# Network Formation Game for Multi-Hop Wearable Communications over Millimeter Wave Frequencies

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***Abstract*—In this paper, the use of multi-hop, device-to-device communications over millimeter wave (mmW) frequencies is studied for effective wearable communications. In particular, a problem of uplink communications is studied for a wearable network, in which each wearable device aims to form a multi-hop path over mmW to access a cellular base station, in order to overcome the high channel loss caused by mmW attenuation and blockage. To analyze the optimal selection of the uplink path, a network formation game is formulated between all wearable devices. In this game, each wearable device autonomously chooses the uplink path that maximizes its quality-of-service that captures the tradeoff between rate, delay, and privacy. To solve this game, a novel algorithm that combines best response dynamics with mixed-strategy techniques is proposed to find the mixed Nash network, which corresponds to a stable uplink structure at which no wearable device can improve its utility by changing its network formation decision. Simulation results show that the proposed game approach improves the average utility per wearable device of over $14\%$ and $78\%$, respectively, compared with the direct transmission and the nearest next-hop schemes.**

## I. Introduction

The next decade will witness an unprecedented proliferation of wearable devices, such as smart watches, augmented-reality glasses, and fitness trackers, among others. These wearable devices can work collaboratively to form a body-surrounding network and provide the human wearers with comprehensive services, such as health monitoring, and interactive entertainment [1]. However, the success of the deployment of wearable devices is contingent upon enabling existing wireless networks to integrate a massive number of such devices. Given the congestion of sub-6 GHz frequency bands, recently, there has been significant interest [1], [2] in using millimeter waves (mmWs) to enable large-scale wearable communications.

MmW frequencies encompass the bands ranging from 30 to 300 GHz. The idea of using mmW to deploy wearable networks stems from its large unexploited spectrum, which is believed to have over 60 GHz available band. Due to the isolation from the current commercial frequencies, mmW can support wearable communications, without degrading the performance of existing communication systems. Moreover, the abundant frequency resource can potentially support the wearable devices with a larger bandwidth and more communications channels, which can potentially provide significant improvements in the transmission reliability of the wearable devices.

However, communications over mmW frequencies face many challenges. The smaller wavelengths of mmW, compared with the sub-6 GHz spectrum, will result in a faster signal degradation. In order to overcome the serious path loss, beamforming can be used to increase the channel gain of the mmW transmissions. However, mmW is also highly sensitive to blockage from common objects, such as a wall and a human body, which will effectively lead to a serious signal attenuation. Several recent works [3]–[5] have studied a multi-hop transmission scheme to improve the communication reliability over mmW in presence of the obstacles.

The authors in [3] consider a wireless personal area network (WPAN) and present a cross-layer model to study a multi-hop medium access control architecture at the 60 GHz band. The authors in [4] propose a multi-hop selection metric, as well as a concurrent transmission scheme to exploit the data rate of a mmW-based WPAN. The recent work in [5] studies a centralized multi-hop routing approach that maximizes the traffic amounts for the multi-hop links in a mmW-based cellular network. However, these existing works [3]–[5] either focus on the individual mmW links without providing a comprehensive analysis from a system level, or do not propoerly capture the unique characteristic of mmW communications, such as the sensitivity to blockage, etc.

The main contribution of this paper is to develop a novel framework using which wearable devices autonomously establish a multi-hop network. An uplink communication scenario is studied, where each wearable device aims to form a multi-hop path over mmW to access the base station (BS), as well as to maximize the uplink quality-of-service (QoS), in terms of rate, delay and privacy. We model the problem as a network formation game between wearable devices to analyze the optimal uplink transmissions. To solve this game, an iterative algorithm, based on the best response dynamics and the mixed strategy approach, is proposed to find the mixed Nash equilibrium (NE), which corresponds to a stable network architecture. The proposed approach guarantees the existence of a mixed NE, while also reducing the complexity of finding the mixed NE. Simulation results show that the proposed game approach significantly improves the average utility of uplink transmissions per wearable device, compared with the conventional direct-transmission scheme and the nearest next-hop approach.

The rest of the paper is organized as follows. Section II presents the system model. The network formation game formulation and solution are proposed in Section III. Simulation results are presented in Section IV. Finally, conclusions are drawn in Section V.

## II. System Model

Consider the uplink of an indoor wireless cellular network consisting of one BS and $M$ human users. Each user is equipped with one mobile phone and $L$ wearable devices (WDs). Let $m$ denote the BS, $\mathcal{I}$ be the set of all WDs, where $|\mathcal{I}| = M \times L$, and $\mathcal{J}$ be the set of all mobile phones. Then, the set of all communication devices in this system is $\mathcal{N} = \mathcal{I} \cup \mathcal{J} \cup \{m\}$. In this model, the WDs transmit data via mmW bands, while the cellular communications between the BS and mobile phones use the sub-6 GHz spectrum. However, we assume that the BS and phones can work both over the mmW and sub-6 GHz frequencies. Therefore, all communication devices in $\mathcal{N}$ can receive mmW signals. Furthermore, we assume that each WD has a dedicated mmW channel, through which it can transmit data directly to the BS. However, such direct communication may not be reliable, as the signal-to-noise-ratio (SNR) of mmW channels is highly susceptible to blockage. Therefore, in order to improve the uplink QoS, the WD can choose one device in $\mathcal{N}$ as its next hop to receive and forward its messages to the BS. The possible next hop can be any other phone or WD. Once the next hop is determined, each WD automatically inherits the uplink path of the next hop, and the uplink path of itself is determined. Naturally, the uplink path of some WD can be multi-hop.

To mathematically represent the architecture of the wearable network in the uplink, a directed graph $G = (\mathcal{N}, \mathcal{E})$ is introduced, where $\mathcal{N}$ is the set of all communication nodes, and $\mathcal{E}$ is the set of directed edges, which correspond to the uplink traffic flows. A directed link from device $i$ to $j$ is denoted as $(i, j)$, and $\mathcal{E}$ is the set of all existing links in $G$. Then, the path $p_i$ from a WD $i \in \mathcal{I}$ to the BS is defined as a sequence of nodes $i_1, i_2, \cdots, i_K$ ($i_k \in \mathcal{N}$) such that $i_1 = i$ is the WD itself and $i_K = m$ is the BS. Since the choice of the next hop determines the uplink path, we denote the uplink path of WD $i$ with a given next hop $i_2$ as $p_i(i_2)$, where $p_i(i_2) = \{(i_k, i_{k+1}) \in \mathcal{E} | k = 1, \cdots, K-1\}$. Note that, for each mobile phone $j \in \mathcal{J}$, the next hop is always the BS, therefore, its uplink is a one-hop path, denoted by $p_j(m) = \{(j, m)\}$. Next, we may abbreviate the uplink path of device $i$ to be $p_i$ if its next hop is not explicit.

Fig. 1 shows an illustrative example of a wearable network within a cellular system. However, such a network architecture does not necessarily maximize the system performance, since the blockage may occur over the mmW channel, which significantly decreases the QoS of the mmW transmission. If so, the involved WD has an incentive to improve the uplink communication by changing the current next hop to some other device, which exhibits a better multi-hop channel. Consequently, our goal is to study how each WD can determine the most efficient multi-hop path to transmit its data to the BS. However, prior to analyzing this network formation process, we need to define the QoS metrics, which each WD can use to evaluate an uplink path, considering three aspects: rate, delay, and privacy, as detailed next.

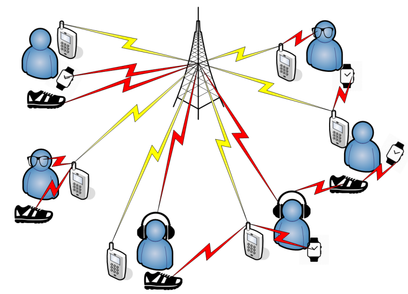


Fig. 1: An illustrative example of the uplink network, where the yellow links denote the cellular channels over sub-6 GHz frequency, and the red links are the wearable communications over mmW.

### A. Transmission Capacity

Since emerging emerging image-based WDs, such as interactive augmented reality glasses, can require a high data rate [6], the communication capacity will be a significant parameter to evaluate the multi-hop transmission for future wearable networks.

*1) Channel Model:* The human body is modeled as a circle to represent the blockage area of the mmW communication links [6]. The most common statistical model, based on the real-world measurements in [7], describes the average path loss and fading value of a mmW link $(i, j)$ in dB as follows:

$$\ell_{ij} = a_{ij} + b_{ij} \log_{10}(||\boldsymbol{x}_i - \boldsymbol{x}_j||) + n_{ij} \log_{10}(f_{ij}) + z_{ij}, \quad (1)$$

where $a_{ij}$, $b_{ij}$ and $n_{ij}$ are the path loss parameters for mmW communications, $\boldsymbol{x}_i$ and $\boldsymbol{x}_j \in \mathbb{R}^2$ represent the location of transmitter $i$ and receiver $j$ with $||\cdot||$ being their distance in meters, $f_{ij}$ denotes the carrier frequency of the link $(i, j)$, and $z_{ij}$ is the shadow fading term of mmW. For the line of sight and non-line-of-sight links over mmW, different of parameters will be applied according to the link state. The typical parameter values are available in [7]. The linear value of such channel model is given as $h_{ij} = 10^{-0.1\ell_{ij}}$.

The path loss of the cellular communications between mobile phones and the BS follows a similar model to (1), but with different parameters, which are available in [8].

*2) Antenna Gain:* In order to compensate for the high attenuation, mmW WDs will typically implement beamforming through directional antenna arrays [9]. For a mmW link $(i, j)$, where $i \in \mathcal{I}$, the overall antenna gain $g_{ij}(\boldsymbol{x}_i, \boldsymbol{x}_j)$ is a function of the coordination pair of transmitter $i$ and receiver $j$ [1]. To facilitate the model, here, we assume a perfect beam alignment between mmW transceivers [6]. Therefore, the function is simplified as $g_{ij} = g_i \cdot g_j$, where $g_i$ and $g_j$ are the main-lobe antenna gains of device $i$ and $j$. For the transceiver in the cellular communications, we assume the single-antenna devices with a constant gain.

*3) Achievable Transmission Rate:* The channel capacity for a general wireless link $(i, j)$ can be given as:

$$c_{ij} = w_{ij} \log_2 \left(1 + \frac{g_{ij} P_i h_{ij}}{w_{ij} N_j + I_{ij}}\right), \quad (2)$$

where $w_{ij}$ is the bandwidth of link $(i, j)$, $P_i$ denotes the transmission power of device $i$, $N_j$ is the noise power density, and $I_{ij}$ represents the interference at receiver $j$. The bandwidth for each mmW link is equal to the total available bandwidth divided by the number of WDs. Here, considering the impenetrability of mmW over obstacles and the dedicated channel for each WD, we assume that $I_{ij} = 0, \forall i \in \mathcal{I}$. However, for the cellular communication links, the interference $I_{ij}, i \in \mathcal{J}, j = m$ is equal to the sum of the received power of co-channel signals from the adjacent cells.

Further, we assume that, for each device in $\mathcal{N}$, the transmitting and receiving antennas are separated. Then, given (2), the achievable end-to-end data rate of an uplink path $p_i$ can be defined as the minimum capacity among all the hops along this path. Let $K_i = |p_i|$ be the number of nodes on path $p_i$, the average uplink rate, which WD $i$ can achieve over path $p_i$, will be [10]:

$$c_i(p_i) = \min_{(i_k, i_{k+1}) \in p_i} c_{i_k i_{k+1}}, \ \forall k = 1, \cdots, K_i - 1. \quad (3)$$

### *B. Latency*

One key metric for multi-hop transmission is latency which stems from the multiple hops on the transmission path from the source to the destination, as well as from the potential buffering at each node on the path [11].

Here, we model each device $i \in \mathcal{N}$ as a data source, which sends packet to its next hop following a Poisson process with an average rate of $\lambda_i$. At each node, an *M/D/1 queuing* [12] model is adopted, and the incoming packets are stored and transmitted in a *first-in-first-out* fashion. Let $\tau_{ij}$ be the latency, experienced by a packet of $B$ bits, on a general link $(i, j) \in \mathcal{E}$. As shown in [12], the average delay will be:

$$\tau_{ij}(G) = \begin{cases} \dfrac{\lambda_{ij}}{2\mu_{ij}(\mu_{ij} - \lambda_{ij})} + \dfrac{1}{\mu_{ij}}, & \mu_{ij} > \lambda_{ij}, \\ \infty, & \mu_{ij} \leq \lambda_{ij}, \end{cases} \quad (4)$$

where $\lambda_{ij} = \sum_{(i,j) \in p_k, k \in \mathcal{N}} \lambda_k$ is the amount of traffic load flowing on the link $(i, j)$, which is equal to the sum of data from the nodes $k \in \mathcal{N}$, whose uplink path $p_k$ includes $(i, j)$. Here, $1/\mu_{ij} = B/c_{ij}$ is the transmission delay over link $(i, j)$. If $\mu_{ij} > \lambda_{ij}$, which indicates the arrival rate of data is smaller than the capacity of the link, the term $\lambda_{ij}/(2\mu_{ij}(\mu_{ij} - \lambda_{ij}))$ captures the waiting time in the queue of node $i$ before the arriving packet can be sent out. Therefore, the first equation in (4) represents the time interval for a packet to pass through link $(i, j)$, when $\mu_{ij} > \lambda_{ij}$. However, for $\mu_{ij} \leq \lambda_{ij}$, the transmission over $(i, j)$ will be congested at node $i$, and the new upcoming packets will experience a large latency before they can be sent to node $j$. Here, for simplicity, such latency is treated as infinite. Note that, the traffic load of each link $(i, j)$ is the traffic sum of all lower branches of the node $i$. Therefore, the latency $\tau_{ij}$ depends not only on the uplink path of WD $i$, but also on all other nodes $\{k | (i, j) \in p_k\}$ that select $i$ as an immediate node on their paths. Therefore, $\tau_{ij}$ should be a function of a subnetwork of $G$, instead of only $p_i$.

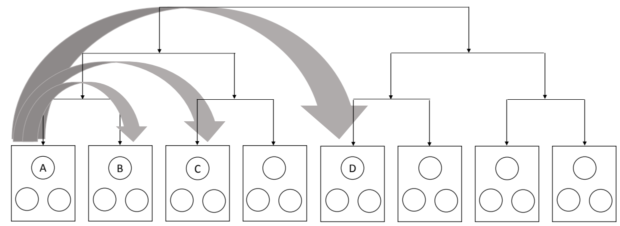


Fig. 2: The binary tree model of the society distance. For example, the social distance between user A and user B is one, the distance between A and C is two and the distance between A and D is three.

Given the latency of each link $(i, j) \in \mathcal{E}$, the latency experienced by a device $i$ to send a packet though the uplink path $p_i$ will be given by:

$$\tau_i(G) = \sum_{(i_k, i_{k+1}) \in p_i} \tau_{i_k i_{k+1}}, \ \forall k = 1, \cdots, K_i - 1. \quad (5)$$

### *C. Privacy Consideration*

Given that WDs are typically affixed to humans, several privacy concerns may arise during multi-hop communications. In order to get a better service, the WD can choose other nodes to forward its messages to the BS. However, as the intermediate nodes on the uplink path could tap into the content, the privacy of the user may be compromised. To avoid any disclosure of private information, in addition to the use of standard encryption techniques, each WD will have a motivation to choose the devices belonging to a trustworthy person to form an uplink path, instead of those that belongs to less trustworthy users.

To capture such privacy concerns, we introduce a binary tree model [13] to formulate the *distance of affinity* between different users, as well as their devices. Note that, the social tree model is independent from the communication architecture of the wearable network. As shown in Fig. 2, for any two given device $i$ and $j$ located on the leaves of the binary tree, the affinity distance $d_{ij}$ is defined as the number of layers to ascend, so that device $i$ and $j$ can find their first common bifurcation, which is defined as the first common generic node on the binary tree. Then, the privacy parameter for WD $i$ that uses a certain path $p_i$ to connect to the BS is defined as

$$v_i(p_i) = e^{-\sum_{(i_k, i_{k+1}) \in p_i} d_{i_k i_{k+1}}}, \forall k = 1, \cdots, K_i - 1. \quad (6)$$

## III. Problem Formulation and Solution

Given the network introduced in Section II, the main objective is to study how each WD chooses the next hop to form a multi-hop uplink towards the BS which optimizes the transmission QoS that is function of rate, latency, and privacy.

Note that, the change of the next hop by any WD will not only vary the uplink QoS of itself, but will also impact many other devices, due to the reallocation of traffic load in the network. In order to model the interactions between WDs, the framework of *network formation games* can be used, which includes a set of tools to analyze how independent decision makers can interact to form a suitable connected graph [11]. Here, we note that there has been some recent works on network formation games in wireless networks, such as in [10] and [11]. However, these works study the traditional cellular communications, while our work deals with mmW communications for wearable devices within the emerging Internet of things (IoT) ecosystem.

### A. Network Formation Game

We formulate the network formation problem as a noncooperative game $\mathcal{G} = (\mathcal{I}, \{\mathcal{S}_i\}_{i\in\mathcal{I}}, \{u_i(G)\}_{i\in\mathcal{I}})$, in which $\mathcal{I}$ is the set of players which are the WDs, $\mathcal{S}_i$ is the strategy space for each player $i$, and $u_i(G)$ is the utility function, which are detailed as follows.

*1) Strategy Space:* The strategy space $\mathcal{S}_i$ of each player $i \in \mathcal{I}$ includes all the feasible devices that WD $i$ can choose to form the uplink path. Each strategy $s_i \in \mathcal{S}_i$ will cause a sequence of operations on the links [10]. For example, by choosing the strategy $s_i = (i, j)$, WD $i$ will first break the link $(i, j^o)$ with its former next hop $j^o$, and then, build a new link $(i, j)$. For notational simplicity, we denote the network structure as $G_{(i,j)}$ to indicate the next hop of WD $i$.

However, whenever a device $j$ accepts a new link, due to the increased traffic load, its uplink delay will increase. Therefore, we assume that each device can reject a device-to-device (D2D) transmission request, if the formation of such a link will degrade its transmission. Consequently, the feasible strategy set of a WD $i$ is defined as the set of devices who are willing to accept the connection from $i$, denoted by

$$\mathcal{S}_i = \{(i,j) | \tau_j(G_{(i,j)}) - \tau_j(G_{(i,j^o)}) < \varepsilon_j, j \in \mathcal{N}\}, \quad (7)$$

where $\varepsilon_j \in \mathbb{R}^+$ is a small positive amount, which denotes the maximum delay increase that device $j$ can tolerate by accepting link $(i, j)$.

As long as each WD $i \in \mathcal{I}$ has chosen its next hop $s_i \in \mathcal{S}_i$, the edge set $\mathcal{E}$ of the network graph is determined as $\mathcal{E} = \{s_1, s_2, \cdots, s_I, s_{I+1}, \cdots, s_{N-1}\}$, where $\{s_1, s_2, \cdots, s_I\} \in \{\mathcal{S}_i\}_{i\in\mathcal{I}}$ is the strategy profile of all players in $\mathcal{I}$, and $\{s_{I+1}, \cdots, s_{N-1}\} = \{(I+1, m), \cdots, (N-1, m)\}$ is the uplink set of mobile phones, which is unaltered.

*2) Utility Function:* The utility function should reflect the incentive of each WD to form a multi-hop path, by taking account the data rate, latency, and privacy concern to evaluate the uplink transmission. To this end, we introduce the concept of the *weighted power of a system* [14], where the power of a network is defined by the ratio of the throughput to the response time of the uplink path, weighted by the privacy parameter. The weighted power emphasizes the tradeoff between three metrics. Then, the utility function of WD $i$ that chooses node $j$ as its next hop will be:

$$u_i(G_{(i,j)}) = v_i(p_i(j))^{\gamma_i} \cdot \frac{c_i(p_i(j))^{\alpha_i}}{\tau_i(G_{(i,j)})^{\beta_i}}, \quad (8)$$

where $c_i, \tau_i$ and $v_i$ are the rate, delay and privacy parameter of path $p_i(j)$, respectively, and $\alpha_i, \beta_i, \gamma_i \in \mathbb{R}^+$ are the weights, which capture the importance of each of the three metrics that WD $i$ will consider when evaluating the uplink QoS of $p_i(j)$.

Thus, the objective of each WD $i \in \mathcal{I}$ is to compare the transmission quality of each uplink path $p_i(j), (i, j) \in \mathcal{S}_i$ by calculating the utility $u_i(G_{(i,j)})$, and choose the optimal hop.

### B. Game Solution

In the framework of a noncooperative game, each WD aims to maximize the uplink QoS of itself, without considering other players. To this end, each device can update its next hop, according to the change of the network architecture, to improve the payoff. However, such an update may impact the utilities of other players, which motivates more WD to revise their uplink paths to get a better utility, and the network structure will change repeatedly. Therefore, a reasonable solution for the game must identify a stable state, at which no WD has the incentive to change its current path. Consequently, we introduce the concept of the *Nash network* as the solution to the network formation game, defined next.

**Definition 1:** A *Nash network* of the network formation game $\mathcal{G} = (\mathcal{I}, \{\mathcal{S}_i\}_{i\in\mathcal{I}}, \{u_i(G)\}_{i\in\mathcal{I}})$ defines a network graph $G^*(\mathcal{N}, \mathcal{E}^*)$, where the edge set $\mathcal{E}^* = \{s_1^*, s_2^*, \cdots, s_I^*, s_{I+1}, \cdots, s_{N-1}\}$ guarantees that for all $i \in \mathcal{I}$, the following holds:

$$u_i\left(G_{(s_i', \mathcal{E}_{-i}^*)}\right) \le u_i\left(G^*_{(s_i^*, \mathcal{E}_{-i}^*)}\right), \forall s_i' \in \mathcal{S}_i, \quad (9)$$

where $\mathcal{E}_{-i}^* = \{s_1^*, \cdots, s_{i-1}^*, s_{i+1}^*, \cdots, s_I^*, s_{I+1}, \cdots, s_{N-1}\}$ is the profile of the next hops for all players in $\mathcal{I}$, except $i$. The Nash network is the concept of *Nash equilibrium* applied to a network formation game [11]. In essence, a Nash network pertains to a stable graph $G^*$, where no WD can improve its uplink QoS, by unilaterally changing its next hop from the current $j^*$, where $s_i^* = (i, j^*)$, to any others $j'$ in its feasible set $\mathcal{S}_i$, given the choices $\boldsymbol{s}_{-i}^*$ of all the other WDs are fixed.

The aforementioned solution, where each player chooses a deterministic strategy to form the uplink path, is called a *pure* NE. However, for a general game, the pure NE may not exist. In order to guarantee a stable output, the *mixed strategy* approach can be used, as the mixed NE always exists [15]. In a mixed-strategy game, WD $i$ can decide a probability distribution $\mathbb{P}(\mathcal{S}_i)$ over all feasible next-hop choices. Then, every time a packet needs to be delivered, the next hop will be chosen from $\mathcal{S}_i$ according to $\mathbb{P}(\mathcal{S}_i)$. The expected utility for a player in a mixed game is defined on the probability profile given by all the mixed-strategy players, which is

$$\bar{u}_i\left(\{\mathbb{P}(\mathcal{S}_j)\}_{j\in\mathcal{I}}\right) = \sum_{s_i\in\mathcal{S}_i}\left(\prod_{j=1}^{I}\mathbb{P}(\mathcal{S}_j)\right)u_i(G_{(s_i,\boldsymbol{s}_{-i})}). \quad (10)$$

The mixed-strategy NE defines a profile of probability $\{\mathbb{P}^*(\mathcal{S}_i)\}_{i\in\mathcal{I}}$, in which no player can improve its expected utility by unilaterally changing its probability $\mathbb{P}^*(\mathcal{S}_i)$. Although the existence of the mixed NE is guaranteed, the complexity to find a mixed NE is much higher than the pure case. Next, to solve the network formation game $\mathcal{G}$ efficiently, we propose a novel approach with a lower complexity.

### C. Network Formation Algorithm

The network formation process starts with a structure, in which each WD connects to the BS directly. Then, WDs take turns to apply the following actions. The sequence depends on the order that WDs make the D2D transmission requests.

*1) Information Collection:* When a WD $i$ must take an action, it will first send a D2D transmission request, which contains the necessary information used for uplink estimation such as the location and the traffic load, via a common mmW channel. Due to blockage, the mmW broadcast can only cover a small range. However, given that WD $i$ must have a good channel gain with any choice of a next hop, the nodes which cannot receive the signal will anyway not be feasible to act as the next hop of WD $i$. After receiving the broadcast, the feasible devices calculate the utility from accepting such a D2D link from WD $i$. If the increase in delay is intolerable, the request will be ignored, otherwise WD $i$ will receive a response from the feasible device in question. This response will contain the next hop's information and the utility.

*2) Best Response:* After receiving the response, WD $i$ will accept choose as its next hop, the WD that has the highest payoff, if such uplink is better than the current path. Otherwise, if no node replies ($\mathcal{S}_i = \emptyset$), or no responding node can offer a better uplink transmission, WD $i$ will keep its current path. Then, WD $i$ informs the BS whether it makes any change, and releases the broadcast channel for other WDs to make the D2D request.

*3) Pure Nash Network:* The process continues until one of the following conditions is satisfied: (i) no WD can improve its utility by deviating from the current uplink path; (ii) the BS realizes that the current network structure $G$ has been visited for more than $\rho \in \mathbb{N}^+$ times. If condition (i) occurs, the game ends with a pure Nash network. If condition (ii) occurs, the network architecture will move between certain patterns periodically, and the best response dynamics fail to converge to the pure Nash network. Then, some of WDs can move to use mixed strategies.

*4) Mixed Nash Network:* According to the network evolution, the set of WDs $\mathcal{I}$ will be divided into two disjoint subsets $\mathcal{I}_1 \cup \mathcal{I}_2$, where $\mathcal{I}_1$ contains the *loop* nodes which keep changing their next-hop choices at each iteration, and $\mathcal{I}_2$ is the set of *stable* WDs that maintain their current next hops and never deviate after a few iterations. Then, the subnetwork formed by stable nodes in $\mathcal{I}_1$ is already a stable network, while the loop WDs in $\mathcal{I}_1$ will start to apply the mixed strategies to find the mixed NE through a centralized approach [15].

*5) Hybrid Solution:* The hybrid Nash network $G^H$, which is formed by the mixed Nash subnet generated by loop players in $\mathcal{I}_1$ and the pure Nash subnetwork formed by stable players in $\mathcal{I}_2$, is the final output of the network formation game $\mathcal{G}$.

However, after the mixed strategy game between players in $\mathcal{I}_1$, one cannot guarantee that the pure strategy for each node in $\mathcal{I}_2$ is still the best response strategy in the final network structure $G^H$. Therefore, more analysis is needed to prove the stability of the final game output, as shown next.

**Theorem 1:** The hybrid Nash network $G^H$ is a mixed Nash equilibrium.

*Proof*: If the best response dynamics fails to converge to a pure Nash network, the network structure will move between certain patterns periodically, and we denote the set of the network structures that appear within one period as $G^W = \{G^1, G^2, \cdots, G^w\}$. Then, the mixed-strategy game is played between wearable nodes in $\mathcal{I}_1$. The output of the mixed strategy game is a probability distribution $\Xi^{\mathcal{I}_1}$ over all network structures in $G^W$, where $\Xi^{\mathcal{I}_1} = \{\xi_1, \xi_2, \cdots, \xi_w\}$, and $\xi_q$ denotes the probability that the network structure $G^q$ is selected when some node in $\mathcal{I}_1$ delivers a packet to the BS. Although $\Xi^{\mathcal{I}_1}$ defines a stable structure of the subnet, formed by nodes of $\mathcal{I}_1$, however, for the nodes of $\mathcal{I}_2$, we need to prove their stability after the mixed game.

Note that, during the network loop $G^W$ in best response dynamics, no node in $\mathcal{I}_2$ changes its next-hop choice, which means the following inequality (11) holds for each device $i \in \mathcal{I}_2$ in each network structure $G^q \in G^W$.

$$u_i(G^q_{(i,j)}) \geq u_i(G^q_{(i,j')}), \forall j' \in \mathcal{S}_i. \quad (11)$$

Then, after the mixed game, given the probability distribution $\Xi^{\mathcal{I}_1}$, the expected utility that each device in $\mathcal{I}_2$ gets from the hybrid network $G^H$ will be

$$\bar{u}_i(G^H_{(i,j)}) = \sum_{q=1}^{w} \xi_q u_i(G^q_{(i,j)}). \quad (12)$$

Then, by substituting (11) into (12), we get

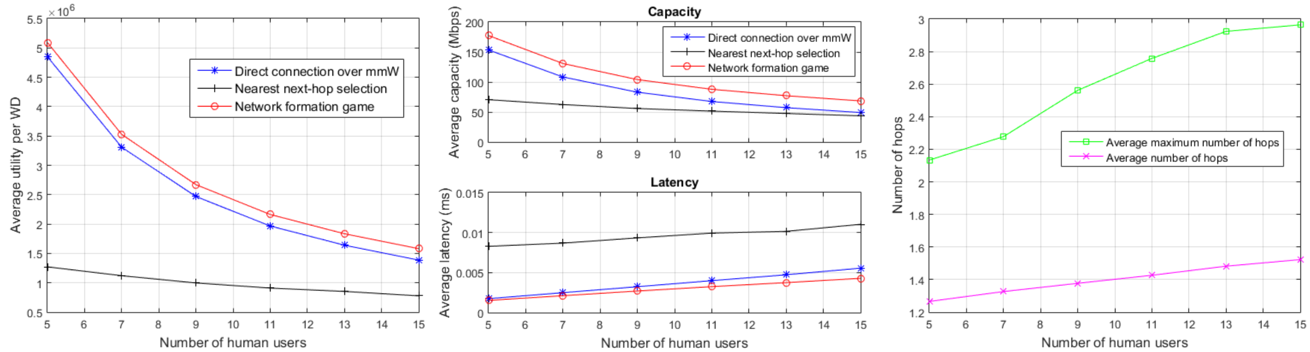
$$\bar{u}_i(G^H_{(i,j)}) \geq \sum_{q=1}^{w} \xi_q u_i(G^q_{(i,j')}) = \bar{u}_i(G^H_{(i,j')}), \forall j' \in \mathcal{S}_i. \quad (13)$$

Therefore, the hybrid Nash network $G^H$ is actually a mixed NE, in which the players in $\mathcal{I}_1$ adopt mixed strategies and the players in $\mathcal{I}_2$ have pure strategies. ■

Such a hybrid approach can be applied in any noncooperative game to find the mixed NE. In the first phase, the best response dynamics is applied to find the pure NE for some players; then, the mixed strategy game is played between the other players to find a mixed NE. This approach guarantees the existence of NE, and the computation to find the mixed NE is reduced by decreasing the number of players in the mixed play through the first pure-strategy game.

## IV. Simulation Results and Analysis

For simulations, a wearable network over 60 GHz frequency band is deployed in a hexagon indoor area with a radius of 6 meters, and the BS is located in the center. In this network, each human user has four wearable devices and one phone. The total available bandwidth for mmW communications is 1 GHz. For the cellular communication, mobiles transmits data to the BS over 2 GHz. The channel parameters of mmW and cellular transmissions are chosen




(a) (b) (c)

Fig. 3: (a) The proposed game approach yields a better uplink QoS, compared with the direct transmission scheme and the nearest next-hop approach. (b) The average capacities of the three approaches decreases as the number of users increases, while the average latency increases linearly. (c) The average number and the average maximum number of hops will both increase as the number of WD increases.

based on [7] and [8], respectively. In all simulations, the *average number of iterations for convergence is around three*.

Fig. 3a shows the average utility per wearable device, as the number of human users increases from five to fifteen. Here, the number of players (i.e. wearable devices) increases from 20 to 60. The weight vector of rate, latency and privacy is set to be $(0.1, 0.1, 1)$. We assess the performance of the formed uplink network structure by comparing it with a direct-transmission scheme, and a nearest next-hop approach. Fig. 3a first shows that, as the number of WDs increases, the average utilities of all three methods decrease. The utility drop is caused by the reduction in the mmW bandwidth per WD. Also, as the network becomes more crowded, the increase of traffic load results in a larger latency. Fig. 3a shows that the proposed game approach yields a significant advantage, in terms of average utility, up to $14\%$ and $78\%$, over the direct transmission scheme and the nearest next-hop method, respectively.

Fig. 3b shows the average capacity and latency per WD, as the number of users increases. First, we can see that the game approach yields a highest capacity, which has an advantage over the direct transmission and the nearest next-hop schemes of $40\%$ and $70\%$, respectively. Also, the game approach decreases the uplink latency by up to $23\%$ and $300\%$, compared with the other two methods. Furthermore, the average capacities of all mentioned approaches decrease as the number of users increases, while the latencies increases in a linear way.

Fig. 3c gives the average hops and the average maximum number of hops in the final network structures. As the number of wearable devices increases, both the average and the maximum number of hops increases, but the increase rate is very slow. Given that the weight of the metrics is dominated by the latency, each wearable device will prefer a shorter path to access the BS to guarantee a lower delay. Therefore, on average, the number of hops remains below three.

## V. Conclusion

In this paper, we have proposed an approach, which enables wearable devices to autonomously establish a D2D multi-hop network over mmW. A network formation game is formulated between all WDs to find the uplink paths, which maximize the transmission QoS, in terms of rate, delay and privacy. To solve this game, a novel algorithm that combines best response dynamics with mixed-strategy techniques is proposed to find the mixed NE, which corresponds to a stable network architecture. Such an approach guarantees the existence of a mixed NE, as well as reduces the complexity significantly. Simulation results show that the proposed game approach can significantly improve the average utility per WD, compared with the direct transmission and the nearest next-hop schemes.

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