c} = 0, \quad \forall\, i \in \mathcal{Q} \setminus \mathcal{Q}^{\mathcal{T}}, m \in \mathcal{M}, c \in \mathcal{C}. \quad (9g)$$

The optimal value of problem (8), U_Σ^*, can be found as

$$U_\Sigma^* = \max_{\mathcal{T} \subseteq \mathcal{S}_1 \cup \mathcal{S}_2} V^*(\mathcal{T}). \quad (10)$$

In problem (9), the subset $\mathcal{T}$ models the admission control process, where only links in $\mathcal{T} \bigcup \mathcal{S}_3$ are admitted for resource allocation. The objective function is concave and is equivalent to the aggregate network utility by adding the constraints (9f) and (9g) according to Lemma 1. The additional constraints indicate that all considered links in $\mathcal{T}$ must have effective throughput no less than their minimum requirements, and the links which are not considered ($i \in \mathcal{S}_1 \cup \mathcal{S}_2 \setminus \mathcal{T}$) are not allocated any RB. Note that problem (9) is a convex mixed integer programming problem, which can be solved using existing approaches such as the GBD method. By solving problem (9) for each $\mathcal{T} \subseteq \mathcal{S}_1 \bigcup \mathcal{S}_2$, we obtain the solution of the original problem according to (10).

IV. Algorithm Design

To solve problem (9), we can use the GBD algorithm, which is a standard technique to solve convex mixed integer programming problem [10]. GBD algorithm solves the problem iteratively, where in each iteration it alternatively updates the integer variables and non-integer variables by solving an integer programming subproblem and a convex optimization subproblem, respectively. The convergence of this method has been proved in [10]. However, since the set of variables is relatively large, i.e., we have 150 variables for the problem with 5 links, and we still need to solve a convex optimization subproblem and an integer programming subproblem in each iteration, it may take a long time for the algorithm to converge. Due to the complexity of GBD algorithm, it may not be applicable to the practical system which requires real time processing. In this paper, we propose a greedy algorithm to find an efficient solution to problem (9) as shown in Algorithm 1, where N_{RB} is the total number of RBs, N_{CTA} is the number of CTA slots, $t^{m,c} \in \{0, 1\}$ is a variable indicating whether CTA slot m in channel c has been allocated, $\Delta r_i(\boldsymbol{x}_i, x_i^{m,c})$ denotes the rate increment for link i if one additional RB (CTA slot m in channel c) is allocated when $p_i^{\max}$ is used, and $\Delta U_i(\boldsymbol{x}_i, x_i^{m,c})$ represents the utility increment for link i when CTA slot m in channel c is allocated.

The proposed algorithm contains two steps. In the first step, we allocate the minimum number of RBs to each link $i \in \mathcal{T}$ to guarantee their rate requirements, assuming the maximum power is used at the transmitting devices (which corresponds to Lines 3 to 11). Specifically, in each iteration, we find the link with the largest rate increment and allocate the corresponding RB to that link (as shown in Lines 4 to 5). Note that problem (9) may be infeasible when the rate requirements for all considered links cannot be satisfied simultaneously. Therefore, in Lines 6 and 11, we check the feasibility conditions, i.e., whether the total number of RBs allocated to a link is greater than the number of CTA slots and whether the rate requirement for some link is not satisfied. In the second step, we allocate the remaining RBs to all the considered links iteratively. In each iteration, we choose the RB and the corresponding link where the network utility increment is the largest if we allocate this RB to this link (as shown in Lines 13 to 15). The selection of the RB and the link also satisfies the constraint that a link cannot utilize multiple channels simultaneously (Lines 16 to 18). The algorithm terminates when all RBs have been allocated or the aggregate utility cannot be increased.

Algorithm 1 Greedy algorithm to solve problem (9)

Set $t^{m,c} := 0, \forall\ m \in \mathcal{M}, c \in \mathcal{C}$.
Set $\boldsymbol{p}_i := (p_i^{\max}, \dots, p_i^{\max}),\ \forall\ i \in \mathcal{T}$.
  While ($\mathcal{T} \neq \emptyset$ and $N_{RB} > 0$)
    Find $i \in \mathcal{T}$, $m \in \mathcal{M}$ and $c \in \mathcal{C}$, such that $t^{m,c} = 0$, $x_i^{m,c} = 0$ and $\Delta r_i(\boldsymbol{x}_i, x_i^{m,c})$ is the largest.
    Set $x_i^{m,c} := 1$, $t^{m,c} := 1$, $N_{RB} := N_{RB} - 1$.
    Return infeasible if $\sum_{m \in \mathcal{M}, c \in \mathcal{C}} x_i^{m,c} > N_{CTA}$.
    If ($r_i(\boldsymbol{p}_i) \geq r_i^{\min}$)
      Set $\mathcal{T} := \mathcal{T} \setminus \{i\}$.
    end if
  end while
Return infeasible if $\mathcal{T} \neq \emptyset$.
  While ($N_{RB} > 0$ and $\exists\ i, m, c$ such that $t^{m,c} = 0$ and $\Delta U_i(\boldsymbol{x}_i, x_i^{m,c}) > 0$)
    Find $i \in \mathcal{Q}^{\mathcal{T}}$, $m \in \mathcal{M}$ and $c \in \mathcal{C}$, such that $t^{m,c} = 0$ $x_i^{m,c} = 0$ and $\Delta U_i(\boldsymbol{x}_i, x_i^{m,c})$ is the largest.
    Set $x_i^{m,c} := 1$, $t^{m,c} := 1$, $N_{RB} := N_{RB} - 1$.
    Update the optimal power $\boldsymbol{p}_i$.
    If ($\sum_{m \in \mathcal{M}, c \in \mathcal{C}} x_i^{m,c} = N_{CTA}$ or $\nexists\ m, c$ such that $t^{m,c} = 0$ and $\Delta U_i(\boldsymbol{x}_i, x_i^{m,c}) > 0$)
      Set $\mathcal{Q}^{\mathcal{T}} := \mathcal{Q}^{\mathcal{T}} \setminus \{i\}$.
    end if
  end while

In Algorithm 1, we allocate one RB in each iteration. Therefore, the maximum number of iterations of this algorithm is N_{RB}, which is relatively small. Since the computation in each iteration is simple, the algorithm can find the solution faster than the standard GBD algorithm. It has been shown that this type of greedy algorithm can achieve optimal solution for convex mixed integer programming problem when the channel gain for a link is independent and identically distributed (i.i.d.) in different time slots [11]. We will evaluate the performance of the greedy algorithm and the standard GBD algorithm in the next section. Based on Algorithm 1, the solution to problem (8) can be found according to (10).

The procedures of the proposed MAC protocol can be summarized as follows:

i) The PNC collects the network information such as topology information and service requirements via beacon frame.

ii) The PNC finds the optimal resource allocation decision by solving problem (8) according to Algorithm 1 and (10).

iii) The PNC informs each user pair the RBs allocated to them and their optimal transmission power during the CAP.

iv) All links that obtain RBs start data transmission in their assigned RBs with the optimal power.

Note that in practice the PNC cannot obtain exact channel gain information of each link ($h_i^{m,c}$) for future time slots due to the random shadowing effect. Therefore, when solving problem (8), the PNC uses the estimated channel gain (i.e., average channel gain obtained via simulation).

V. Performance Evaluation

In this section, we evaluate the performance of the proposed MAC protocol. We consider the devices are randomly located in a $20 \times 20\ m^2$ region. For each link, the average distance between the transmitting and receiving device is $1.5\ m$. The bandwidth of each channel is 2.16 GHz, and the noise power spectrum density is -174 dBm/Hz. The service requested by each user pair is randomly selected from $\mathcal{S}_1$, $\mathcal{S}_2$ and $\mathcal{S}_3$. The parameters for channel model are from the IEEE 802.15.3c standard [6]. Other simulation parameters are $K_{1i} = 1, K_{2i} = 0.7, r_i^{\min} = 0.95$ Gbps, $\forall\ i \in \mathcal{S}_1$, $K_{1i} = 1.5, K_{2i} = 1, r_i^{\min} = 1.54$ Gbps, $\forall\ i \in \mathcal{S}_2$, $K_{3i} = 0.15, \forall\ i \in \mathcal{S}_3$, $w_i^r = 1$, $w_i^p = 1000$, $L_i = 100, \forall\ i \in \mathcal{Q}$ and $\eta = 0.7$. For fair comparison, we allow existing MAC in IEEE 802.15.3c standard use the aggregate bandwidth of three considered channels.

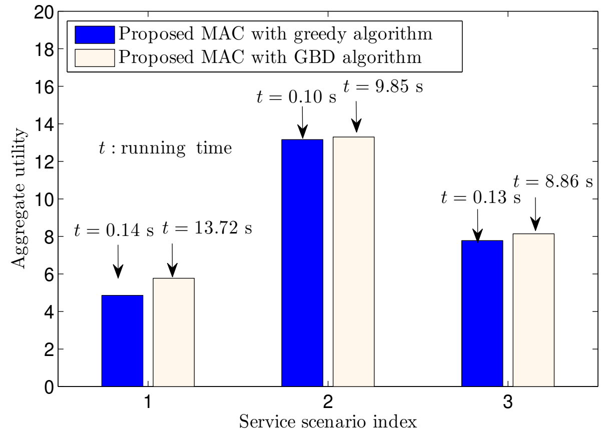

Fig. 3. Aggregate utility versus usage scenarios.

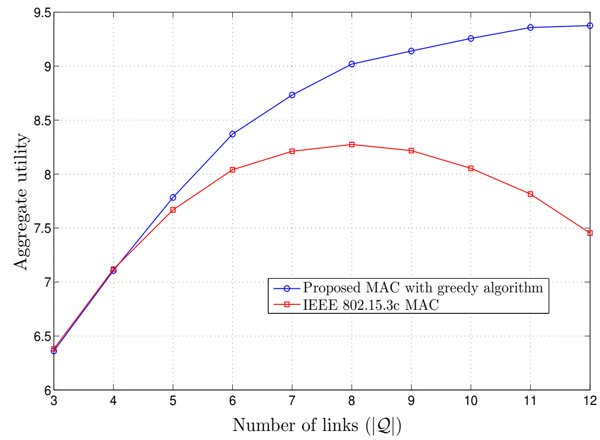

Fig. 4. Aggregate utility versus number of links.

We first compare the performance of the proposed MAC with greedy algorithm and GBD algorithm. Fig. 3 shows the aggregate network utility with respect to different service scenarios, where we fix the number of links to be 6. We also include the average running time per simulation for both algorithms in each scenario. It is shown that the greedy algorithm achieves 84% of the performance compared to the GBD algorithm in service scenario S1. In service scenarios S2 and S3, the aggregate utilities of both algorithm are almost the same. However, the running time using GBD is much longer than the greedy algorithm, as indicated in Fig. 3, which demonstrates the efficiency of the proposed algorithm.

Next, we compare the performance of the proposed MAC with the existing MAC in IEEE 802.15.3c standard. Fig. 4 shows the aggregate network utility versus different number of links $|\mathcal{Q}|$. It is shown that the proposed MAC outperforms the existing IEEE 802.15.3c MAC when $|\mathcal{Q}|$ is greater than 4, and the performance gap becomes larger as $|\mathcal{Q}|$ increases.

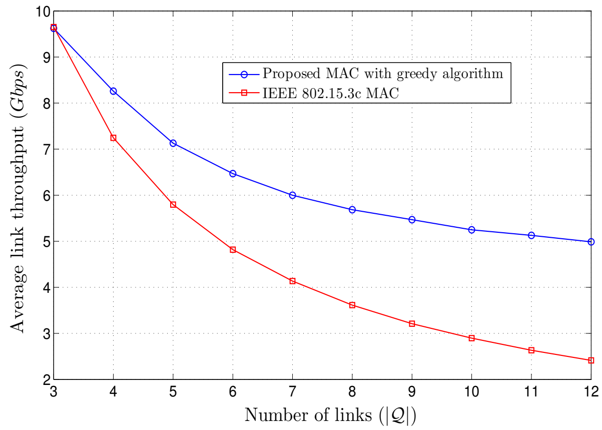

Fig. 5. Average throughput of an active link versus number of links.

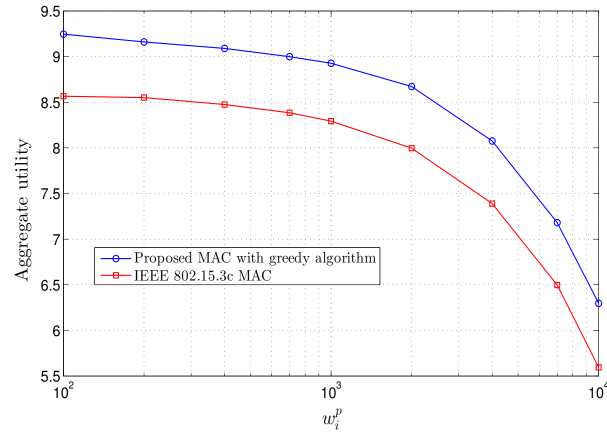

Fig. 6. Aggregate utility versus w_i^p.

The reason is that as the number of links increases, there are more available CTA slots in a superframe, and the proposed MAC maximizes the aggregate network utility considering the diversity of channel gains in each CTA slot. However, the existing IEEE 802.15.3c MAC uses a round-robin scheduling algorithm, which allocates equal number of CTA slots to each link. Therefore, the existing MAC may decrease the aggregate utility since some links may have negative utilities.

Fig. 5 shows that the average throughput of an active link decreases with respect to different number of links $|\mathcal{Q}|$. When the number of links increases, the average amount of resources allocated to a link becomes smaller, which reduces the average throughput of an active link. We observe that the throughput decrement of the proposed MAC is smaller than that of the IEEE 802.15.3c MAC. The reason is that the proposed MAC performs admission control when optimizing the network utility, as discussed in Section III, and only the admitted links share the resources. Therefore, the throughput of each admitted (or active) link does not decrease much. However, using the IEEE 802.15.3c MAC, the resources are shared by all links in $|\mathcal{Q}|$ using TDMA, and the throughput for each link changes with a factor of $1/|\mathcal{Q}|$.

In Fig. 6, we show the aggregate network utility with respect to different values of w_i^p, where $|\mathcal{Q}| = 8$. It is shown that the aggregate utility decreases as w_i^p increases. This is because when w_i^p increases, energy consumption is considered to have a greater weight in the utility function, as shown in (4), which decreases the utility of each link. However, the proposed MAC protocol achieves at least 13% gain compared to the existing IEEE 802.15.3c MAC under different values of w_i^p.

VI. Conclusion

In this paper, we proposed a novel multi-channel MAC for multimedia content delivery in mm-wave based smart home networks. We formulated a joint power and channel allocation problem to optimize the aggregate network utility, which is a non-convex mixed integer programming problem. We transformed the problem into a series of convex problems, and designed an efficient greedy algorithm to find the solution. Simulation results showed that our proposed MAC has superior performance compared to the existing IEEE 802.15.3c MAC protocol. This paper considered resource allocation in a single piconet without interference. In the future work, we will study resource allocation further for multiple coexisted piconets. We will also investigate the resource management problem in IEEE 802.11ad mm-wave based WLANs, and consider the possible co-channel interference.

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