IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 6, 2022, accepted June 8, 2022, date of publication June 13, 2022, date of current version June 17, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3182388

Dynamic D2D Communication in 5G/6G Using a Distributed AI Framework

IACOVOS I. IOANNOU[1,2], CHRISTOPHOROS CHRISTOPHOROU[1,2], VASOS VASSILIOU[1,2], (Senior Member, IEEE), MARIOS LESTAS[3], (Member, IEEE), AND ANDREAS PITSILLIDES[1,4], (Senior Member, IEEE)

[1]Department of Computer Science, University of Cyprus, 1678 Aglandjia, Cyprus
[2]CYENS Center of Excellence, 1016 Nicosia, Cyprus
[3]Department of Electrical and Electronic Engineering Science, Frederick University, 3080 Nicosia, Cyprus
[4]Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg 2092, South Africa

Corresponding author: Iacovos I. Ioannou (iioann06@cs.ucy.ac.cy)

This work was supported in part by the European Union's Horizon 2020 Research and Innovation Programme under Grant 739578, and in part by the Government of the Republic of Cyprus through the Directorate General for European Programmes, Coordination and Development.

ABSTRACT This paper focuses on D2D communication for 5G/6G in dynamic environments where the D2D network topology changes through time due to D2D Devices' mobility. Specifically, we consider a scenario within the coverage area of a Base Station (BS) serving a number of User Devices (UEs), with variations in speed and direction causing changes in the D2D network topology, either via direct connections or via D2D single-hop or D2D Multi-hop paths. Based on this scenario, we formulate a problem aiming to maximise the total Spectral Efficiency (SE) whilst minimising the total Power Consumption (PC), by selecting the best transmission mode that the D2D devices will operate. In order to address the aforementioned problem, the Distributed Artificial Intelligence Solution (DAIS) plan proposed in our earlier work and designed for static environments is extended to consider the mobility (i.e., speed, direction and indirectly link distance change) of the D2D Device, targeting the dynamic creation of stable and efficient clusters and good backhauling links towards the gateway. The enhanced DAIS performance is comparatively evaluated in terms of SE and PC against selected variations in UE speed and direction, changes in the link Transmission Power (TP), and an increase in the number of Devices in the D2D network. Overall, the results obtained demonstrated superior performance of enhanced DAIS over all the other related investigated approaches (i.e., Distributed Sum Rate (DSR), Single Hop Relay Approach (SHRA), Distributed Random (DR)), in terms of Spectral Efficiency (SE) and Power Consumption (PC). Also, the ability of enhanced DAIS to react and adapt quickly and efficiently to D2D network topology changes, with reduced signalling overhead and control delay in responding to changes, shows that it is a well-poised approach to be used in a Dynamic D2D Environment.

INDEX TERMS 5G, 6G, D2D, transmission mode selection, distributed artificial intelligence, dynamic transmission mode selection, clustering, BDI agents, BDIx agents.

I. INTRODUCTION

5G and 6G technical requirements motivated the academic community to find alternative ways to optimise the mobile network infrastructure and increase network performance. These technical requirements include: i) support for a huge number of devices (IoT included) under the same network (e.g., 1000s of devices per square kilometre), called massive Machine Type Communications (mMTC); ii) provide an ultra-reliable low latency communication (e.g., 1 ms) for supporting new applications, such as remote medical operations, and new technologies, such as Augmented Reality (AR) and Virtual Reality (VR), called Ultra-Reliable Low Latency Communications (URLLC); and iii) provide high service quality and quantity in terms of bandwidth, in order to meet the users demanding bandwidth requirements coming from

The associate editor coordinating the review of this manuscript and approving it for publication was Ramakrishnan Srinivasan.

mobile applications that use live video, high-quality images, voice and text (e.g., 1 Gbps per user), called enhanced Mobile Broadband (eMBB) [1].

Given the above technical 5G/6G requirements, specific network management and control issues are becoming more complex, demanding more efficient communication establishment control and faster decisions in handling dynamic aspects that can occur in the network operation (e.g., in a disaster recovery case). For example, to realise quick decisions, the time needed for communication establishment should be minimised by reducing the volume of messages exchanged between the collaborative devices, as well as the decision horizon. To achieve this, the devices should become autonomous, able to react dynamically and independently to changing conditions of network operation. A joint management and control approach realising Self-healing/self-organised networks to handle the above issue effectively becomes necessary.

A promising approach to tackle a diverse range of complex problems is to use an AI/ML (Artificial Intelligence/Machine Learning) framework [2]–[4]. Furthermore, a distributed approach is encouraged, given the complexity of the forthcoming networks and the strict requirements imposed, including tackling the mobility aspect [5]. The latest literature in 6G [6]–[14] indicates that for 6G to satisfy connectivity demands and satisfy the requirements of near-future services, a distributed control with virtual resources is needed. In addition, it is suggested that intelligence will be shifting from centralised computing facilities down to every terminal in the network to promote real-time network decisions through prediction and achieve self-organised networks at the UE level.

To tackle the aforesaid 5G/6G technical requirements, in previous work we implemented a novel Distributed AI framework [15]–[19], exploiting Belief-Desire-Intention (BDI) agents extended with Machine Learning (we refer to these as BDIx agents) running on the UEs, to better manage the network and offer increased network performance. To demonstrate its potential, we focused on a Device-to-Device (D2D) communication setup and proposed the DAIS plan [15], a specific plan executed by the BDIx agents of the DAI framework using only local knowledge,[1] for selecting the transmission mode that the D2D device will operate. However, the first version of the DAIS plan did not consider the dynamic case of incorporating UE mobility in which the speed and direction exist and influence the D2D communication network topology.

In this paper, we consider a dynamic D2D environment for a 5G/6G scenario within the coverage area of a Base Station (BS) serving a number of User Devices (UEs) either via direct connections or via D2D single-hop or D2D Multi-hop paths. We also formulate a problem aiming to maximise the total Spectral Efficiency (SE) whilst minimising the total Power Consumption (PC), by selecting the best transmission mode that the D2D devices will operate, targeting the creation of stable and efficient clusters and good backhauling links towards the gateway in environments where the D2D network topology changes through time due to UE mobility according to speed and direction.

The DAIS plan was initially introduced in [15] and designed for static environments. It is enhanced to consider the speed in its algorithm targeting the dynamic creation of stable and efficient clusters and good backhauling links towards the gateway, considering a D2D Communication setup where the D2D network topology changes through time mainly due to the mobility of the D2D/UE devices (see Section IV-A).

Moreover, in Section V-D1 we show that the dynamic version of DAIS outperforms initial DAIS [15] under an environment that is dynamic in terms of the speed and direction. The algorithm is executed in Time Steps (i.e., every 100 ms), updating the transmission mode in each link. The difficulty here is that in each Time Step (TS) of execution, the new selected transmission mode can affect existing clusters, as well the formation of new clusters and backhauling links, whilst also respecting any constraints, such as the Speed of the D2D device. In other words, the objective of the enhanced DAIS plan is to achieve a transmission mode selection in such a way that would avoid, or at least minimise, disconnected/disjointed clusters due to the speed and direction of the relay nodes, thus keeping a stable network performance in terms of maximising SE and minimising PC.

Moreover, to set a benchmark and allow for a fairer comparison, we also enhanced the DSR approach [15], [18], [19], so as to make it competitive and aligned with DAIS in a dynamic environment (see Section IV-B). DSR is a distributed algorithmic approach that focuses on maximising the aggregated data rate of all the links established in the network by using global network knowledge.[2] For the same reason, the SHRA approach [20] is enhanced in order to enable D2D-Relays to support multiple connections and allow cluster formation (see Section IV-C). The comparative evaluation results (see Section V-D) demonstrate superior performance of DAIS over the SHRA, DSR, DR [15][3] and non-D2D UE approach[4] in terms of SE and PC.

The key contributions of this paper are summarised below:

- We provide a problem formulation of a dynamic environment for D2D communication in terms of speed, direction, and a network topology by considering the SE and PC formulation, Devices transmission mode and D2D communication protocols used (i.e., WiFi Direct, LTE Direct). Moreover, we indicate the objective of the

[1] Information that can be retrieved from other nodes in the proximity of the D2D device.

[2] Information that can be retrieved from all the nodes under the D2D network that the D2D device is located.

[3] DR is a distributed approach that randomly performs transmission mode selection using global network knowledge.

[4] The non-D2D UE is the current implementation of the mobile network without the D2D communication.

problem formulation, which is the maximisation of SE and the minimisation of PC.
- We provide an investigation related to D2D and transmission mode selection in order to tackle the dynamic aspects of the mobile network with the use of DAI/ML.
- We implement an enhanced D2D transmission mode selection plan (DAIS) using the DAI framework (with DAI and ML) in order to improve the network SE and PC in a dynamic environment. The framework makes use of BDIx agents, which reside on Mobile Devices (shown in Fig. 1), enabling them to intercommunicate and cooperate in achieving, in a distributed artificial intelligence manner, efficient D2D communication (Section IV-A) for a dynamic environment.
- We enhance DAIS and DSR [15] (Section IV-A and Section IV-B) so as to offer improved SE and PC in a dynamic D2D network (Section V-D1) by considering the speed of a device before selecting transmission mode.
- We show that the new enhanced DAIS is better than the DAIS shown in [15] in the dynamic environment.
- To allow a fairer comparative evaluation with enhanced DAIS and DSR, we enhanced an approach from literature called SHRA and adapted the D2D transmission mode selection of D2DSHR to accept as clients more than one D2D device, and we enhanced the approach to consider the speed before selecting the transmission mode (Section IV-C).
- We examine how Transmission Power (TP) affects the investigated approaches (DAIS, DSR and SHRA) after forming the D2D network. Based on this investigation, a Reservation Power Plan for DAIS is introduced (Section V-D2).
- We provide an extensive comparative evaluation between the investigated approaches considering the behaviour of the researched techniques on: i) dynamic TP; ii) Network Topology changes over the Time Steps (TS) of Execution; iii) dynamic UE Speed; iv) different number of Devices in the network; and v) dynamic UE Direction (Section V).

The rest of the paper is structured as follows. Section II provides some background information on the DAI Framework, the main characteristics of the D2D Communication, the DAIS plan and the other investigated approaches. It also provides related work on approaches addressing D2D transmission mode in a dynamic and static network environment. The assumptions, terms, system model, problem description and formulation, including an overview on how the investigated approaches are associated with the optimisation objective (i.e., SE maximisation that will result to PC minimisation), are elaborated in Section III. Additionally, the enhanced implementations of the DAIS plan, DSR and SHRA approaches are provided in Section IV. The efficiency of the investigated approaches is examined, evaluated and compared in Section V. Finally, Section VI includes concluding remarks and our future directions.

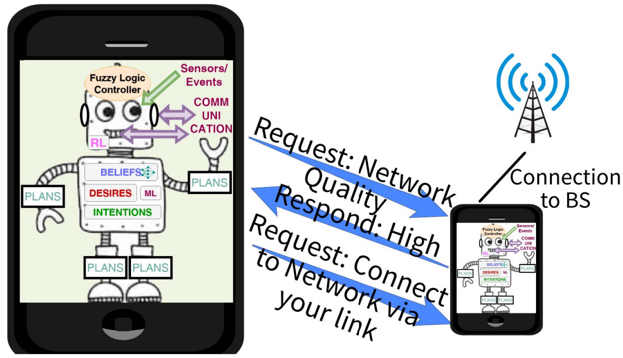


FIGURE 1. BDIx agents residing on mobile devices.

II. BACKGROUND KNOWLEDGE AND RELATED WORK
A. BACKGROUND KNOWLEDGE
This section provides a brief introduction to the DAI Framework and the main characteristics of D2D communications, including the types of control utilised for establishing the D2D communication links and the types of transmission modes that a D2D device can operate. Also, a short description of the implementation of the DAIS Plan, the Sum Rate Approach, the Distributed Random and the non-D2D UEs algorithms is provided. Further details appear in [15], [18], [19].

1) THE DISTRIBUTED ARTIFICIAL INTELLIGENCE FRAMEWORK
The DAI framework is realised in an efficient, distributed, autonomous and flexible way, and it focuses on the local environment rather than the global environment. It is implemented using a BDI extended agent (BDIx agent) that consists of Beliefs (knows the environment),[5] Desires (what it has as objective) and Intentions (current running objectives realised from Desires that are executed through selected plans). Desires can become Intentions using priority values and well-defined IF-THEN rules in the Fuzzy Logic Plan Library according to the Requirements based on values from Sensors, violation of pre-specified thresholds and raise of Events. More specifically, changes in values of Beliefs or incidents that trigger an event act as reinforcement learning and enable the reactive behaviour of an agent that changes Desires, Intentions and plans to be executed (as shown in Fig. 1) [16].

2) TYPES OF CONTROL IN D2D COMMUNICATION
From the open literature, the types of control that are used for the implementation of D2D communication and the establishment of links are the following (see [15], [18], [19]):
- Centralised: In the centralised control approach, the BS completely supervises the UE nodes, even when the nodes are communicating directly. The controller

[5]Beliefs can also comprise part of other forms of AI/ML techniques (e.g. Fuzzy Logic, Deep Learning Neural Networks etc).

supervises interference/connections/path or any other metrics amid cells with D2D UEs.

- Distributed: In a distributed scheme, the control of the management of the D2D nodes (e.g., interference/data rate/path) does not require a central entity of authority, but it is performed autonomously by the UEs themselves. Thus, the distributed scheme diminishes the control and computational overhead, which is why it is mainly appropriate for large D2D networks.
- Semi Distributed: Both centralised and distributed schemes have advantages and drawbacks. Trade-offs can be accomplished between them for better performance. Such D2D management schemes are referred to as "semi-distributed" or "hybrid".Thus, "semi-distributed" is a combination of the "Centralised" and "Distributed" approaches.
- DAI control: This is a sub-class of a distributed control; With DAI, all the distributed control processes are autonomous (in terms of information sharing) and are expected to begin simultaneously, run in parallel and conclude independently to the result extracted by the other process. This is the type of control that is used by our proposed DAI Framework [15].

3) TYPES OF TRANSMISSION MODES IN D2D COMMUNICATION

There exist different transmission modes for D2D communication based on how UEs interact with the BS and other D2D nodes (see [15], [18], [19]):

- D2D Direct (D2DD): Two UEs connect and communicate with each other by utilising licensed or unlicensed spectrum.
- D2D Single-hop Relaying/D2D Relay (D2DSHR): In this mode, the D2D device shares its bandwidth from its shared link that is directly connected to a backhauling link composed of other D2D devices or a BS or an Access Point with other UEs. Also, it provides access, by sharing its bandwidth, to other D2D devices / UE devices [21] that are clients to the relay. It is called Single Hop because the D2D Client devices connected to it, access the other D2D client devices under it by the one-hop D2D relay device.
- D2D Cluster: a D2D cluster is a group of UEs connected to a D2D relay node (D2DSHR), performing as a Cluster Head (CH) and acts as an intermediate router to the network through an access point or BS. Clustering is appropriate in high user densities [22], [23].
- D2D Client (D2DC): D2DC is the client that connects to a CH D2D Relay (D2DSHR) node in a D2D Cluster.
- D2D Multi-hop Relay (D2DMHR): The single-hop mode is extended by enabling the connection of more D2D UEs as a bridge with mode D2DMHR in a path to achieve both backhauling links from the single-hop relay or a multi-hop relay towards BS (internet) and/or D2D communications. Please note that both backhaul links and D2D transmissions are performed in an uplink with other D2DMHR/D2DSHR nodes (as a bridge), and they are subject matter to the control of the former D2DMHR nodes [23]. If a D2DMHR is equipped with more than two interface cards, it can also share bandwidth with D2DCs; otherwise, at the end of the backhauling path (D2DMHR chain), a D2D Single-hop Relay node can be connected for sharing purposes.

4) THE DISTRIBUTED ARTIFICIAL INTELLIGENCE SOLUTION (DAIS) PLAN

DAIS is a specific plan executed in a DAI framework making use of BDIx agents, for selecting the transmission mode that the D2D Devices will operate. This plan is implemented to run when a UE device enters the D2D network. For choosing the transmission mode that the UE device will perform in the D2D network, the "Weighted Data Rate" (WDR) metric is considered. This metric is defined as the minimum data rate of the weakest D2D link in the path that the UE device has selected for either directly connected to the BS or through another D2D Device towards the BS (i.e., WDR = max(min(Link Rate)) [15]. Specifically, the DAIS plan selects the transmission mode that a D2D Device will operate such that the WDR of the chosen path is maximised. Below we provide the steps that the BDIx agents executing the DAIS plan perform to select the transmission mode that the D2D device will operate. Before going into the details is essential to note that the D2D-Relays: i) Are using proximity services to broadcast the connection information (i.e., WDR, coordinates) as message advertisement; ii) Use WiFi Direct when forming a D2D cluster for communication within the cluster and within-cluster D2DCs and Cluster Head; and iii) Establish a link among them using LTE Direct [15].

Once a UE device enters the D2D network for the first time (see Fig. 2), the initial WDR is estimated as the data rate of the link between the UE device and the BS. Afterwards, other candidate indirect paths between the UE device and other neighbouring D2D-Relays[6] towards the BS are identified, their associated WDR is calculated, and the best path (i.e., the one with the highest WDR) is selected. Based on the path selected (i.e., direct or indirect path), the transmission mode of the UE device is selected and adopted.

Basically, the following steps are executed:

a. Using LTE Proximity Services, the entering UE device scans the network for any neighbouring D2D-Relay devices. The broadcast LTE proximity advertisement messages also include additional information, such as the number of D2D devices supported by the D2D-Relay, coordinates of the D2D device and the D2D device that each D2D-Relay connects to next (with their associated link data rate), along the path to the BS/GW.
b. For each D2D-Relay device detected in the proximity of the UE device. A D2D communication path is

[6]For clarity, we will use D2D-Relay to represent both the direct D2D Relay/D2D Single-hop Relaying and the D2D Multi-Hop Relay (D2DSHR/D2DMHR) cases.

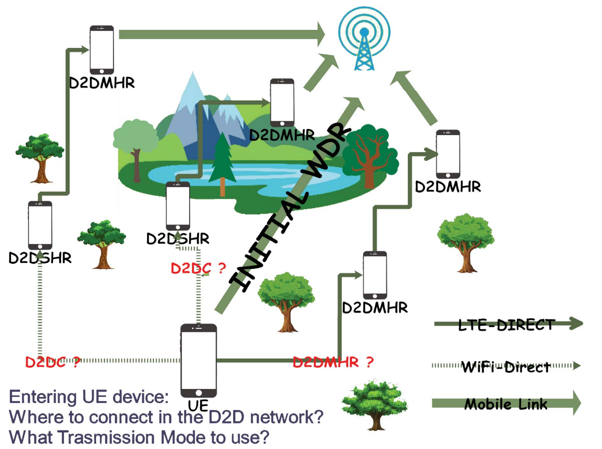


FIGURE 2. UE device entering a D2D communication network and the dilemma of selection of most appropriate transmission mode and access point.

identified, having the D2D-Relay device as a starting point.

c. The WDR of each path is calculated and sorted in descending order based on the WDR achieved.
d. Starting from the D2D-Relay device related to the path with the best WDR achieved, up to five of the D2D-Relay devices that meet the following conditions are selected as follows:
   - D2D-Relay 1: The D2D-Relay that operates as D2DSHR (single-hop D2D-Relay) and located within a Wi-Fi Direct (200 m) range from the entering UE device (maxD2DSHR).
   - D2D-Relay 2: The D2D-Relay that operates as a D2DMHR (multi-hop D2D-Relay) with no connections and located within a Wi-Fi Direct range from the entering UE device (maxD2DMHR_NC).
   - D2D-Relay 3: The D2D-Relay that operates as a D2DSHR (single-hop D2D-Relay) with no connections and located within a range of LTE Direct (600 m) from the entering UE device (maxD2DSHR_NC_D2DMHR).
   - D2D-Relay 4: The D2D-Relay that operates as a D2DSHR (single hop D2D-Relay) or a D2DMHR (multi-hop D2D-Relay) with no connections, located within a range of LTE Direct and with a WDR lower than the data rate of the link between the UE device and the BS (referred as the initial WDR) (maxD2DSHR_UED2DMHR).
   - D2D-Relay 5: The D2D-Relay that operates as a D2DMHR (multihop D2D-Relay) with no connections and located within the range of LTE Direct from the entering UE device (maxD2DMHR_MultiHop).
e. Transmission Mode Assignment (implementation details appear in [15], Algorithm 1): The entering D2D device, by considering the threshold values set for the WDR and Battery Power Level (BPL) (WDR Threshold, BPL Threshold; see Section II-A4.a) selects its transmission mode. This is achieved by executing the following steps progressively, with execution moving to the next step only if the current step is not satisfied. These steps are:
   - If "D2D-Relay 1" exists and its WDR is greater than the initial WDR x (1 + WDR Threshold), the UE device will set its transmission mode to "D2DC" and connect to "D2D-Relay 1".
   - If "D2D-Relay 2" exists and its WDR is greater than the initial WDR x (1 + WDR Threshold), the UE device will inform the "D2D-Relay 2" to change its transmission mode from D2DMHR to D2DR, set its transmission mode to "D2DC" and connect to "D2D-Relay 2".
   - If "D2D-Relay 3" exists and its WDR is greater than the initial WDR x (1 + WDR Threshold), the UE device will inform the "D2D-Relay 3" to change its transmission mode from D2DR to D2DMHR, set its transmission mode to "D2D Single Hop Relay" and connect to "D2D-Relay 3".
   - If "D2D-Relay 4" exists and its WDR is less than the initial WDR x (1 − WDR Threshold)), the UE device will set its transmission mode to"D2DMHR", inform the "D2D-Relay 4" to change its transmission mode to D2DSHR and connect to the entering UE device. In this case, the entering UE device "breaks" an existing connection.
   - If "D2D-Relay 5" exists and its WDR is greater than the initial WDR x (1 + WDR Threshold), the UE device will set its transmission mode to "D2D Single Hop Relay" and connect to "D2D-Relay 5".
   - The entering device sets the transmission mode to be "D2DMHR" and selects to connect to the BS.
f. Once the Transmission mode of the UE device is selected, the path towards the BS is established, and the UE device estimates its link data rate with the selected D2D-Relay. Then the UE device sets its WDR as the *min(data rate of the link between the UE device and the selected D2D-Relay, selected D2D-Relay WDR)*.

More details about the DAIS algorithm that is implemented as a DAI framework plan, the problem formulation, the assumptions, constraints, sum rate and power consumption estimations (the formulations of sum rate and power consumption are utilised from [24]), parameters, thresholds calculations, and terminology can be found in [15], [18], [19].

a: WDR AND BPL THRESHOLDS USED BY DAIS

In [15], we have introduced the Battery Power Level (BPL) and Weighted Data Rate (WDR) threshold values, which are also investigated in [18], [19]. The following paragraphs provide the Thresholds information utilised by DAIS Plan.

The BPL Threshold (We set the value to 75% BPL Threshold, even though it does not affect the SE and PC) is utilised by the plan in order to preserve energy for D2D devices performing as D2DSHR or D2DMHR Devices. Consequently, for a device to select D2DMHR/D2DR mode and support other D2D UEs, it must have a battery power level more than the threshold.

The WDR threshold (20% WDR for low (<= 200) UEs [18], and 35% WDR for large (<= 1000) UEs [19]) is used by the plan for four purposes. Through the WDR Threshold, an entering new D2D device in the network:

- Can perform a quality check of the D2DSHR in order to connect to it as a D2DC.
- Can perform a quality check of the D2DMHR in order to connect to it either as a D2DC or a D2DSHR.
- Can replace a D2D-Relay Device and take its role if the new D2D device's WDR is greater than the WDR of the existing D2D-Relay device.
- Can connect to a D2D-Relay device in its proximity and act as a D2DSHR.

Note that the WDR threshold is used for restricting the creation of new D2D-Relays. More specifically, the WDR Threshold is used for quality check in order to evaluate how good, in terms of WDR is: i) an entering Device to be D2D-Relay; and ii) an existing D2D-Relay device to keep its mode and connection versus an entering UE device. This aim's to reduce the possibility of breaking existing connections and establishing new connections with the new D2D-Relays (see Section II-A4).

5) DSR APPROACH, DISTRIBUTED RANDOM, AND NON-D2D UE FOR TRANSMISSION MODE SELECTION [15]

The DSR Approach uses the sum rate[7] of the network as a metric to select the best transmission mode for the entering UE device by having all the knowledge of the network (i.e., D2DSHRs, D2DMHRs, D2DCs, connection links, Data Rates of each link, interference among the D2D devices). On the other hand, the Distributed Random approach is a distributed approach that randomly performs transmission mode selection using global network knowledge (taken from BS). Note that DR acquires only the D2DSHR and D2DMHR near the D2D Candidate Device according to constraints. Finally, the non-D2D UE approach is the current implementation of the mobile network. More precisely, the non-D2D UE approach does not form D2D Communication links and keeps all the UEs connected directly to the BS with constant predefined transmission power.

Overall in [15], in static environments, the Sum Rate approach was concluded as the best approach because it uses brute force investigation to conclude with the best transmission mode in terms of SE and PC in each D2D device. On the other hand, the Distributed Random was concluded to be the worst approach that results in the worst SE, and the non-D2D UE approach was concluded to be the worst approach in terms of PC.

[7]The Sum Rate of the D2D network is calculated by adding all the achieved data rates of all nodes in the network.

B. RELATED WORK

This section provides a brief review of the open literature approaches related to static and dynamic transmission mode selection in D2D Communication.

1) RELATED WORK ON TRANSMISSION MODE SELECTION IN D2D COMMUNICATION [19], [25], [26]

It is worth mentioning that all the approaches investigated in the literature separate the UEs into categories. The categories are for those that are candidates to become D2D devices and those that will stay connected to the BS as regular UEs. On the other hand, our approach [15] considers all the UEs as candidates to become a D2D device, which can provide better network performance. Furthermore, to the best of our knowledge, there is not any other approach that tackles the problem of having a D2D device utilising all transmission modes (D2DSHR, D2DMHR and D2DC) in a distributed manner.

A classification based on the type of control (see Section II-A2) used by each paper examined is found below:

- Centralized approaches [27]–[39], where the decision is taken by the BS. The benefit of Centralised approaches is that the control is executed on the BS, which is easier and simpler. However, a lot of messages are needed to be exchanged between D2D devices and the BS, which implies significant signalling overhead and decision delays in the BS.
- Distributed approaches [40], where the decision is taken by the D2D devices; however, in this case, the D2D devices need some information from the BS. The need for the BS information implies the use of a lot of message exchange and delays. However, in distributed control, after the message exchange with the BS, the control is executed at UEs with no restriction on the number of devices that the approach can support. Thus, the distributed approaches are dynamic and flexible.
- Semi-distributed approaches [41], where the decision is taken by both the BS and the D2D devices in collaboration. In the case of semi-distributed approaches they have the pros and cons of the distributed and centralised approaches.
- Distributed Artificial Intelligent (DAI) approaches, where the decision is taken by each D2D device independently; however, in this case, they may share information with other D2D devices [15]–[17]. The benefit of DAI is that it can be utilised in dynamic environments, as it is distributed, autonomous, dynamic, flexible, react fast and adapts quickly and efficiently to D2D network topology changes.

A classification on the related approaches based on the type of transmission (see Section II-A3) is:

- D2D device Selection only [27]–[30], [41]
- D2DD and D2DSHR selection mode only [31]–[37], [40]
- D2DD and D2DMHR [38], [39]

Note that most approaches described above are Centralised, and only a few use Semi-Distributed or Distributed algorithms.

2) RELATED WORK ON DYNAMIC TRANSMISSION MODE SELECTION IN D2D COMMUNICATION

The related approaches described above are focused on a static environment, an environment without consideration of the mobility of the devices. To the best of our knowledge, not a lot of work was done indirectly addressing Dynamic transmission mode Selection. What we found in the open literature closely related to the work performed in this paper is [20], an interesting heuristic algorithmic approach, which is described below. For comparison evaluation reasons (see Section V), we will refer to this approach as SHRA, reflecting the title "D2D Single Hop Relay Approach" that the authors of [20] gave.

The approach described in [20] uses only two D2D modes, the: i) D2DD mode; and ii) D2DSHR mode in a reduced distance of 20m. Also, it uses three modes of operation of the UEs the: i) infrastructure mode, ii) D2DD mode, and iii) D2DSHR mode. In the experiments performed, mobility is simulated using the random way-point model and the linear mobility model. The SHRA approach uses only D2D single-hop Relay communications, and it considers the distance between the D2D devices (based on their GPS coordinates) for selecting the device that will operate as a D2DSHR. It has two thresholds, namely:

- The minimum "threshold distance for D2D Direct communication" (called α) used for establishing D2DD assisted communication and
- The maximum "threshold distance for relay-aided single hop relay D2D communication" (called γ) used for establishing D2DSHR communication.

Based on the distance among two D2D devices (referred as R) that want to communicate, the approach executes the following cases:

- If R is greater than γ, then the D2D devices must communicate through the BS.
- If R is less than γ and greater than α, then the D2D devices must find a D2D device that should convert to D2DSHR, connect to it and communicate through it.
- If R is less than α, then the D2D devices should directly communicate using D2DD mode.

The simulation evaluation results provided in [20] showed that the D2DSHR mode in the Dynamic and Static environment could provide a better data rate.

Compared to SHRA described above, with the DAIS approach (described in Section II-A4) a D2D device is allowed to operate as a D2DSHR, forming a cluster in the D2D network and connecting to a path creating a backhauling link towards the BS. With this concept, indirectly, all the D2D devices in the network will access the BS.

Table 1 provides the type of control performed and network knowledge needed by each approach mentioned above.

TABLE 1. Evaluated approaches type of control & network knowledge they need.

Approach(es) Investigated	Type of Control	Network Knowledge
DAIS	DAI (Distributed, Decentralized)	Local Knowledge
Distributed Random	Distributed	Global Knowledge
SHRA	Distributed	Reduced Knowledge
DSR	Distributed	Global Knowledge
non-D2D UE	Centralised	Global Knowledge

III. PROBLEM FORMULATION

In this research, our primary goal is to tackle the D2D challenges mentioned in [15], [42], aiming for the implementation of 5G/6G D2D communication in a dynamic environment. More specifically, our objective is to utilise our findings on the DAIS plan and DAI Framework [15]–[19] (implemented using BDIx agents) to select the most appropriate transmission mode (i.e., D2DSHR, D2DMHR, D2DC) to form a good backhauling network and good formation of clusters. By selecting the most appropriate transmission mode of a D2D device, we seek to jointly maximise the total SE while minimising the total PC through clustering and backhauling.

Below we provide the assumptions and terms used in our investigation, and then we present the problem formulation.

A. ASSUMPTIONS AND TERMS

Our investigation considers the following assumptions:

1) a single Base Station (BS) with a total number of Q moving UEs (D2D devices) forming the D2D communication network.
2) a D2D communication network with a total number of N devices representing the devices that share their link (i.e., D2DSHR, D2DMHR, BS).
3) the Weighted Bandwidth is calculated by each D2D device. The Weighted Bandwidth calculated by a D2D device is estimated as the percentage of the bandwidth allocated to the D2D device divided by the stable constant bandwidth allocated to a standard UE connection that uses a direct connection with the Base Station as a reference bandwidth.
4) a link connection with a single-antenna, point-to-point communication between the D2D devices and an uplink communication scenario.
5) a Free Space Path Loss model (for calculating average received power) and a basic noise model, the Additive White Gaussian Noise (AWGN), for calculating the signal to noise ratio (SNR) and then the signal to interference plus noise ratio (SNIR).
6) a scenario that D2DSHR shares over WiFi Direct and D2DMHR over LTE Direct Mobile Frequencies in an overlay fashion.
7) a well defined D2D security protocol for the D2D devices to access the D2D communication and Telecom network securely as well as the LTE ProSe service and guarantee access to all the features provided by the operator.

8) for all TSs all D2DC devices have a pre-specified initial speed and direction set randomly from the beginning of the simulation. However, in each TS, each D2DC device can change its speed from the initial value to the speed threshold value (see Section IV) or vice versa, in a random manner, before the execution of the transmission mode selection process. After this process, if the device is selected again to be a D2DC[8] it resets its speed to the initial speed of the TS.
9) when the simulation is initiated (TS = 0, as shown in Section V-B), all devices have a speed below or equal to the speed threshold (e.g., pedestrian speed). Also, the D2D devices that selected their transmission mode as D2D-Relay (D2DSHR or D2DMHR) at that time step, in the subsequent runs they do not change speed and transmission mode,[9] whilst the rest of D2D devices (that are D2DCs) can.
10) in any subsequent TS, when a D2DC selects a speed equal to the speed threshold (e.g., pedestrian speed) and changes its transmission mode to D2DSHR or D2DMHR, in the subsequent runs, it is not allowed to change its speed and transmission mode (as explained above).
11) the Doppler effect [43] is not considered. How the Doppler effect can affect the decision-making process will be considered in future investigations.
12) The proposed network system for the D2DSHR Devices that act as Cluster Head (CH). The local entity CH that is included in each cluster (shown as D2D-Relay in Fig. 3) acts as the control unit that resolves the conflicts (in terms of interference) among D2D Relays client devices (D2DC) with the use of the WiFi Direct protocol. Additionally, the LTE Direct frequencies are assumed to use orthogonal resources to the macro-BS with the use of the preassigned by the BS frequency band; thus, the problem of Intercarrier interference (ICI) between the D2DSHR, D2DMHRs and the macro-BS is not addressed but handled by the connection protocols. This is consistent with the self-autonomy envisioned for D2D devices.
13) Note that the transmission mode related to WiFi Direct/LTE Direct protocol used cases of the D2D-Relay Devices are the following:
    - when the transmission mode is D2DSHR and acts as CH, it serves a maximum number of 200 users (WiFi Direct restriction) and can accept connections from other devices of the D2DC mode.
    - when the transmission mode is D2DMHR, the maximum number of clients that the device can share is one (LTE Direct restriction) and can accept connection from another device of mode D2DMHR or D2DSHR.
    - when the shared device is the BS, it can serve more than one and less than Q devices (see Section III-B) of mode D2DSHR and D2DMHR devices or serve every other UE under the mobile network.

[8]The reason is for our simulation to be more dynamic and to simplify the calculations and simulation. Moreover, to have a straightforward interpretation of the results and to show the potential of each approach. Another reason is to evaluate each approach in terms of SE and PC per speed in each TS.

[9]This is a realistic assumption because in the subsequent Time steps the device is sharing bandwidth the speed must be low. Also, this assumption is for simplification of the simulation and results.

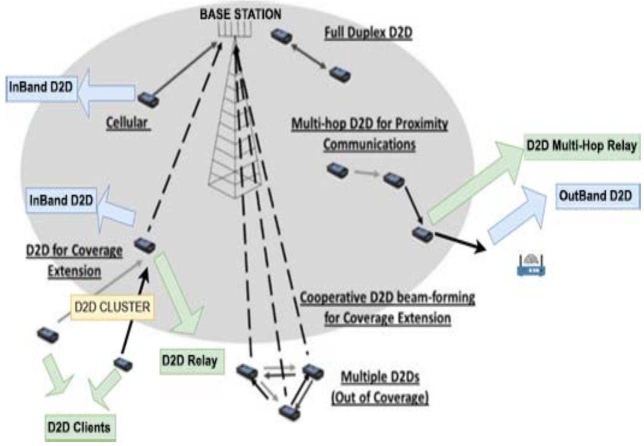


FIGURE 3. A typical D2D communication network.

Furthermore, according to the standards, the following restrictions apply:

- The maximum number of D2DCs connected to D2DSHR is restricted to 200 (WiFi Direct).
- The number of D2D-Relay connected to D2DMHR is restricted to 1 (LTE Direct).
- The maximum Distance between D2DSHR and D2DC is 200m (WiFi Direct).
- The maximum Distance between D2DMHR, D2DSHR to D2DMHR is 600m (LTE Direct).
- The maximum Distance for standard connection is 1000m.

B. SYSTEM MODEL

In our approach, we consider a dynamic environment where the devices are moving at a certain speed and direction. The mobile system is considered as an uplink D2D Orthogonal Frequency-Division Multiple Access (OFDMA) cellular network that consists of the deployment of D2D Single-Hop Relays (D2DSHR) that act as Cluster Heads (CH), D2DMHRs (D2DMHR) that act as intermediate nodes in backhauling links, and D2DC Devices (D2DC) that connect to D2DSHR Devices. Furthermore, each D2DSHR serves as CH and shares its bandwidth with its D2DCs using WiFi Direct. Additionally, the D2DMHRs serve as intermediate nodes in the backhauling path toward the gateway (i.e. the BS), providing better connection links and bandwidth towards the BS. For the backhauling links, LTE Direct is used between the intermediate inter-connected D2D devices, and for direct connections towards the BS, regular mobile

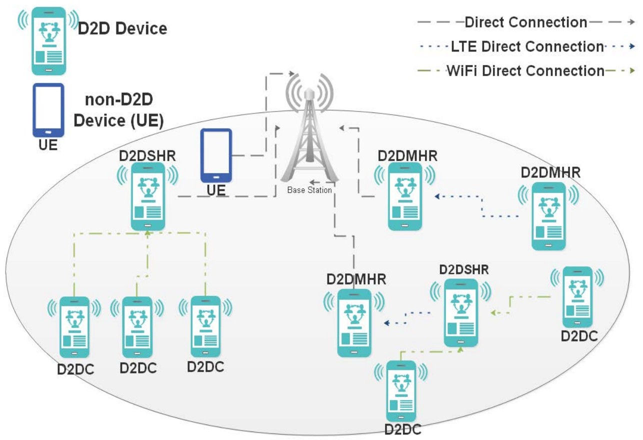


FIGURE 4. Snapshot of a typical D2D communication network showing D2DSHR,D2DMHR,D2DC and UE connections.

connections are used. Regarding the transmission mode cases of the D2D-Relay sharing devices, it's worth noting the following: i) when the transmission mode is D2DSHR, the device serves a maximum number of 200 users (WiFi Direct restrictions) and can accept connections from other devices of the D2DC mode; ii) when the transmission mode is D2DMHR, the maximum number of clients that the device can share is one (LTE Direct restrictions) and can accept a connection from another device of mode D2DMHR or D2DSHR; and iii) when the shared device is the BS, it can serve a limited number of D2D devices of mode D2DSHR and D2DMHR, or serve every other UE under the mobile network.

We consider a D2D enabled 5G/6G communication network (see Fig 4). Within the coverage area of the BS bs, there are Q D2D devices, indexed by $q=\{1,2,..,Q\}$, such that d_q denotes the D2D-Device with index q. Next, we extend this set with two special cases as follows. Index $q=0$, which is reserved for the bs, denoted as q_0, and index $Q+1$, which is reserved for a non-D2D UE device with a standard mobile connection connecting the UE to the bs, denoted as q_{Q+1}. The reason for including a non-D2D UE device in the set of devices is so as to use it for comparison between a standard mobile connection towards the BS with either a connection of LTE Direct or WiFi-Direct (discussed in Assumptions at III-A.13). Note that when a new D2D device enters the D2D communication network, a reordering of the set takes place, ensuring that the UE always has the last index. Thus the extended set becomes $q=\{0,1,2,..,Q,Q+1\}$.

The set q includes two subsets. The subset of R D2D-Relay devices, indexed by $n=\{\Gamma,\ldots,N\}$, $n \subset q$. Further, each D2D-Relay device is also characterised by its transmission mode $t=\{D2DSHR,D2DMHR,BS\}$ such that r_n^t denotes the D2D-Relay with index n and transmission mode t. Furthermore, the set n is extended to include the bs, with index 0, i.e. $n=\{0,\Gamma,\ldots,N\}$. The subset of M D2D-Client devices are indexed by $m=\{\Delta,\ldots,Q,Q+1\}$, $m \subset q$, with each D2D-Client device characterised by its transmission mode D2DC such that c_m^{D2DC} denotes the D2D-Client device with index m that has D2DC as the selected transmission mode. Note that the special transmission mode UE indicates a direct connection with the bs, in which case $m = Q + 1$. Also, note that the special case of the reference UE device is appended to the set of D2D-Client devices as $m=\{B,\ldots,Q,Q+1\}$ with transmission mode UE. Thus c_{Q+1}^{UE} denotes this special case.

The bs is also associated with Z paths that are directed towards it, indexed by $k=\{1,\ldots,Z\}$, where each P^k path is defined by a set of directed links starting with one or more D2D device(s). Each link in the path is denoted by l_{q_i,q_j} : $i,j \in \{q\}$.

Moreover, the nodes q_i and q_j in a path link are connected with the information flow from q_i to q_j ($q_i \rightarrow q_j$). This can be represented by an adjacency matrix A such that $a(i,j)^k = 1$ if node q_i is connected to node q_j in the path k with direction from q_i to q_j ($q_i \rightarrow q_j$). Note that the path always starts with one or multiple D2D-Client device(s) connected to a D2DSHR, or it starts with any other D2D-Relay device (i.e., D2DSHR, D2DMHR) and always ends with a connection to the bs, and each link has a direction towards the bs. Also, the intermediate D2D devices in the path are D2D-Relay devices (discussed in Assumptions at III-A.14). Since each path finishes at the bs (q_0), we can backwards trace all paths towards the bs by traversing from column 0 to trace all devices emanating from that path (see example in problem formulation).

Furthermore, for each link in the path we associate the types of transmission mode at each end of the link as a set $cm(P^k)$ that contains as elements (o, t) the connection modes of each link. The association of each link with its transmission mode is denoted as $l_{q_i^o,q_j^t}$, where $t=\{D2DSHR,D2DMHR,BS\}$, $o=\{D2DC,D2DSHR,D2DMHR,UE\}$. Also, for each link we associate the spectral efficiency $e(l_{q_i^o,q_j^t})$, as defined in Eq. 13, and the Power Consumption $p(l_{q_i^o,q_j^t})$, as defined in Eq. 17. Also, the number of D2D devices that utilise a sharing link connected to a sharing D2D device in a path P^k is denoted by R_j^k, which can be calculated from the adjacency matrix for the row(s) that have the value "1" at the same column (q_j).

Whenever a new device enters the network, if it is a D2DC, it is introduced as the one before the last item in the list (index Q), thus retaining the UE as the (Q+1) item in the set. Moreover, if the D2D device is a D2D-Relay (i.e., D2DSHR, D2DMHR), then it will be added as the last item of the D2D-Relays set; thus, it will be assigned the index N in the set of Relays.

Additional symbols used within the system model and the problem formulation description are shown in the Table 6 of the Appendix.

Below we present the formulation of this problem.

C. PROBLEM FORMULATION

In our previous work [15]–[19] we investigated the problem of identifying the best paths that include all D2D devices toward the BS in terms of SE and PC in a static environment. In the problem formulation of the current work, we consider the problem of identifying the best paths that include all D2D devices toward the BS in terms of SE and PC in a dynamic environment where each device has speed and direction.

Each path must consist of a set of links, where each link is associated with two D2D nodes. The first node is the node that can utilise a sharing link (i.e., UE, D2DC, D2DSHR, D2DMHR), and the second node is the sharing node (i.e., BS, D2DSHR, D2DMHR). Note that the last link of the path always connects to the BS as the last sharing device. The most challenging task when selecting the transmission mode between two devices in our problem is to satisfy the constraints of the sharing nodes, emanating from the bandwidth restrictions and the limit in the number of clients connections due to the specific protocol used (i.e., WiFi Direct, LTE Direct).

More specifically, we aim to construct the paths from all D2D devices towards the BS and identify each path link. That is, in each link, identify where the D2D device will connect to, the type of connection it will select (i.e., WiFi Direct if connected to a D2DSHR, LTE Direct if connected to a D2DMHR, direct mobile if connected to the BS), and the transmission mode (i.e., D2DC or D2DSHR or D2DMHR or BS) of both nodes sharing the link. This selection of path, links and transmission mode of the D2D nodes should be made in such a way so as to maximise the Total Sum Rate[10] (SR) of the network, either directly or via a path of D2D-Relay devices, whilst keeping the PC in a dynamic environment at a minimum. So, our objective is to maximise the Sum Rate whilst keeping the Power Consumption to a minimum through the transmission mode Selection of the D2D devices and the selection of the most profitable link/path connecting the devices.

Thus, our decision variables are whether a link can be established (using a binary link selection variable called $(SV(l_{q_i^o,q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o,q_j^t})) \in 0, 1)$ with the 'best' transmission modes of the sharing device (t) and the client device (o). Furthermore, when a device selects to be a D2D device that is connected (q_i^o) to a specific link sharing device (r_n^t), some constraints must be satisfied in order for the selection variable SV to result in "1".

The optimisation problem is:

$$\max_{(t,o,SV(l_{q_i^o,q_j^t},R_j^k,s(q_j^t),x(l_{q_i^o,q_j^t}))} \{y^{total}\} \tag{1}$$

$$\min_{(t,o,SV(l_{q_i^o,q_j^t},R_j^k,s(q_j^t),x(l_{q_i^o,q_j^t}))} \{p^{total}\} \tag{2}$$

$$s.t.$$

$$C1: R_j^k \in \{1, 2, .., 200, Q\} \tag{3}$$

$$C2: s(q_j) \le s^{max} \;\; m/s \tag{4}$$

$$C3: x(l_{q_i^o,q_j^t}) \le X : X \in \{x_{LTE\_D}^{max}, x_{WIFI\_D}^{max}, x^{max}\} \tag{5}$$

$$C4: \sum_{\{l_{q_i^o,q_j^t} \in P^k\}} p^t(l_{q_i^o,q_j^t}) \le p^{max} \tag{6}$$

$$C5: \exists!\, q_i^o \in \{q\}\; \forall i: \{\, q_i^o \; and \; l_{q_i^o,q_j^t}\} \tag{7}$$

$$C6: \forall\, q_i^o, q_j^t \;\exists\, i, j \; and \; l_{q_i{}^o,q_j{}^t} \in P^k \{l_{q_i{}^o,q_0{}^{bs}}; a(i,0)^k = 1\} \tag{8}$$

where y^{total}, p^{total} are given by Eq. 14 and Eq. 19 respectively (see Appendix A).

$$y^{total} = w(l_{0,(Q+1)}) \cdot \sum_{k=1}^{K-1}\{ \sum_{\{l_{q_i^o,q_j^t} \in P^k\}} (W(l_{q_i^o,q_j^t}) \times \cdot (e_{l_{q_i^o,q_j^t}}) \cdot SV(l_{q_i^o,q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o,q_j^t})))\}$$

$$p^{total} = \sum_{k=1}^{K-1}\{ \sum_{\{l_{q_i^o,q_j^t} \in P^k\}} (P(l_{q_i^o,q_j^t}) \times \cdot SV(l_{q_i^o,q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o,q_j^t})))\}$$

where $t \in \{D2DSHR, D2DMHR, BS\}$, $o \in \{D2DC, D2DSHR, D2DMHR\}$

The constraints are justified below:

1) The constraint on the number of already connected devices to the sharing device is required due to the LTE Direct and WiFi Direct limitations on the number of clients it can support (i.e., LTE Direct can only support one client, and WiFi Direct can support 200 Clients).
2) The max speed that a sharing device can have is required due to limitations on the speed that a service device can have in order to share its link over some time.
3) The max distance between the sharing device and the D2D device that is utilising the sharing link is required due to the coverage limitation that we have among the two nodes of the link, which is dependent on the modes o,t that are selected (as discuss in assumptions).
4) The presence of inter-cell interference is required due to the maximum power consumption imposed by the network. Thus, in each link constructed by a sharing device and a device that will utilise the sharing device and act as a client, the channel link power consumption $p(l_{q_i^o,q_j^t})$ is considered to be the transmit power of the D2D sharing device on the specified channel connection. The sum of all link transmission power overall paths should be less than the maximum power consumption of the whole network.
5) A D2D device can only connect to a sharing D2D device and act as a client to this device at only one link $l_{q_i^o,q_j^t}$ for all the links and all paths.
6) A D2D device can only be a part of a link when the corresponding path is directly connected to the BS.

Fig. 6 shows an example system architecture and the problem formulation. Indicatively, in Fig. 6 we have the following sets:

[10]The total sum rate is the aggregated Data Rate of all links. The Data Rate of each link is estimated using Eq. 12 and Eq. 13.

- The D2D devices set $q=\{0,1,2,..,7,8\}$, UE is q_8 and BS is q_0
- D2D-Relay devices set $n=\{0,1,2,3,7\}$, BS is r_0^{BS}
- The adjacency matrix A is

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

  where the rows are the nodes q_i and the columns are the q_j.
- The paths are:
  - $P^1 = \{(3 \rightarrow 7), (7 \rightarrow 1), (1 \rightarrow 0)\}$
  - $P^2 = \{(4, 5, 6 \rightarrow 2),\ (2 \rightarrow 0)\}$ and
  - $P^3 = \{(8 \rightarrow 0)\}$
- The connection mode types are:
  - $cm(P^1) = \{(D2DMHR \rightarrow D2DMHR), (D2DMHR \rightarrow D2DMHR), (D2DMHR \rightarrow bs)\}$
  - $cm(P^2) = \{(D2DC, D2DC, D2DC \rightarrow D2DSHR), (D2DSHR \rightarrow bs)\}$ and
  - $cm(P^3) = \{(UE \rightarrow bs)\}$
- D2DCs set $m=\{4,5,6\}$ and
- Number of D2D devices in a path $R_2^2 = 3$, $R_7^1 = 1$, and $R_2^1 = 1$

Note 1: The sum of ones in column 0 of the adjacency matrix provides the total number of paths leading to the *bs*. The paths can be extracted from the adjacency matrix as follows: Considering Path "k=2" we begin from column index "0" (*bs*) in the adjacency matrix and find the row with an index 2. Since it has a "1" as a value (indicating a path to the *bs*), then we move to column "2" and identify the row(s) that have a value of "1". From there, we move to the column(s), which have an entry of "1" in a particular row. We continue backtracing until for the specific label(s) of row(s) the value of "1" is not found in that column. This is shown in Fig. 5 where for path"k=1" we use a broken line and for path "k=2" a solid line.

Note 2: The D2DC set can also be extracted from the adjacency matrix by having the count of "1" non-zero entries along the rows be more than zero.

In the next section we implement in a heuristic way a specific DAI framework and Plan considering a dynamic environment and thereafter evaluate its performance. To further simplify the problem, in our approach, we examine the Spectral Efficiency by setting the $W(l_{q_i^o,q_j^t})$ to "1" and that we consider the power consumption of each link the same (independently of the protocol used, i.e., LTE Direct, WiFi Direct). As a result, we accept that the Weighted Bandwidth rate[11] among the WiFi Direct, BS Link, and LTE Direct is the same. Therefore, our Eq. 14 and Eq. 19 are simplified as in Eq. 9 and Eq. 10. Additionally, the aforementioned assumptions and constraints on the calculation of the SE are accounted for in our system. So, our optimisation objective is to maximise the optimal sought Total SE (Eq. 9) that will result in a decrease of the Total Power Consumption (Eq. 10). The optimisation formulation is given by:

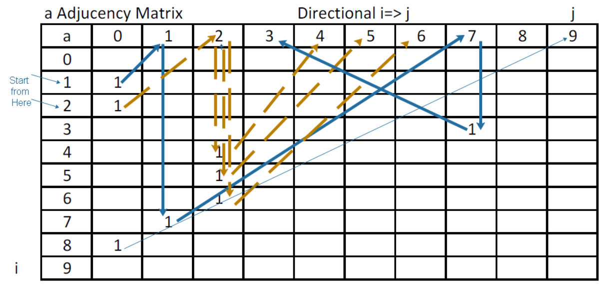


FIGURE 5. Example traverse of adjacency matrix.

$$Max\_Total\_SE = \sum_{k=1}^{K-1}\{\max\{\sum_{l_{q_i^o,q_j^t} \in P^k} e(l_{q_i^o,q_j^t}) \times \cdot SV(l_{q_i^o,q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o,q_j^t}))\}\} \tag{9}$$

$$Min\_Total\_PC = \sum_{k=1}^{K-1}\{\min\{\sum_{l_{q_i^o,q_j^t} \in P^k} p(l_{q_i^o,q_j^t}) \times \cdot SV(l_{q_i^o,q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o,q_j^t}))\}\} \tag{10}$$

IV. ENHANCEMENTS OF THE INVESTIGATED APPROACHES TO SUPPORT DYNAMIC ENVIRONMENT

In this section, the enhancements performed on DAIS, DSR and SHRA approaches to consider the dynamics of the Mobile Network and allow them to react and adapt to D2D network topology changes are described. These relate to changes in UE speed, UE direction, number of devices in a D2D communication network and other conditions such as change of TP and change of the network topology through time (through TSs).

A. ENHANCED DAIS PLAN TO SUPPORT DYNAMIC ENVIRONMENT

Our target is to adjust the DAIS plan to dynamically re-form the backhauling connections and clusters over time, based on the D2D network topology changes, targeting better SE and PC. This is achieved by introducing, in addition to the BPL and WDR thresholds (see Section II-A4.a), the Speed Threshold in the transmission mode selection process. The aim of this threshold, which is referred to as

[11] The Weighted Bandwidth rate can be calculated as a constant ratio that indicates the rate between the bandwidth of the chosen UE technology (i.e., WiFi Direct, LTE Direct) and the bandwidth of the direct link towards BS.

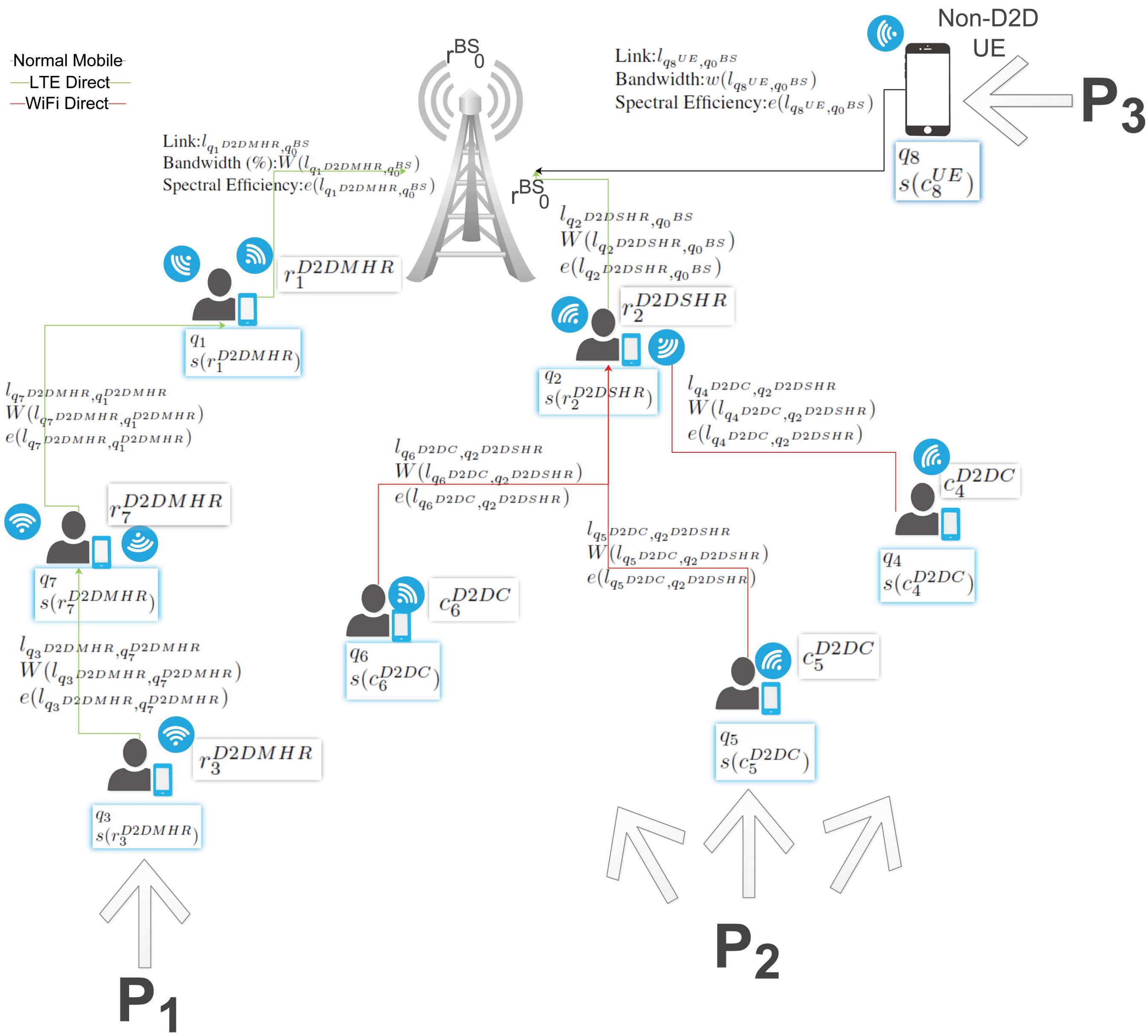


FIGURE 6. Example of the problem formulation.

"MAXSpeed_D2D-Relay" in Alg. 1, is to restrict a D2D device that is moving more than this threshold value from becoming a D2D-Relay, as this would cause bad connections.

The enhanced DAIS Plan is shown in Alg. 1. In our evaluation, we set the Speed threshold equal to 15m/s (i.e., 54Km/h), and the BPL and WDR Threshold values (referred to as DeviceBatteryThreshold and PERCDataRate, respectively) are set based on our findings in [18], [19] and provided in Section II-A4.a. Note that the WDR threshold value will take depends on the number of the D2D devices in the network (i.e., <= 200%20 and >200 %35). This info is made known through LTE ProSe messages that the D2D-Relays share with all other devices, incorporating in the message, among others, their WDR and GPS Coordinates as well as the number of D2DCs they support.

B. ENHANCED DSR APPROACH TO SUPPORT DYNAMIC ENVIRONMENT

The enhanced DSR approach is adapted to use and accommodate the algorithm defined for DAIS (shown in Section IV-A) and utilise the same terms, parameters and some of its thresholds (i.e., BPL Threshold, Speed Threshold). This provided the ability for the enhanced DSR approach to operate in a distributed manner and allow an entering D2D device to alter the D2D network structure.[12] Additionally, the Sum Rate metric used in the enhanced DSR is calculated as

[12]The entering D2D device can alter the D2D network structure and either: i) replace an existing D2D-Relay device and take its role accordingly; or ii) break an existing sharing connection of a D2D-Relay (with another D2D device) update its transmission mode (if needed) and connect with it accordingly.

Algorithm 1 Enhanced DAIS Plan for Transmission Mode Selection in Dynamic D2D Network Topologies

D: maximum distance allowed between the Entering UE device and the candidate to connect to D2D-Relay devices
WDR_0: initial WDR of the entering UE device (WDR of the direct link between the UE and the BS)
Speed: the speed of the entering UE device
DeviceBatteryThreshold: 75%
PERCDataRate: 20% for $<$ 200 D2D devices else 35%
MAXSpeed_D2D-Relay: 15 m/s (54 Km/h); low vehicular speed)
T: a set containing information acquired by the UE device through LTE ProSe Messages broadcast by each D2D-Relay of the Network
procedure TransmissionModeSelectionWithWDR(T_{th}, D, WDR_0)
    By considering info included in T_{th} calculate the following with their associated WDRs among entering device and the D2D-Relay:
    $maxD2DSHR \Rightarrow WDR_1$, $maxD2DMHR\_NC \Rightarrow WDR_2$,
    $maxD2DSHR\_NC\_D2DMHR \Rightarrow WDR_3$,
    $maxD2DSHR\_UED2DMHR \Rightarrow WDR_4$,
    $maxD2DMHR\_MultiHop \Rightarrow WDR_5$
    if $\{\exists\ maxD2DSHR$ *and* $\{WDR_0 \times (1 + \text{PERCDataRate})\} \leq WDR_1\}$ **then**
        Connect UE as D2DC to maxD2DSHR using WiFi Direct
    else if $\{\exists\ maxD2DMHR\_NC$ *and* $\{WDR_0 \times (1+\text{PERCDataRate})\} \leq WDR_2\}$ **then**
        Request from maxD2DMHR_NC D2D-Relay to become D2DSHR
        Connect UE as D2DC to maxD2DMHR_NC using WiFi Direct
    else if $\{\exists\ maxD2DSHR\_NC\_D2DMHR$ *and* $Speed <$ MAXSpeed_D2D-Relay *and battery* $>$ *DeviceBatteryThreshold and* $\{WDR_0 \times (1 + \text{PERCDataRate})\} \leq WDR_3\}$ **then**
        Request from maxD2DSHR_NC_D2DMHR D2D-Relay to become D2DMHR
        Connect UE as D2DSHR to maxD2DSHR_NC_D2DMHR using LTE Direct
    else if $\{\exists\ maxD2DSHR\_UED2DMHR$ *and* $Speed <$ MAXSpeed_D2D-Relay *and battery* $>$ *DeviceBatteryThreshold and* $\{WDR_0 \times (1 - \text{PERCDataRate})\} \geq WDR_4\}$ **then**
        Set UE as D2DMHR
        Request from maxD2DSHR_UED2DMHR D2D-Relay to become D2DSHR
        Connect D2DSHR (maxD2DSHR_UED2DMHR) to D2DMHR (UE) using LTE Direct
    else if $\{\exists\ maxD2DMHR\_MultiHop$ *and* $Speed <$ MAXSpeed_D2D-Relay *and battery* $>$ *DeviceBatteryThreshold and* $\{WDR_0 \times (1 + \text{PERCDataRate})\} \leq WDR_5\}$ **then**
        Set UE as D2DSHR
        Connect UE as D2DSHR to maxD2DMHR_MultiHop using LTE Direct
    else
        Set UE as D2DMHR
        Stay connected to BS
    end if
end procedure

the sum of all data rates of each link in the network. Moreover, it has an additional threshold called the Date Rate (DR) threshold, which acts similarly to the WDR threshold of DAIS and restricts the link creation according to the data rate of the link achieved with the BS and the data rate of the proposed link to a D2DSHR/D2DMHR/BS. The implementation of the enhanced DSR Approach is shown in Alg. 2 and is executed whenever a new D2D device enters the D2D communication network.

With DSR, once a UE device enters the D2D network for the first time, the data rate of the link between the UE device and the BS is estimated (we refer to this as the initial Data Rate). Afterwards, other candidates' indirect paths between the UE device and other neighbouring D2D-Relays towards the BS are identified, their associated Data Rate is calculated, and the best path that achieves the highest Sum Rate is selected. Based on the chosen path (i.e., direct or indirect path), the transmission mode of the UE device is selected and adopted. Basically, the following steps are executed:

1) The entering UE device, requests from BS the network topology, such as the number of D2D devices supported by the D2D-Relay, coordinates of the D2D device and the D2D device that each D2D-Relay connects to next (with their associated link data rate), along the path to the BS/GW.
2) For each D2D-Relay device detected in the proximity of the UE device, a D2D communication path is identified, having the D2D-Relay device as a starting point, and the Data Rate of the link between the entering UE with the D2D-Relay device is calculated.
3) The achievable Sum Rate of each path is calculated and sorted in descending order based on the Sum Rate achieved. In this Sum Rate value, the data rate of the link between the entering UE device with the path's starting D2D-Relay device is also considered.
4) Starting from the D2D-Relay device related to the path with the best Sum Rate achieved, up to five of the D2D-Relay devices that meet the following conditions are selected:
   - A D2D-Relay operates as D2DSHR and is located within a Wi-Fi Direct (200 m) range from the entering UE device. This is referred to as maxSRD2DSHR in Alg. 2.
   - A D2D-Relay operates as a D2DMHR with no connections and is located within a Wi-Fi Direct range from the entering UE device. This is referred to as maxSRD2DMHR_NC in Alg. 2.
   - A D2D-Relay operates as a D2DSHR with no connections and is located within a range of LTE Direct (600 m) from the entering UE device. This is referred as maxSRD2DSHR_NC_D2DMHR in Alg. 2.
   - A D2D-Relay that operates as a D2DSHR with no connections, located within a range of LTE Direct and with a Sum Rate lower than the data rate of the link between the UE device and the BS (referred to as the initial Sum Rate). This is referred in Alg. 2 as maxSRD2DSHR_UED2DMHR.
   - A D2D-Relay operates as a D2DMHR with no connections and is located within the range of LTE Direct from the entering UE device. This is referred to as maxSRD2DMHR_MultiHop in Alg. 2.
5) A Transmission Mode is selected for the UE device. The implementation details appear in Alg. 2.

Similarly to the enhanced DAIS approach described above, for the Speed Threshold, referred as "MAXSpeed_D2D-Relay", we consider a low vehicular speed (i.e., 15 m/s, 54Km/h). Also, for the Battery Power Level (BPL) threshold, referred as "DeviceBatteryThreshold", a value of 75% is used. Additionally, the Date Rate (DR) threshold (set empirically to 35%), referred to as "DataRateThreshold" in Alg. 2 is used. To this end, the enhanced DSR approach allows a UE device to operate in D2D-Relay transmission mode only aforesaid thresholds are satisfied.

Algorithm 2 Enhanced DSR Plan for Transmission Mode Selection in Dynamic D2D Network Topologies

D: maximum distance allowed between the Entering UE device and the candidate to connect to D2D-Relay devices
DR_0: initial DR of the entering UE device (DR of the direct link between the UE and the BS)
Speed: the speed of the entering UE device
DeviceBatteryThreshold: 75%
DataRateThreshold: 35%
MAXSpeed_D2D-Relay: 15 m/s (54 Km/h); low vehicular speed)
T: a set containing information acquired by the UE device through BS for all D2D-Relays of the Network
procedure TransmissionModeSelection(T_{th}, D, DR_0)
  By considering info included in T_{th} calculate the following with their associated DRs among entering device and the D2D-Relay:
  maxSRD2DSHR $\Rightarrow DR_1$, *maxSRD2DMHR_NC* $\Rightarrow DR_2$,
  maxSRD2DSHR_NC_D2DMHR $\Rightarrow DR_3$,
  maxSRD2DSHR_UED2DMHR $\Rightarrow DR_4$,
  maxSRD2DMHR_MultiHop $\Rightarrow DR_5$
  if {$\exists$ *maxSRD2DSHR and* $\{DR_0 \times (1 + \text{DataRateThreshold})\} \leq DR_1$} **then**
    Connect UE as D2DC to maxD2DSHR using WiFi Direct
  else if {$\exists$ *maxSRD2DMHR_NC and* $\{DR_0 \times (1+\text{DataRateThreshold})\} \leq DR_2$} **then**
    Request from maxD2DMHR_NC D2D-Relay to become D2DSHR
    Connect UE as D2DC to maxD2DMHR_NC using WiFi Direct
  else if {$\exists$ *maxSRD2DSHR_NC_D2DMHR and Speed* < MAXSpeed_D2D-Relay *and battery* > *DeviceBatteryThreshold and* $\{DR_0 \times (1 + \text{DataRateThreshold})\} \leq DR_3$} **then**
    Request from maxSRD2DSHR_NC_D2DMHR D2D-Relay to become D2DMHR
    Connect UE as D2DSHR to maxSRD2DSHR_NC_D2DMHR using LTE Direct
  else if {$\exists$ *maxSRD2DSHR_UED2DMHR and Speed* < MAXSpeed_D2D-Relay *and battery* > *DeviceBatteryThreshold and* $\{DR_0 \times (1 - \text{DataRateThreshold})\} \geq DR_4$} **then**
    Set UE as D2DMHR
    Request from maxSRD2DSHR_UED2DMHR D2D-Relay to become D2DSHR
    Connect D2DSHR (maxSRD2DSHR_UED2DMHR) to D2DMHR (UE) using LTE Direct
  else if $\exists$ *maxSRD2DMHR_MultiHop and Speed* < MAXSpeed_D2D-Relay *and battery* > *DeviceBatteryThreshold and* $\{DR_0 \times (1 + \text{DataRateThreshold})\} \leq DR_5$} **then**
    Set UE as D2DSHR
    Connect UE as D2DSHR to maxSRD2DMHR_MultiHop using LTE Direct
  else
    Set UE as D2DMHR
    Stay connected to BS
  end if
end procedure

1) THE DATE RATE THRESHOLD USED BY DSR

DR Threshold is used by DSR for four purposes. By using the DR Threshold, an entering UE device in the D2D network:

- Can perform a quality check of the D2DSHR in order to connect to it as a D2DC.
- Can perform a quality check of the D2DMHR in order to connect to it either as a D2DC or a D2D-Relay.
- Can replace a D2D-Relay device and take its role if the total Sum Rate with the new UE device as D2D-Relay in the path is greater than the current Sum Rate achieved.
- Can connect to a D2D-Relay device in its proximity and act as a D2DSHR.

Similarly to WDR, the DR threshold is used for restricting the creation of new D2D-Relays. More specifically, when a UE device attempts to connect as a client to a D2D-Relay device, this threshold is used for quality check in order to evaluate how good enough in terms of Total Sum Rate the Data Rate of: i) an entering UE device to become a D2D-Relay; and ii) an existing D2D-Relay device to keep its mode and connection versus an entering UE device.

C. ENHANCED SINGLE HOP RELAY APPROACH

In order to be fair in our investigation, we enhanced SHRA to consider the same parameters as the other approaches. The SHRA approach is enhanced in our research in the sense that the D2DSHR accepts more than one connection and serves as a regular D2DSHR rather than an intermediate D2D device, as the author suggests. As with the previous approaches, the SHRA is modified to use Wi-Fi Direct when selecting D2DSHR with the limitation of distance to clients to 200m and the limitation of the number of clients to 200. The D2D connection distance among two D2D devices is the same as it was defined in the investigated section to the value of "30 meters" as in [20]. Additionally, in this approach, we consider that each D2D device in the network uses LTE ProSe to share its coordinates and transmission mode with all other devices.

V. PERFORMANCE EVALUATION

This section examines, evaluates, and compares the efficiency of DAIS, DSR Approach, SHRA and non-D2D UE under a D2D communications network with a range (10..1000) number of UEs in a dynamic D2D communication network setting. In addition, this examination considers the random change of speed and direction, hence proximity among the D2D devices.

A. EVALUATION OF EXECUTION TIMES AND SIGNALLING OVERHEAD

Due to the importance of the execution time[13] and its dependency of the signalling overhead of each investigated algorithm, we are initially simulate our approaches in terms of signalling overhead and execution time in a dynamic environment. The most important reason to prioritise this investigation is to examine the results from the perspective/view of time to complete each approach and to explain why the results of one approach is expected to be poorer than another. As shown in Table 2, the following observations are made: i) there is a large diversity in the number of messages

[13] time to complete an approach.

that need to be exchanged by each approach; ii) DAIS and SHRA are using a constant execution time (1 TS,100 ms) and it is the same for all instances (i.e., for 10 UEs, 50 UEs, 100 UEs, 200 UEs, 500 UEs, 1000 UEs); and iii) DSR is the only approach that needs an excessive amount of messages to be exchanged, and therefore it takes a lot of time to conclude and decide the transmission mode of the D2D devices.

B. METHODOLOGY

Our examination focuses on the dynamicity of the mobile network. Consequently, we consider changes in the transmission power, speed and direction of the UEs, number of Devices in the network and changes in the D2D network topology through subsequent TSs of execution. Our examination specifies a TS of 100 ms. TS=0 relates to the initial D2D network topology. TS=1 relates to the network topology after 100ms, TS=2 to the network topology after 200ms, and so on. We evaluate the investigated approaches with maximum execution of TS=5 at 1000 UEs. Additionally, to be fair with the time of execution, all approaches, except the DSR approach due to its large execution time (as shown in [18], [19]), are executed every 100ms (i.e., every TS) to adapt to the transmission mode of the D2D devices based on the changes occurred on the D2D network topology.

To simplify the investigated problem, those D2D devices initialized in TS=0 to D2D-Relay mode will keep the same transmission mode (D2D-Relay) and speed (e.g., pedestrian speed) during all TSs of execution. Additionally, for the rest of the D2DCs, if they decide to become D2D-Relays in the subsequent TS, they need to keep the same transmission mode (D2D-Relay) and speed (e.g., pedestrian speed) during all TSs of execution. Also, for the DAIS approach, we assume that the BDIx agents accept any suggestion/proposal from another agent and the suggested action from the other agent is aligned with the agent's Desires. So, the agent replies with an ''accept'' message in each proposal and executes the required actions.

For the DSR approach, we have from previous examinations ([18], [19]) specific delays in the time of executions that makes the approach not appropriate for dynamic environments and as shown in the dynamic investigation shown in Section V-A. More specifically, with the DSR approach, when the number of devices in the network increases, the execution time needed for deciding on the transmission mode selection also increases. This makes the DSR approach not fast enough to be ready for recalculation after a specific TS with the network topology changing rapidly, resulting in degradation of SE and PC. The table of the different time Steps execution according to the number of devices in the D2D network is shown in Table 2. According to this table, the DSR approach runs for the first time with the initial D2D network topology at TS=0 (initial step) for all UEs. Then, it runs a second time at TS=1 to accommodate any changes in the network topology for a device range of 10 to 50. Afterwards, it takes more than the upper limit of our investigation of 5 TSs to finish execution and conclude (as shown in Table 2).

Also, the SHRA (Section IV-C), the Distributed Random clustering approach (Section II-A5), the non-D2D UE Approach (Section II-A5), the DSR Approach (SectionIV-B) and the DAIS Plan/algorithm (Section IV-A) are compared in terms of SE and PC by taking under consideration the dynamics of the Mobile Network. These relate to changes in the transmission power, UE speed, UE direction, number of devices in a D2D communication network, and network topology in different time steps of execution.

As a starting point (i.e., TS=0), we set the initial values of UE speed to 15 m/s, transmission power to 160 mW and UE direction to 90 degrees. Afterwards, we rerun our simulation to examine the behaviour of the different approaches in subsequent TSs (from TS=1 to TS=5) by changing a random parameter (e.g., speed, direction, transmission power) generated by a randomizer and increasing the number of UEs in the D2D network from 10 to 1000 UEs. In most evaluations, we examine the D2D network topology at TS=5 and 1000 UEs cases. Also, the speed and direction are set at a constant 15 m/s and 90 degrees, respectively.

Overall, in our investigation (as shown in Section V-D2), the following have been examined and demonstrated:

- The effect of the transmission power on the dynamic DAIS, in terms of overall power consumption and total spectral efficiency achieved over time with a variable number of Devices. A ''brute force'' investigation was executed for the communication power with values from 160 mW to 60 mW using a decreasing step of 10 mW.
- The behaviour and performance of the investigated approaches in terms of SE and PC considering the dynamics of the Mobile Network. These relate to changes in the transmission power, D2D network topology in different TSs of execution, UE speed, Number of Devices in the network and UE direction.

C. SIMULATION ENVIRONMENT

In the simulation, a range of 10 to 1000 D2D devices was used. The devices are placed in a cell range of 1000 meter radius from the BS using a Poisson Point Process distribution model. We keep the same comparison measurements of performance (Total Spectrum Efficiency and Total Power Consumption) and the same equations/formulas for D2D UEs for battery power level estimation and WDR as in [15]. However, the Total SE and Total PC of the D2D network are calculated as shown in Section III, basically by adding all the achieved data rates of all nodes in the network.

For all approaches, the assumptions of the simulation are shown in Section III-A. Also, the constraints are shown in Section III and the simulation parameters in Table 3. The DAIS and DSR terms and parameters are the same as shown in the Appendix.

The simulation environment is implemented in Java using specific libraries from Matlab 2020a and more specifically the ''5G/LTE Toolbox'' [44] in conjunction with the JADE

TABLE 2. Messages exchange and execution time for 10, 50, 200, 500 and 1000 devices.

Approach	Number of Messages Exchanged	Execution Time (Control Decision Delay) ms	Execution in Number of TSs (approx.)		Approach	Number of Messages Exchanged	Execution Time (Control Decision Delay) ms	Execution in Number of TSs (approx.)
	10 UEs (Running Instance)					200 UEs (Running Instance)		
DAIS	12	2	0		DAIS	256	99	1
Non-D2D UE	10	0.1	0		Non-D2D UE	200	0	0
DSR	215	45	0		DSR	62123	1185	11
DR	2	1	0		DR	3	95	1
SHRA	16	2	0		SHRA	280	99	1
	50 UEs (Running Instance)					500 UEs (Running Instance)		
DAIS	65	9	0		DAIS	556	99	1
Non-D2D UE	50	0.1	0		Non-D2D UE	500	0	0
DSR	1336	100	1		DSR	125790	3495	34
DR	2	9	0		DR	3	312	3
SHRA	67	16	0		SHRA	591	99	1
	100 UEs (Running Instance)					1000 UEs (Running Instance)		
DAIS	230	98	1		DAIS	1058	100	1
Non-D2D UE	200	0.1	0		Non-D2D UE	1000	0	0
DSR	20321	694	7		DSR	501561	5012	50
DR	2	75	0		DR	5	796	7
SHRA	247	99	1		SHRA	1192	100	1

TABLE 3. Simulation parameters.

Simulation Parameters	Value
D2D power	130 mW or otherwise defined [50]–[52]
UE power	260 mW or otherwise defined [50]–[52]
WiFi Direct Radius	200 m [53]
LTE Direct Radius	600 m [54]
BS Range	1000 m [50]–[52]
Path loss exponent (Urban Area)	3.5
BS Antenna gain	40 dB [50]–[52]
UE/D2D antenna gain	2 dB [50]–[52]
PERCDataRate	20% (<=200) and 35% (>200) [18], [19]
DeviceBatteryThreshold	75% [19]
MAXSpeed_D2D-Relay	15 m/s
No	0.0001
D	200 Users
N (no of UEs)	10-1000
Shadowing	Log-normal
Mobility	Dynamic scenario

library [45]–[49]. The hardware used for the simulation is the following: i) an Intel(R) Core(TM) i7-8750H CPU @ 2.20GHz; ii) 24 GB DDR4; iii) 1TB SSD hard disk; and iv) NVIDIA GeForce GTX 1050 Ti graphics card with 4GB DDRS5 memory.

D. RESULTS

This section compares the enhanced DAIS with the non-enhanced DAIS in a dynamic environment in terms of SE and PC. In our belief, the enhanced DAIS should achieve better performance than the non-enhanced DAIS. Also, we examine the effect that the transmission power (TP) has on the DAIS regarding total power consumption and total spectral efficiency (i.e., Total Sum Rate). Also, we analyse the behaviour of the investigated approaches in terms of SE and PC, considering the dynamics of the Mobile Network. This relates to changes in TP and D2D network topology in different TSs of execution, UE speed, UE direction, and Number of Devices in the network.

1) ENHANCED DAIS FOR DYNAMIC COMPARED TO DAIS FOR STATIC

In this section, we compare the enhanced DAIS algorithm in terms of SE and PC over the non-enhanced static DAIS algorithm examined in [15] in a dynamic environment. In this investigation, we run two simulations; the simulations examine the SE and PC when the number of UEs in the network increases from 50 to 1000, while the transmission power (160mW) and the direction (90 Degrees) of the UEs are kept constant. Also, we used the speed (15 m/s) in the first simulation, and in the second simulation, the speed (21 m/s). The results relate to the D2D network topology at TS=5 and examine how each approach can react to the increasing number of UEs with different speeds in terms of SE and PC. As shown in Fig. 7, the best performance in terms of SE and PC is provided by the enhanced DAIS algorithm in both speeds and for all the number of devices.

2) DAIS TP EXAMINATION RESULTS

The effect that the transmission power has on DAIS, in terms of total power consumption and total spectral efficiency (sum rate) achieved, is illustrated in Fig. 8 and Fig. 9. In the scenario used, the TP is reduced from 160 mW to 60 mW, the amount of UEs is increased from 10 to 1000, while the speed (15 m/s) and direction (90 Degrees) of the UEs are kept constant. The results related to the D2D network topology changes that occured from TS=0 to TS=5 are also examined. Thus, this section focuses on how the DAIS approach can react to the changes associated with the link transmission power, network topology changes, and the number of devices in the D2D network.

As observed in Fig. 9, for all time steps, by reducing the transmission power of the communication and increasing the number of UEs (D2D devices), gains are provided

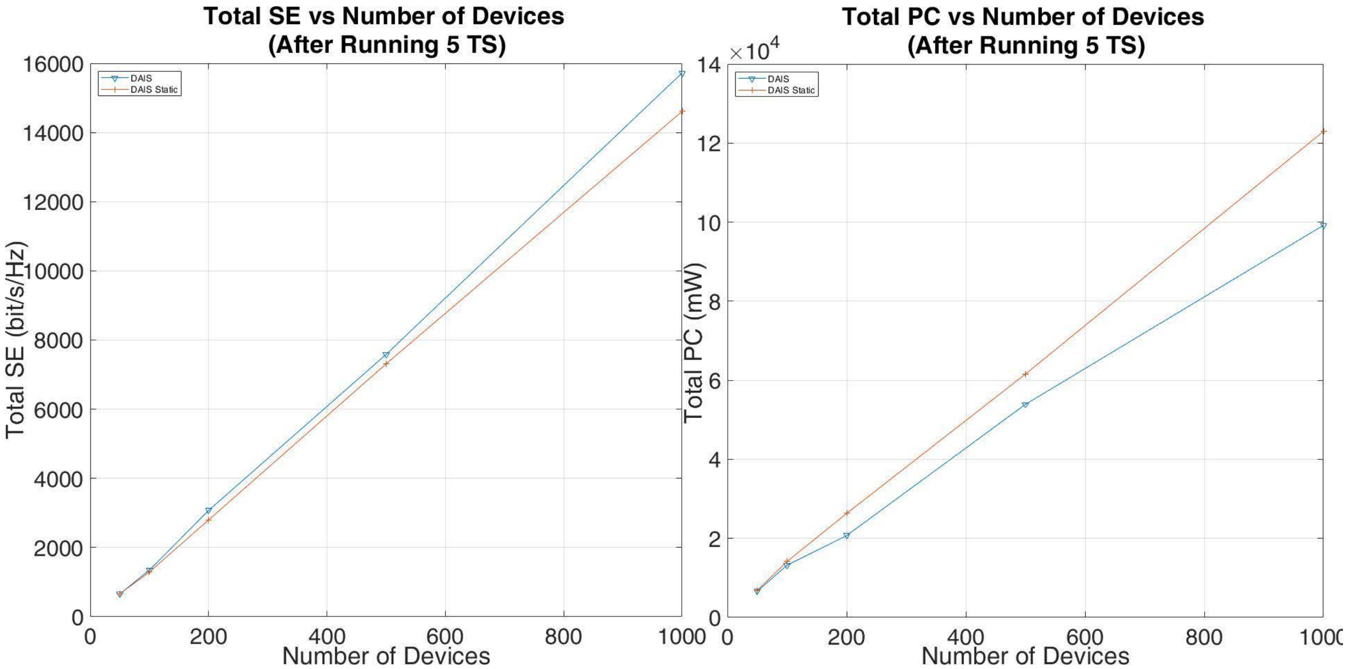
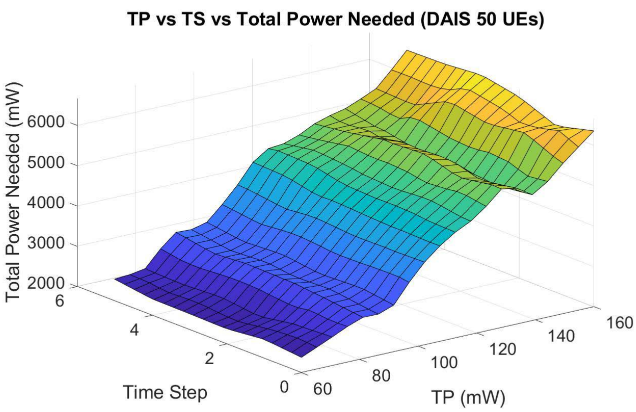
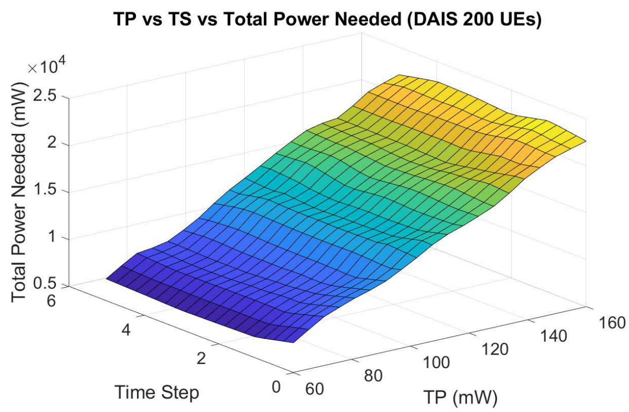


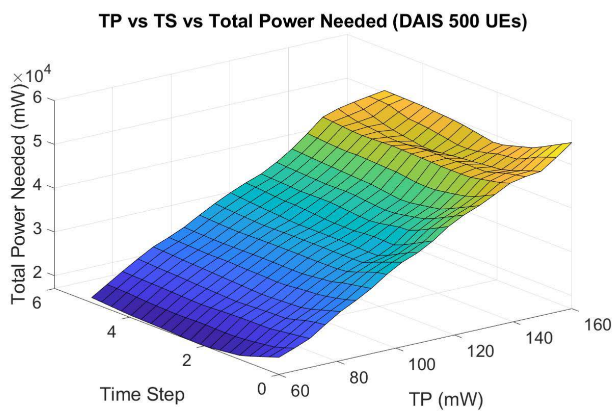
FIGURE 7. Total SE and total PC vs number of devices (50-1000) with 5 TSs, 15 m/s and 22 m/s speeds and 90 degree direction.



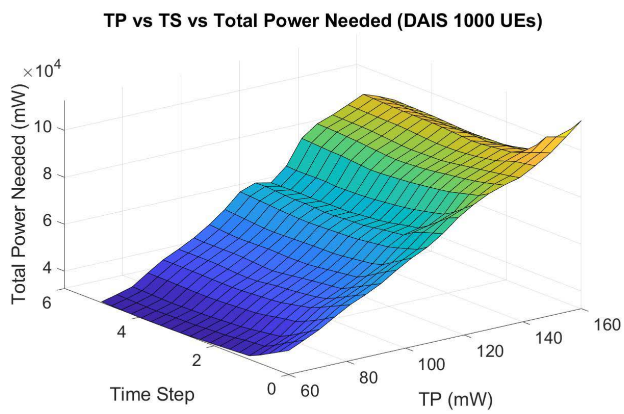
(a) TP vs TS vs Total PC (50 UEs)



(b) TP vs TS vs Total PC (200 UEs)

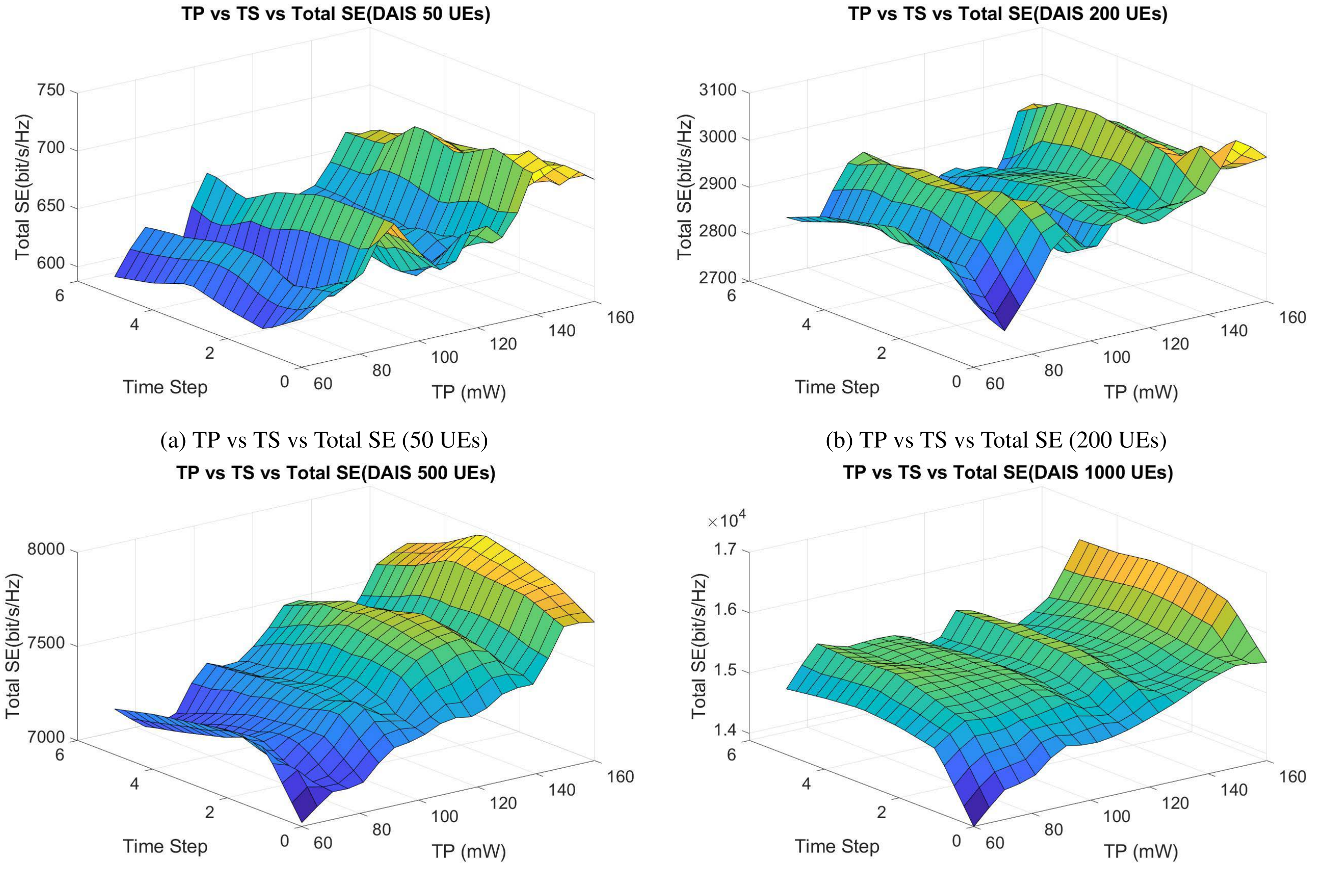


(c) TP vs TS vs Total PC (500 UEs)



(d) TP vs TS vs Total PC (1000 UEs)

FIGURE 8. TP vs TS vs total PC.



(a) TP vs TS vs Total SE (50 UEs)
(b) TP vs TS vs Total SE (200 UEs)
(c) TP vs TS vs Total SE (500 UEs)
(d) TP vs TS vs Total SE (1000 UEs)

FIGURE 9. **TP vs TS vs total SE.**

on the power consumption with a small trade-off on the spectral efficiency. Also, the improvements mentioned earlier vs trade-offs can be seen in more extended ranges in networks with large numbers of devices (500, 1000). More specifically, for any number of UEs in all TSs, the maximum percentage change observed in SE is 22% and in PC is 70%.

Additionally, we can see from the figures that there are some noticeable unexpected increments in measurements in terms of SE when we change the TP at specific values.[14] These unexpected increments follow the same pattern at specific TP levels during each time step. The increments drastically affect the SE in the small number of devices (<= 200). In our opinion, the above increments are related to an increment of cluster numbers under the D2D network that, when reached, are restricted and reduced, along with the backhauling links, by the use of the WDR threshold (as shown in Section II-A4). More precisely, we have the following cases per range of TP and number UEs:

- from 90-100 mW TP with 50 UEs we have an increment of clusters from 7 to 19.
- from 90-100 mW TP with 200 UEs we have an increment of clusters from 49 to 106.
- from 130-140 mW TP with 50 UEs we have an increment of clusters from 6 to 9.
- from 130-140 mW TP with 200 UEs we have an increment of clusters from 59 to 160.
- from 110-120 mW TP with 500 UEs we have an increment of clusters from 99 to 201.
- from 110-120 mW TP with 1000 UEs we have an increment of clusters from 159 to 201.

Moreover, our examination showed that in terms of PC, the changes are smooth with no unsuspected increments. Another important observation is that DAIS seems unaffected in terms of SE and PC irrespective of any changes in the TP, number of devices and TSs in a dynamic environment.

3) BEHAVIOUR OF THE INVESTIGATED APPROACHES ON DYNAMIC TP

This section examines the case where the TP is reduced from 160 mW to 60 mW while the speed (15 m/s), the number of devices (1000 D2D devices) and direction (90 Degrees) of the UEs are kept constant. The results relate to the D2D network topology at TS=5 and examine how each approach can react to TP changes.

[14]For example, with 90-100 mW TP for 50 UEs; with 130-140 mW TP for 200 UEs; and with 110-120 mW TP for 500 and 1000 UEs.

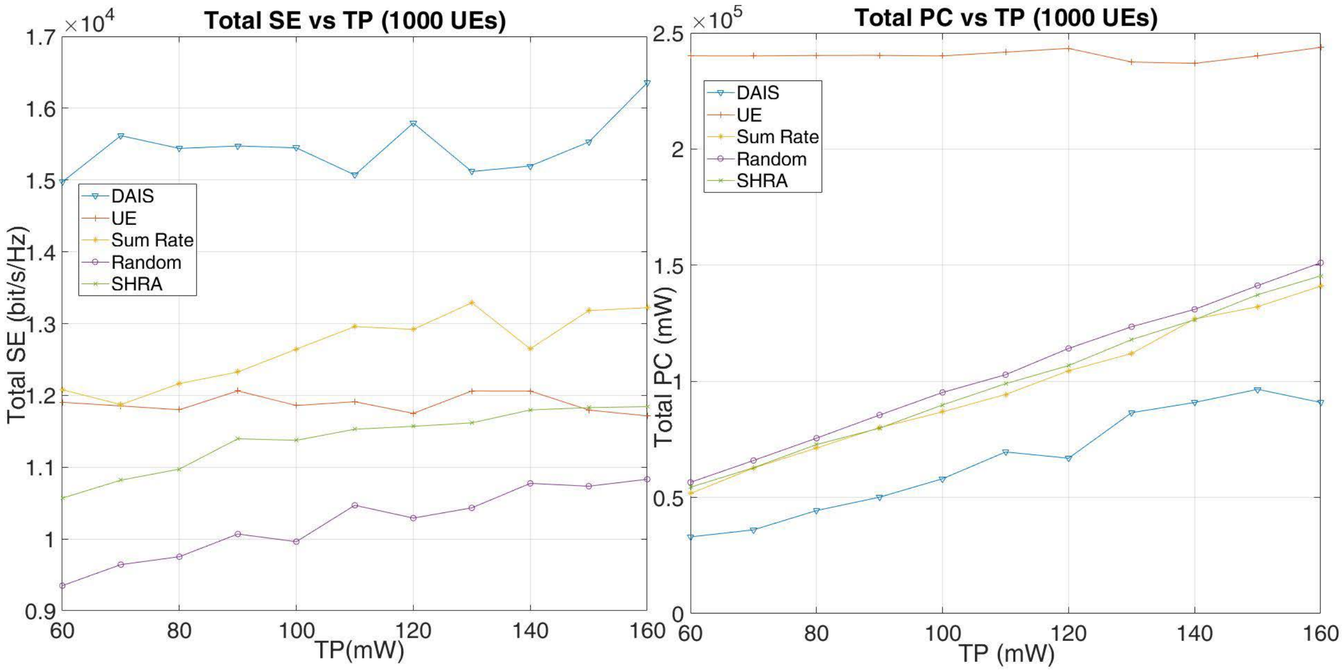


FIGURE 10. TP change investigation among the examined approaches.

TABLE 4. Examination of variable TP of each approach for 1000 UEs, 15m/s speed and 90 degree Direction.

1000 D2D UEs - 5 TS - 15 m/s - 90 Degrees					
	DAIS	**UE**	**DSR Approach**	**Distributed Random**	**SHRA**
MAX SE	**16354.4**	12062.4	13290.4	*10832.1*	11843.5
MAX PC	*96551.6*	**243778.3**	140987.0	151041.0	145399.1
MAX Change of SE	*0.08*	*0.03*	0.11	**0.14**	0.11
MAX Change of PC	**0.66**	*0.03*	0.63	0.63	0.63

As illustrated in Table 4 and Fig. 10, in this investigation DAIS approach provides the best results in terms of SE and PC. Additionally, DAIS achieves the maximum PC reduction (followed by Sum Rate) and the minimum SE reduction (followed by the non-D2D UE approach) compared to all other related approaches. Please note that the number in bold represents the maximum value in the table while the values in italic represent the minimum value.

4) BEHAVIOUR OF THE INVESTIGATED APPROACHES ON NETWORK TOPOLOGY CHANGES OVER THE TIME STEPS OF EXECUTION

This section examines the case where the TS is increased from 0 to 5 (which mainly relates to changes in D2D network topology), while the transmission power (160mW), the speed (15 m/s), the number of devices (1000 D2D devices) and direction (90 Degrees) of the UEs are kept constant. The performance of the investigated approaches is compared in terms of total spectral efficiency (Sum Rate) and Power Consumption. The results are provided in Fig. 11.

The best results from 0 TS until 2.5 TS, in terms of SE and PC for 1000 devices, are provided by the DSR approach. These results have been achieved with the enhancements made, introducing the speed, Data Rate and Battery Power level thresholds in the DSR Approach to enhance it to support dynamic networks. However, after 2.5 TS, the DSR approach degrades performance. The DSR approach does not keep the highest SE and PC values after 2.5 TS due to the considerable execution time (i.e., 50 TS) needed to decide on the transmission mode selection. This makes the DSR approach not fast enough to be ready for recalculation after 2.5 TSs. For more details see Section V-B and V-A Table 2) and [18], [19]. The second-best performance, from 0 TS until the 2.5 TS, however very close to the one provided by DSR, is achieved by DAIS. Non-D2D-UE, SHRA and Distributed Random follow because of the execution time that Distributed Random achieves in 1000 UES. After 2.5 TS, the best results in terms of SE are achieved by DAIS.

The results related to PC follow a similar pattern. The best results from 0 TS until the 2.5 TS are provided by the DSR approach, which, for the same reason described above, degrades performance after the 2.5 TS. After the 2.5 TS, the DAIS approach outperforms DSR, followed by SHRA, Distributed Random and then non-D2D-UE.

Overall, what made DAIS outperform all other approaches in both SE and PC, are the adaptations and thresholds (i.e., speed, WDR, BPL) implemented (see Section IV-A), making DAIS capable to efficiently support dynamic environments (note that in our previous work considering static environments [15] Sum Rate Approach and DAIS had the same spectral efficiency).

Additionally, according to Fig. 11, except for the DSR approach, all other methods do not have any significant changes, in terms of SE and PC, over subsequent TSs. More precisely, over subsequent TSs, the DSR Approach has a

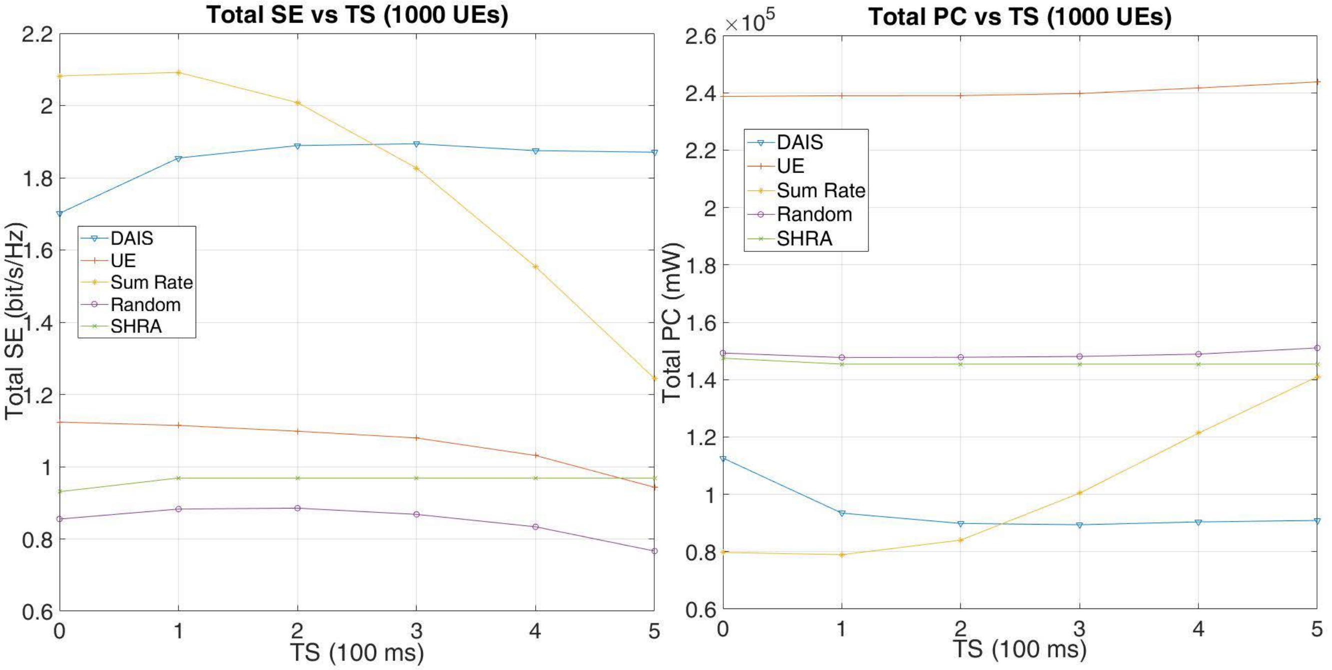


FIGURE 11. **Total SE and total PC vs TSs with 1000 UEs, 15 m/s speed and 90 degree direction.**

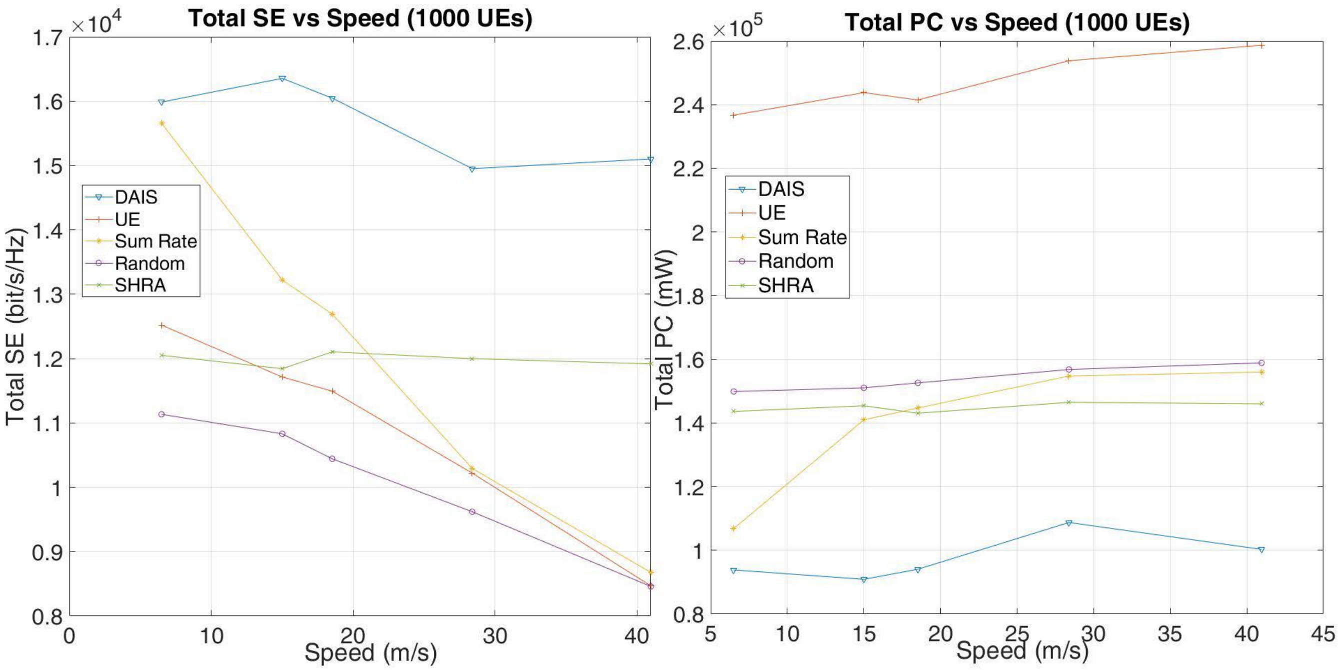


FIGURE 12. **Total SE and total PC vs speed with 1000 UEs, at 5 TS and 90 degree Direction.**

maximum SE reduction of 25% and a maximum PC increase of 45%.

5) BEHAVIOUR OF THE INVESTIGATED APPROACHES ON DYNAMIC UE SPEED

This section examines the case where the Speed of the UE changes randomly while the transmission power (160mW), the number of devices (1000 D2D devices) and the direction (90 Degrees) of the UEs are kept constant. The results relate to the D2D network topology at TS=5 and examine how each approach can react to the UE speed changes. The performance of the investigated approaches is compared in terms of total spectral efficiency (Sum Rate) and Power Consumption. As shown in Fig. 12), the best performance in terms of SE

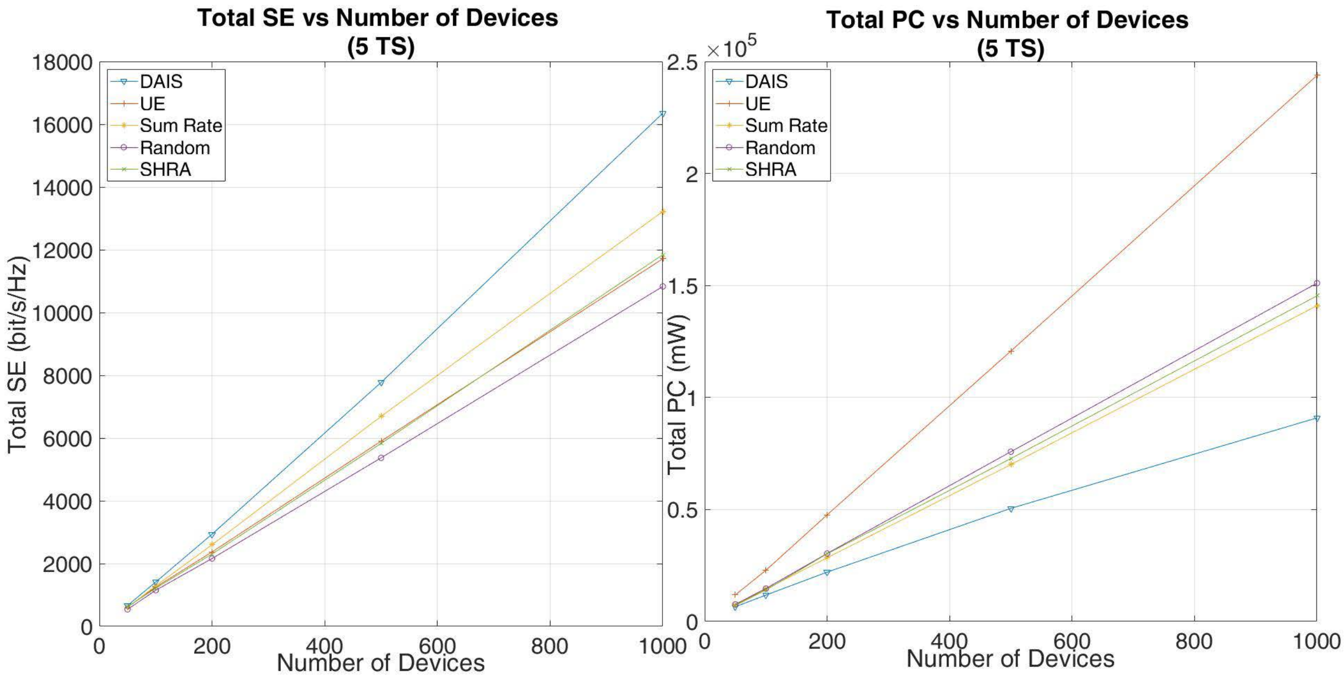


FIGURE 13. Total SE and total PC vs number of devices at 5 TS, 15m/s speed and 90 degrees Direction.

and PC is provided by DAIS, followed by SHRA. Note that DAIS and SHRA, in contrast with Distributed Random, non-D2D UE and DSR (that approach close to zero (0)), are the only two approaches that still provide good results in terms of SE as the speed of the UEs increases, justifying their ability to support dynamic mobile environments. Also, only the DSR Approach is highly affected by the UE speed in terms of PC.

6) BEHAVIOUR OF THE INVESTIGATED APPROACHES ON DIFFERENT NUMBER OF DEVICES IN THE NETWORK

This section examines the case where the number of UEs in the network increase from 10 to 1000 while the transmission power (160 mW), the speed (15 m/s) and the direction (90 Degrees) of the UEs are kept constant. The results relate to the D2D network topology at TS=5 and examine how each approach can react to the increasing number of UEs. As shown in Fig. 13, the best performance in terms of SE and PC is provided by DAIS, irrespective of the number of devices in the network. The second-best performance in terms of SE is provided by the DSR approach, followed by the non-D2D UE, SHRA and Distributed Random. Additionally, the second-best performance in terms of PC is provided with the DSR Approach, followed by the SHRA, the non-D2D UE and the Distributed Random approach.

7) BEHAVIOUR OF THE INVESTIGATED APPROACHES ON DYNAMIC UE DIRECTION

This section examines the case where the Direction of the UE changes randomly while the transmission power (160mW), the number of devices (1000 D2D devices) and the speed (15 m/s) of the UEs are kept constant. The results relate to the D2D network topology at TS=5 and examine how each approach can react to changes in the UE direction. As shown in Fig. 14), the best performance in terms of SE and PC is provided by DAIS, irrespective of the way the devices are moving in the network. The second-best performance in terms of SE is provided by the DSR approach, followed by the non-D2D UE, SHRA and Distributed Random. Additionally, the second-best performance in terms of PC is provided with the DSR Approach, followed by the SHRA, the non-D2D UE and the Distributed Random approach.

8) OVERALL REMARKS

Overall, in this research, we examined the enforcement of the most significant thresholds, such as the maximum speed to select a D2D-Relay, the use of specific WDR (set to 20% when the number of UEs (<= 200) or 35% otherwise) and BPL (set to 75%) thresholds, as shown in Section IV-A). Additionally, as shown in Section IV-B, we enforce new thresholds for the DSR approach. These thresholds are related to the maximum speed to select D2D-Relay, the specific Data Rate that a D2D candidate device can connect to a D2DSHR (set empirically to 35%) and the Battery Power Level Threshold (that is set to 75%). Also, as shown in Section IV-C, in the case of the SHRA approach, we have made a slight change in the algorithm for the D2DSHR to receive multiple connections and not be restricted by one (i.e., to allow the formation of clusters). The adjustments made on DAIS, DSR and SHRA algorithms are implemented to achieve the maximum possible total sum rate (i.e., maximum

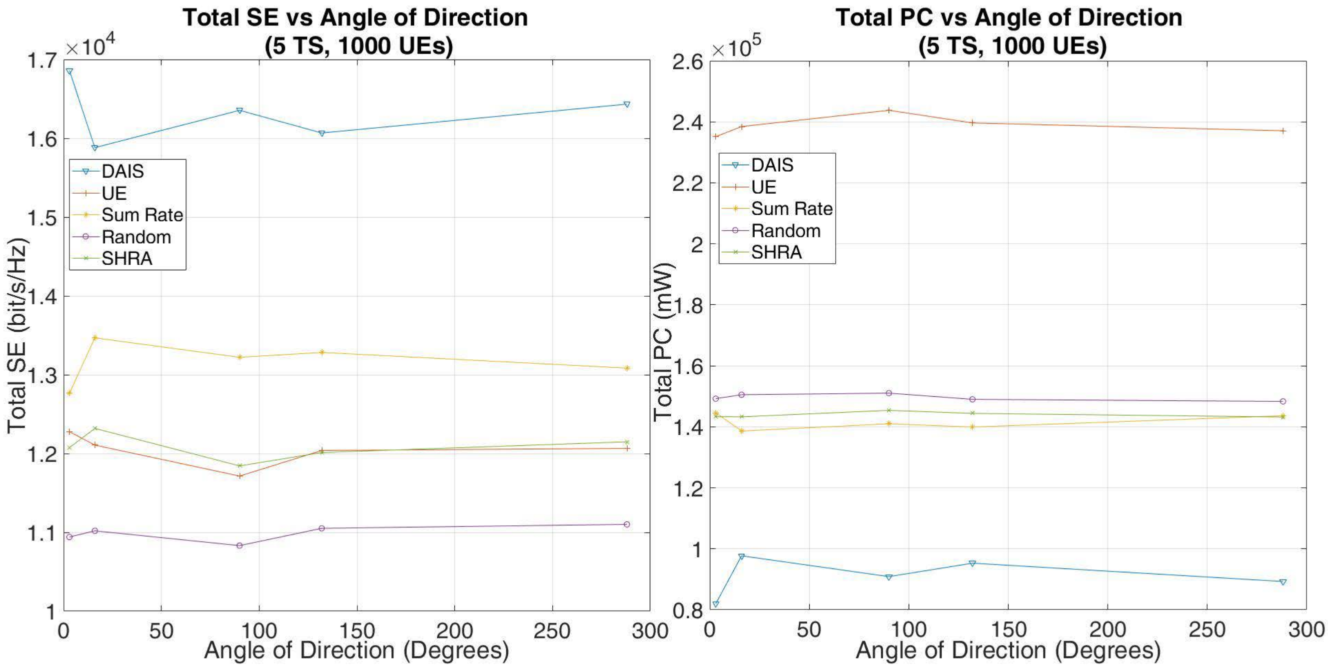


FIGURE 14. Total SE and Total PC vs Direction at 5 TS, 15 speed and 1000 UEs.

TABLE 5. Overall evaluations of the approaches using the dynamic variables in terms of SE and PC.

Metric	SE					PC				
Investigation /Approach	DAIS	DSR	SHRA	Random	non-D2D UE	DAIS	DSR	SHRA	DR	non-D2D UE
Transmission Power	Excellent	Good	Poor	Poor	Average	Excellent	Average	Average	Poor	Poor
TS	Excellent	Good	Average	Poor	Average	Excellent	Good	Average	Average	Poor
Speed	Excellent	Poor	Good	Poor	Poor	Excellent	Average	Good	Average	Poor
Number of Devices	Excellent	Good	Average	Poor	Average	Excellent	Good	Average	Poor	Poor
Direction	Excellent	Good	Average	Poor	Average	Excellent	Good	Average	Average	Poor

spectral efficiency) and maximum power reservation (i.e., minimum power consumption) in a range of 10 to 1000 of the number of devices in a dynamic environment.

In this examination, we analysed the behaviour of the investigated approaches considering the dynamics of the Mobile Network. More specifically, we examined how each approach can react to the changes in UE speed and direction, causing variations in the D2D network topology, as well as to changes in the TP and number of Devices in the Network. Based on this examination, we compared the efficiency of each approach[15] in terms of SE and PC. The results are summarised in Table 5.

Overall, based on the results collected, the only approach that can provide excellent results in a dynamic environment, both in terms of SE and PC, is DAIS. More specifically, DAIS can react quickly to D2D network topology changes caused through time (i.e., in the different TSs), either these are caused by variations in UE Speed, UE Direction, number of Devices in the network or TP, and decide efficiently on the transmission mode that the D2D devices will operate.

DSR Approach comes second in terms of SE and PC. More specifically, in terms of SE, it provides "Good" results except for where network topology changes are caused due to variations in the UE Speed. In this case, the results provided are considered "Poor". Also, "Good" results are provided in terms of PC, except in the cases where network topology changes are caused due to variations in the UE Speed and Transmission power. In these cases, the results provided are considered "Average". Additionally, DSR is the only approach that, in some cases, drops its SE and increases its PC drastically than all other approaches (see Fig. 11). Thus, in our belief, if we introduce more time steps in the simulation, the DSR Approach could conclude to be the last.

The SHRA approach, in terms of SE, in most cases it is evaluated as "Average", except in the case where

[15]Here we used the following scale to qualitative characterise the efficiency of each approach: Excellent, Good, Average and Poor.

variations in the UE Speed cause network topology changes. In this case, the results provided are considered ''Good''. Also, SHRA performance in TP variations is considered ''Poor''. Furthermore, SHRA performance in terms of PC is considered ''Average'', except for where variations in UE speed occur. In this case, the results of SHRA are ''Good''.

The Random approach, in terms of SE, provides ''Poor'' results in all respects. In terms of PC, the results provided are considered Average except in the cases where changes occur on the TP and the number of Devices in the D2D network. In these cases, the performance of the Random approach is ''Poor''.

Finally, the non-D2D UE approach, in terms of SE, provides ''Average'' performance, except in the case where changes occur in the UE speed. In this case, its performance is considered ''Poor''. In terms of PC, the performance of the non-D2D approach is considered ''Poor'' in all respects.

VI. CONCLUSION AND FUTURE WORK

This paper builds on our previous work and develops an enhanced version of DAIS for selecting the D2D transmission mode that the D2D devices will operate in dynamic environments incorporating UE mobility and changes in the D2D network topology. To set a benchmark and allow for a fairer comparison, we also enhanced and adapted: i) the DSR approach, previously proposed in [15] to also support D2D Communication in dynamic environments; and ii) the SHRA approach [20], to additionally allow the D2D-Relays to accept more than one connections (i.e., create clusters). Furthermore, an extensive comparative evaluation of the enhanced DAIS, SR, SHRA, Distributed Random and non-D2D UE is provided. During this evaluation, we analysed the behaviour of the investigated approaches considering the dynamics of the Mobile Network and comparatively evaluated their performance, in terms of SE and PC, against a number of metrics. More specifically, we examined how each approach can react to the changes in UE speed and direction, causing variations in the D2D network topology, as well as to changes in the TP and number of Devices in the Network.

Overall, the results obtained demonstrated superior performance of DAIS over the SHRA, Distributed Random and non-D2D UE approach in terms of SE and PC. Additionally, the insight gains into the comparative evaluation of the different approaches allows one to observe that DAIS is the only approach that can react quickly to D2D network topology changes caused through time, either these are caused by variations in UE Speed, UE Direction, number of Devices in the network or TP.

For future work we will extend DAIS in a Multi-Agent System with norms, conflict resolution and Nash equilibrium checks in a dynamic environment. More precisely, the BDIx agents will not accept the proposals of the other BDIx agent without considering its Believes and Desires/Intentions for the decision to accept or refuse an offer from the other BDIx agent. Moreover, we will investigate a secure D2D communication protocol using blockchain technology to ensure security and privacy concerns in a distributed manner for the BDIx agents to communicate safely under a secure distributed D2D communication environment. Additionally, we will investigate the use of blockchain technology for establishing smart contracts among the D2D-Relay devices and the D2DC devices under the D2D communication network. Moreover, we will concentrate on the implementation of other Plans and Intentions, such as the remainder of the unexplored D2D Challenges, as well as a thorough evaluation using simulation and a (small scale) test-bed. Using the DAI framework, other 5G/6G challenges, such as efficient routing, could be overcome in order to achieve the ultra-reliable low latency (URLL) 5G use case and, ultimately achieve all 5G use cases. Also, we will use the DAIS and DAI framework in the concept of Metaverse to investigate the achievement of the required metrics. Finally, in future work, we will explore a different model other than the Free Space Path Loss model to match the city scenario.

APPENDIX. SPECTRAL EFFICIENCY AND POWER CONSUMPTION MODELS WITH ADDITIONAL SYMBOLS

A. ADDITIONAL SYMBOLS TABLE

The additional symbols shown in Table 6 are used within the problem formulation description:

B. SPECTRAL EFFICIENCY MODEL

For estimating the Spectral Efficiency of a D2D link (measured in bits/s/Hz), Eq. 11 extracted from the Shannon–Hartley theorem, is used. Also, given the Additive White Gaussian Noise (AWGN) as a basic noise model, considering a power- and bandwidth-limited scheme, and a Free Space Path Loss model, we calculate the spectral efficiency from the channel capacity in (Eq. 11). Moreover, to calculate the bandwidth the Eq. 12 is used, and it is calculated with the use of the Eq. 13. Furthermore, to calculate the total spectral efficiency of all the links under a mobile network the Eq. 14, and to calculate the total Sum Rate the Eq. 16 is used.

$$e(l_{q_i^o,q_j^t}) = \frac{y(l_{q_i^o,q_j^t})}{w(l_{q_i^o,q_j^t})} = \log_2\left(1 + \frac{p(l_{q_i^o,q_j^t})}{p^n(l_{q_i^o,q_j^t})}\right) \tag{11}$$

$$\begin{aligned} e(l_{q_i^o,q_j^t}) &= \log_2\left(1 + \frac{\bar{p}^r(l_{q_i^o,q_j^t})}{p'^n(l_{q_i^o,q_j^t}) \cdot w(l_{q_i^o,q_j^t})}\right) \\ &= \log_2(1+\sigma) \end{aligned} \tag{12}$$

$$y(l_{q_i^o,q_j^t}) = w(l_{q_i^o,q_j^t}) \log_2\left(1 + \frac{p(l_{q_i^o,q_j^t})}{p^n(l_{q_i^o,q_j^t})}\right) \Longrightarrow$$

$$y(l_{q_i^o,q_j^t}) = w(l_{q_i^o,q_j^t}) \log_2\left(1 + \frac{\bar{p}(l_{q_i^o,q_j^t})}{p'^n(l_{q_i^o,q_j^t})}\right) \tag{13}$$

$$y(l_{q_i^o,q_j^t}) = e(l_{q_i^o,q_j^t}) \cdot w(l_{q_i^o,q_j^t}) \tag{14}$$

TABLE 6. Additional symbols used within the problem formulation description.

Symbol	Notation
$e(l_{q_i^o,q_j^t})$	is the SE of the link $l_{q_i^o,q_j^t}$
$w(l_{q_i^o,q_j^t})$	is the bandwidth of a frequency band used by the link $l_{q_i^o,q_j^t}$ in Hertz Hz.
$cm(P^k)$	is a set that contains as elements (o,t) the connection modes of the each link in the path.
$p(l_{q_i^o,q_j^t})$	is the signal power of the link $l_{q_i^o,q_j^t}$ in mW.
$p^t(l_{q_i^o,q_j^t})$	is the transmission power of the link $l_{q_i^o,q_j^t}$ in mW. Note that in our examination the transmission power is known and it is 160 mW.
$\bar{p}^r(l_{q_i^o,q_j^t})$	is the average received power calculated using a Free Space Model and a Free Space Path Loss of the link $l_{q_i^o,q_j^t}$ in mW.
$p^n(l_{q_i^o,q_j^t})$	is the noise power of the link $l_{q_i^o,q_j^t}$ in decibel dB.
$p'^n(l_{q_i^o,q_j^t})$	is the noise of the link $l_{q_i^o,q_j^t}$ in Watts per Herz W/Hz.
σ	is the Signal to Noise Ratio (SNR) of the link $l_{q_i^o,q_j^t}$. The σ is calculated as $\sigma = \frac{\bar{p}^r(l_{q_i^o,q_j^t})}{p'^n(l_{q_i^o,q_j^t})\cdot w(l_{q_i^o,q_j^t})}$.
$x(l_{q_i^o,q_j^t})$	be the distance of a link $l_{q_i^o,q_j^t}$ connecting two devices. The distance can be calculated with the coordinates of each D2D device and for example the $d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$.
$y(l_{q_i^o,q_j^t})$	is the Data Rate of the link $l_{q_i^o,q_j^t}$.
$y(q_i^o, q_j^t)$	is the Data Rate among the sharing device q_j^t and the device that utilises the share q_i^o.
y^{total}	the Weighted Sum Rate.
$w(l_{(q^{UE}_{(Q+1)},q_0^{BS}}), w(l_{0,(Q+1)})$	is the bandwidth of a regular UE (that is not D2D device) link towards BS. Thus the index of a regular UE is 0 and the index of the BS is Q+1.
$W(l_{q_i^o,q_j^t})$	is the percentage bandwidth related to the $w(l_{(q^{UE}_{(Q+1)},q_0^{BS}})$ bandwidth that the D2D-Relay device q_j^o with index j is sharing to D2D device q_i^o with index i. The purpose is to have a ratio for comparison among the Data Rate of the D2D devices compared to the data rate of the UE that has a direct connection to BS. Please note if the sharing device is D2DMHR and the client Device D2DR then we use LTE Direct with a specific bandwidth elsewhere if the sharing device is D2DR and the client device D2DC then we use WiFi Direct with different bandwidth or else if we have a BS sharing device with UE or D2DMHR then the bandwidth is the same with the $w(l_{(q^{UE}_{(Q+1)},q_0^{BS}})$.
s	denotes the speed of a Device. Such as $s(r_n^t)$ is the speed of the sharing device and $s(c^D 2DC_m)$ is the speed of the client. If the device is a sharing device to a link and at the same time client to another sharing device then the $s(r_n^t) = s(q_j^t)$ and maybe if it is a D2DC device $s(c^D 2DC_m) = s_{q_i^o}$
c	denotes the direction of a Device.
$p^{(max)}$	is the total maximum power limit that the D2D communication network can have.
$p(l_{q_i^o,q_j^t})$	is the power consumption that the D2D communication network can have.
p^{total}	is the total power consumption of the D2D communication network.
$W(l_{q_i^o,q_j^t})$	is the function of the % of the bandwidth. This function is required because the % bandwidth is defined based on the sharing D2D device (i.e., t) and the client D2D device (i.e., o) selected transmission mode (to use LTE Direct or WiFi Direct).
$P^t(l_{q_i^o,q_j^t})$	is the function that returns the transmission power which is dependent based on the sharing D2D device (i.e., t) and the client D2D device (i.e., o) selected transmission mode (to use LTE Direct or WiFi Direct). Because each protocol has a different transmission power to be used by the devices.
$P(l_{q_i^o,q_j^t})$	is the function that returns the power consumption which is dependent based on the sharing D2D device (i.e., t) and the client D2D device (i.e., o) selected transmission mode (to use LTE Direct or WiFi Direct). Because each protocol has a different transmission power to be used by the devices.
$SV(l_{q_i^o,q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o,q_j^t}))$	binary variable that it will return one if a sharing device (q_j^t) having as speed the $s(q_j^t)$, index j and transmission mode t with the number of its client devices (cardinality of the set) (R_j^k) out of we examine a specific D2D device q_i^o with its transmission mode o and index i.

$$e^{total} = \sum_{k=1}^{K-1} \{ \sum_{\{l_{q_i^o, q_j^t} \in P^k :\}} (e(l_{q_i^o, q_j^t})\} \quad (15)$$

$$y^{total} = w(l_{0,(Q+1)}) \cdot \sum_{k=1}^{K-1} \{ \sum_{\{l_{q_i^o, q_j^t} \in P^k\}} (W(l_{q_i^o, q_j^t}) \cdot (e(l_{q_i^o, q_j^t})) \times \cdot SV(l_{q_i^o, q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o, q_j^t})))\} \quad (16)$$

where $t \in \{D2DSHR, D2DMHR, BS\}$, $o \in \{D2DC, D2DSHR, D2DMHR\}$ and $SV(l_{q_i^o, q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o, q_j^t})) \in \{0, 1\}$. Also, where $\{l_{q_i^o, q_j^t} \in P^k : i, j \in \{q\} \; a(i,j)^k = 1\}$; $x(l_{q_i^o, q_j^t}))$; where $e(l_{q_i^o, q_j^t})$ is directly related to SNR (Eq. 11). The binary variable (SV) corresponds to the transmission mode selection of the D2D-Relay sharing Device (e.g., D2DSHR, D2DMHR or BS) and the allocation decision of the Device to another D2D device that share its link according to the A adjacency matrix, where

$$l_{q_i^o, q_j^t} \in P^k : \; i, j \in \{q\}; \; a(i,j)^k = 1.$$

C. POWER CONSUMPTION MODEL

Additionally, for estimating the Power Consumption of a D2D link, measured in mWatts, Eq. 17 and Eq. 17 are used. Also, for the calculation of total power consumption of the whole mobile network the Eq. 19 can be used.

$$p(l_{q_i^o, q_j^t}) = P^t(l_{q_i^o, q_j^t}) - \bar{p}^r(l_{q_i^o, q_j^t}) \quad (17)$$

$$\bar{p}^r(l_{q_i^o, q_j^t}) = \frac{P^t(l_{q_i^o, q_j^t})}{10^{\tau/10}} \quad (18)$$

where τ is the Path Loss.

In the following equation, Eq. 19 we calculate the total of the power consumption in our network.

$$p^{total} = \sum_{k=1}^{K-1} \{ \sum_{\{l_{q_i^o, q_j^t} \in P^k :\}} (P(l_{q_i^o, q_j^t}) \times \cdot SV(l_{q_i^o, q_j^t}, R_j^k, s(q_j^t), x(l_{q_i^o, q_j^t})))\} \quad (19)$$

In the D2D communication network, the problem of network optimization with the use of the correct transmission mode Selection can be translated to a weighted sum rate maximization problem where the purpose is to increase the sum rate whilst keeping the power consumption of the network to a minimum.

Note that the data rate in the weighted sum rate is considered weighted, according to our formulation, for two reasons: i) due to different technologies that the device can use according to the transmission mode that is selected (e.g., WiFi Direct to share over D2DCs, LTE Direct to share a link to other D2D-Relays); and ii) because the D2D-Relay device shares a fraction of its link bandwidth $w(l_{q_i^o, q_j^t})^{\%}$ with its clients. This fraction of bandwidth is calculated as a percentage of the maximum achievable bandwidth in the network according to the protocol used (i.e, WiFi Direct or LTE Direct).

APPENDIX. DAIS AND SUM RATE APPROACHES TERMS AND PARAMETERS USED

In this section of the Appendix we provide the terms and parameters (as shown in [15]) used in the Dynamic DAIS algorithm/plan and the Sum Rate Approach, these are following:

- **D2DR**: D2D-Relay.
- **D2DMHR**: D2DMHR.
- **D2DSHR**: D2D Single Hop Relay.
- **D2DCH**: D2D Cluster Head.
- **WDR**: Weighted Data Rate (Used only in DAIS).
- **MAXUsersCH**: Maximum Users Supported by a D2DCH = 200.
- **MAXQueryD2DRelayDistance**: Maximum distance for querying D2DRs = 200m.
- **MAXDistancetoFormCluster**: Maximum distance of D2D devices from the D2DR acting as D2DCH for accepting connections = 200m.
- **MAXSpeed_D2D-Relay**: Maximum speed of the D2D device in order to operate as D2D-Relay =15 m/s (more than the pedestrian speed of 1.5 m/s) (called MAXSpeedToFormBackhauling in [15]).
- **MAXDistanceMultiHop**: Maximum distance of a D2D device from the nearest D2DR in order to operate as D2DMHR = 1000m.
- **MAXDistanceMoveAway**: Maximum distance that a D2D device acting as D2DC/D2DR moves away from its connected D2D-Relay, in order to rerun the transmission Selection Algorithm = 200m.
- **PERCDataRate**: This is associated with the WDR Threshold in DAIS. Its value is expressed in percentage (%) and considered by a D2D device[16] in order to: i) decide the transmission mode that will operate; or ii) decide if and how the D2D network structure will alter.
- **DeviceBatteryThreshold**: This is associated with the BPL Threshold. This threshold determines the minimum value (in percentage) that the remaining battery level of a D2D device must be, in order to be able to become a D2DR or a D2DMHR and accept connections from other D2D devices.
- **maxD2DSHR**: The D2DR with the maximum WDR (for DAIS) within MAXQueryD2DRelayDistance distance from the D2D device that is running the transmission mode Selection algorithm. The formulas used to estimate this parameter can be found in [15].
- **maxD2DMHR_NC**[17]: The D2DMHR with the maximum WDR (for DAIS) and with no connection links

[16] A D2D device that is running the transmission mode selection algorithm (DAIS).

[17] The selected D2DMHR will change transmission mode to D2DR and the D2D investigated Device will connect to it as D2DC.

with other D2DRs/D2DCs located within MAXDistancetoFormCluster distance from the D2D device that is running the transmission mode selection algorithm. The formulas used to estimate this parameter can be found in [15].

- **maxD2DSHR_NC_D2DMHR**[18]: The D2DR with the maximum WDR and with no connection links with other D2DRs/D2DCs located within MAXDistanceMultiHop distance from the D2D device that is running the transmission mode selection algorithm. The formulas used to estimate this parameter can be found in [15].
- **maxD2DSHR_UED2DMHR**[19]: The D2DR with the maximum WDR, but worst than the one of the D2D device that is running the transmission mode selection algorithm, and with no connection links with other D2DCs located within MAXDistanceMultiHop distance from the D2D device. The formulas used to estimate this parameter can be found in [15].
- **maxD2DMHR_MultiHop**[20]: The D2DMHR with the maximum WDR and with no connection links with other D2DRs/D2DCs located within MAXDistanceMultiHop distance from the D2D device that is running the transmission mode selection algorithm. The formulas used to estimate this parameter can be found in [15].
- **DR**: The data rate among the candidate D2D device and the BS.
- **DataRateThreshold**: Its value is expressed in percentage (%) and considered by a D2D device[21] in order to do quality check, when a Device is valuable to connect as client to the D2DSHR Device.
- **maxSRD2DR**: The D2DR with the maximum Sum Rate within MAXQueryD2DRelayDistance distance from the D2D device that is running the transmission mode Selection algorithm.
- **maxSRD2DMHR_NC**[22]: The D2DMHR with the maximum Sum Rate (for DAIS) and with no connection links with other D2DRs/D2DCs located within MAXDistancetoFormCluster distance from the D2D device that is running the transmission mode selection algorithm.
- **maxSRD2DRNoConnectionsToBeD2DMHR**[23]: The D2DR with the maximum Sum Rate and with no connection links with other D2DRs/D2DCs located within MAXDistanceMultiHop distance from the D2D device that is running the transmission mode selection algorithm.
- **maxSRD2DRToUseUED2DMHR**[24]: The D2DR with the maximum Sum Rate, but worst than the one of the D2D device that is running the transmission mode selection algorithm, and with no connection links with other D2DCs located within MAXDistanceMultiHop distance from the D2D device.
- **maxSRD2DMHR_MultiHop**[25]: The D2DMHR with the maximum Sum Rate and with no connection links with other D2DRs/D2DCs located within MAXDistanceMultiHop distance from the D2D device that is running the transmission mode selection algorithm.

[18]The selected D2DR will change its transmission mode to D2DMHR and the D2D device running the transmission mode selection algorithm will set its transmission mode to D2DR and will connect to it.

[19]The D2D device running the transmission mode selection algorithm will select the D2DMHR mode and the D2DR will connect to it.

[20]The D2D device running the transmission mode selection algorithm will set its transmission mode to D2DR and connect to the D2DMHR.

[21]A D2D device that is running the transmission mode selection algorithm (Sum Rate).

[22]The selected D2DMHR will change transmission mode to D2DR and the D2D investigated Device will connect to it as D2DC.

[23]The selected D2DR will change its transmission mode to D2DMHR and the D2D device running the transmission mode selection algorithm will set its transmission mode to D2DR and will connect to it.

[24]The D2D device running the transmission mode selection algorithm will select the D2DMHR mode and the D2DR will connect to it.

[25]The D2D device running the transmission mode selection algorithm will set its transmission mode to D2DR and connect to the D2DMHR.

REFERENCES

[1] *5G Applications and Use Cases | Digi International*. Accessed: Jul. 24, 2021. [Online]. Available: https://www.digi.com/blog/post/5g-applications-and-use-cases

[2] H. Yang, F. Xie, and Y. Lu, "Clustering and classification based anomaly detection," in *Fuzzy Systems and Knowledge Discovery* (Lecture Notes in Computer Science: Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 4223. Berlin, Germany: Springer, 2006, pp. 1082–1091.

[3] W. Lee and S. J. Stolfo, "A framework for constructing features and models for intrusion detection systems," *ACM Trans. Inf. Syst. Secur.*, vol. 3, no. 4, pp. 227–261, 2000.

[4] X. Liu, C. E. Athanasiou, N. P. Padture, B. W. Sheldon, and H. Gao, "A machine learning approach to fracture mechanics problems," *Acta Mater.*, vol. 190, pp. 105–112, May 2020.

[5] S. Wang, T. Sun, H. Yang, X. Duan, and L. Lu, "6G network: Towards a distributed and autonomous system," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Mar. 2020, pp. 1–5.

[6] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y. A. Zhang, "The roadmap to 6G: AI empowered wireless networks," *IEEE Commun. Mag.*, vol. 57, no. 8, pp. 84–90, Aug. 2019.

[7] K. David and H. Berndt, "6G vision and requirements: Is there any need for beyond 5G?" *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 72–80, Sep. 2018.

[8] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "Toward 6G networks: Use cases and technologies," *IEEE Commun. Mag.*, vol. 58, no. 3, pp. 55–61, Dec. 2020.

[9] E. C. Strinati, S. Barbarossa, J. González-Jiménez, D. Kténas, N. Cassiau, and C. Dehos, "6G: The next frontier," 2019, *arXiv:1901.03239*.

[10] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE Access*, vol. 8, pp. 133995–134030, 2020.

[11] R.-A. Stoica and G. T. F. de Abreu, "6G: The wireless communications network for collaborative and AI applications," 2019, *arXiv:1904.03413*.

[12] L. A. Rui, "White paper for research beyond 5G," Instituto de Telecomunicaηues, White Paper, Version: 1.0, Oct. 2015. [Online]. Available: https://www.networldeurope.eu/

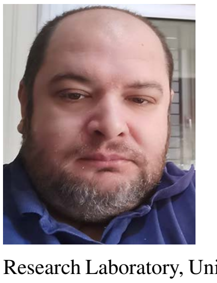
[13] N. Y. Seppo, "5G evolution and beyond a verticals perspective talk," 6G Wireless Summit, Finland, Tech. Rep., pp. 1–2, Apr. 2019.

[14] C. Liaskos, A. Tsioliaridou, S. Nie, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "An interpretable neural network for configuring programmable wireless environments," in *Proc. IEEE 20th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2019, pp. 1–5.

[15] I. Ioannou, V. Vassiliou, C. Christophorou, and A. Pitsillides, "Distributed artificial intelligence solution for D2D communication in 5G networks," *IEEE Syst. J.*, vol. 14, no. 3, pp. 4232–4241, Sep. 2020.

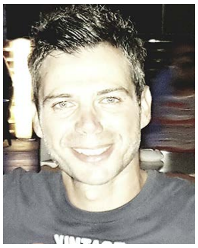
[16] I. Ioannou, C. Christophorou, V. Vassiliou, and A. Pitsillides, "A novel distributed AI framework with ML for D2D communication in 5G/6G networks," *Comput. Netw.*, vol. 211, Jul. 2022, Art. no. 108987.

[17] I. Ioannou, C. Christophorou, V. Vassiliou, and A. Pitsillides, "A distributed AI/ML framework for D2D transmission mode selection in 5G and beyond," *Comput. Netw.*, vol. 210, Jun. 2022, Art. no. 108964.
[18] I. Ioannou, C. Christophorou, V. Vassiliou, and A. Pitsillides, "5G D2D transmission mode selection performance & cluster limits evaluation of distributed artificial intelligence and machine learning techniques," 2021, *arXiv:2101.08014*.
[19] I. Ioannou, C. Christophorou, V. Vassiliou, and A. Pitsillides, "Performance evaluation of transmission mode selection in D2D communication," in *Proc. NTMS Conf.*, Jan. 2021, pp. 1–7.
[20] U. N. Kar and D. K. Sanyal, "Experimental analysis of device-to-device communication," in *Proc. 12th Int. Conf. Contemp. Comput. (IC)*, Aug. 2019, pp. 1–6.
[21] J. Deng, A. A. Dowhuszko, R. Freij, and O. Tirkkonen, "Relay selection and resource allocation for D2D-relaying under uplink cellular power control," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2015, pp. 1–6.
[22] L. Song, D. Niyato, Z. Han, and E. Hossain, "Game-theoretic resource allocation methods for device-to-device communication," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 136–144, Jun. 2014.
[23] B. Peng, T. Peng, Z. Liu, Y. Yang, and C. Hu, "Cluster-based multicast transmission for device-to-device (D2D) communication," in *Proc. IEEE 78th Veh. Technol. Conf. (VTC Fall)*, Sep. 2013.
[24] Z. Zhou, M. Dong, K. Ota, J. Wu, and T. Sato, "Energy efficiency and spectral efficiency tradeoff in device-to-device (D2D) communications," *IEEE Wireless Commun. Lett.*, vol. 3, no. 5, pp. 485–488, Oct. 2014.
[25] P. Gandotra and R. K. Jha, "Device-to-device communication in cellular networks: A survey," *J. Netw. Comput. Appl.*, vol. 71, pp. 99–117, Aug. 2016.
[26] Y. Qiu, Z. Ji, Y. Zhu, and G. Meng, "Joint mode selection and power adaptation for D2D communication with reinforcement learning," in *Proc. IEEE Int. Symp. Wireless Commun. Syst. (ISWCS)*, Aug. 2018, pp. 1–6.
[27] K. Doppler, C.-H. Yu, C. B. Ribeiro, and P. Jänis, "Mode selection for device-to-device communication underlaying an LTE-advanced network," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2010, pp. 1–6.
[28] M. Jung, K. Hwang, and S. Choi, "Joint mode selection and power allocation scheme for power-efficient device-to-device (D2D) communication," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, May 2012, pp. 1–5.
[29] H. Pang, P. Wang, X. Wang, F. Liu, and N. N. Van, "Joint mode selection and resource allocation using evolutionary algorithm for device-to-device communication underlaying cellular networks," *J. Commun.*, vol. 8, no. 11, pp. 751–757, 2013.
[30] M.-H. Han, B.-G. Kim, and J.-W. Lee, "Subchannel and transmission mode scheduling for D2D communication in OFDMA networks," in *Proc. IEEE Veh. Technol. Conf. (VTC Fall)*, Sep. 2012, pp. 1–5.
[31] S. Xiang, T. Peng, Z. Liu, and W. Wang, "A distance-dependent mode selection algorithm in heterogeneous D2D and IMT-advanced network," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2012, pp. 416–420.
[32] C. Xu, J. Feng, B. Huang, Z. Zhou, S. Mumtaz, and J. Rodriguez, "Joint relay selection and resource allocation for energy-efficient D2D cooperative communications using matching theory," *Appl. Sci.*, vol. 7, no. 5, pp. 1–24, 2017.
[33] B. Ma, H. Shah-Mansouri, and V. W. S. Wong, "A matching approach for power efficient relay selection in full duplex D2D networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.
[34] M. Zhao, X. Gu, D. Wu, and L. Ren, "A two-stages relay selection and resource allocation joint method for D2D communication system," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2016, pp. 1–6.
[35] H. Feng, H. Wang, X. Chu, and X. Xu, "On the tradeoff between optimal relay selection and protocol design in hybrid D2D networks," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 705–711.
[36] L. Wang, T. Peng, Y. Yang, and W. Wang, "Interference constrained D2D communication with relay underlaying cellular networks," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Sep. 2013, pp. 1–5.
[37] T. Kim and M. Dong, "An iterative Hungarian method to joint relay selection and resource allocation for D2D communications," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 625–628, Dec. 2014.
[38] G. Rigazzi, F. Chiti, R. Fantacci, and C. Carlini, "Multi-hop D2D networking and resource management scheme for M2M communications over LTE-A systems," in *Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Aug. 2014, pp. 973–978.
[39] J. Gui and J. Deng, "Multi-hop relay-aided underlay D2D communications for improving cellular coverage quality," *IEEE Access*, vol. 6, pp. 14318–14338, 2018.
[40] X. Ma, R. Yin, G. Yu, and Z. Zhang, "A distributed relay selection method for relay assisted device-to-device communication system," in *Proc. IEEE Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2012, pp. 1020–1024.
[41] Y. Liu, "Optimal mode selection in D2D-enabled multibase station systems," *IEEE Commun. Lett.*, vol. 20, no. 3, pp. 470–473, Mar. 2016.
[42] I. F. Akyildiz, S. Nie, S.-C. Lin, and M. Chandrasekaran, "5G roadmap: 10 key enabling technologies," *Comput. Netw.*, vol. 106, pp. 17–48, Sep. 2016.
[43] D. A. Basnayaka and T. Ratnarajah, "Doppler effect assisted wireless communication for interference mitigation," *IEEE Trans. Commun.*, vol. 67, no. 7, pp. 5203–5212, Jul. 2019.
[44] Mathworks. (2016). *MATLAB Mathworks MATLAB & Simulink*. Accessed: Sep. 19, 2020. [Online]. Available: https://www.mathworks.com
[45] *Jade Site | Java Agent DEvelopment Framework*. Accessed: Feb. 15, 2021. [Online]. Available: https://jade.tilab.com/
[46] L. Braubach, A. Pokahr, and W. Lamersdorf, "Jadex: A BDI-agent system combining middleware and reasoning," in *Software Agent-Based Applications, Platforms and Development Kits*, R. Unland, M. Calisti, and M. Klusch, Eds. Basel, Switzerland: Birkhäuser, 2005, pp. 143–168.
[47] A. Pokahr, L. Braubach, and W. Lamersdorf, *Jadex: A BDI Reasoning Engine*. Boston, MA, USA: Springer, 2005, pp. 149–174.
[48] M. Ughetti, D. Gotta, T. Trucco, S. Semeria, C. Cucè, A. M. Porcino, "Jade Android add-on guide," CSIE tw, Tech. Rep., 2010, pp. 1–19. [Online]. Available: http://www.csie.ncu.edu.tw and http://www.agilemethod.csie.ncu.edu.tw/download/agent/JADE_ANDROID_Guide.pdf
[49] G. Iavarone, T. Italia, M. Izzo, T. Italia, K. Heffner, and P. Simulation, "Jade tutorial jade programming for Android creating the Android chat client project," JADE Tilab, Tech. Rep., Jun. 2012, pp. 1–20.
[50] S. Xiao, D. Feng, Y. Yuan-Wu, G. Y. Li, W. Guo, and S. Li, "Optimal mobile association in device-to-device-enabled heterogeneous networks," in *Proc. IEEE 82nd Veh. Technol. Conf. (VTC-Fall)*, May 2015, pp. 1–5.
[51] *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) System Scenarios (3GPP TR 36.942 Version 13.0.0 Release 13)*, document TR 136 942-V13.0.0, ETSI, 2016, p. 84.
[52] B. Station and E. Spectrum, "LTE (FDD) transmitter characteristics," Nat. Telecommun. Inf. Admin., United States Dept. Commerce, Washington, DC, USA, Tech. Rep., 2003, pp. 3–7.
[53] *WiFi Direct—The Worldwide Network of Companies that Brings You Wi-Fi*. Accessed: Sep. 19, 2020. [Online]. Available: https://www.wi-fi.org/
[54] *LTE Direct; The Case for Device-to-Device Proximate Discovery*, Qualcomm, San Diego, CA, USA, 2013.



IACOVOS I. IOANNOU received the associate degree in computer science from the Cyprus College, in 2001, the B.Sc. degree in computer science from the University of Cyprus, in 2006, the M.Sc. degree (Hons.) in computer and network security from the Open University of Cyprus, in 2017, and the Ph.D. degree from the University of Cyprus, in 2021, focusing on telecommunications with AI/ML.

He is currently a Researcher at the Networks Research Laboratory, University of Cyprus. He is also a Junior Researcher at the Smart Networked Systems Research Group, RISE Center. He is a highly skilled developer with 20 years of hands on working experience in the IT industry, ranging the spectrum of IT systems from analysis, development, installation, and management. He has worked at the Phileleftheros Publishing Group as an IT Administrator and a Programmer for seven years, Cyprus Stock Exchange as an IT and a Programmer for seven years, and PrimeTel as an IT and Software Engineer at the Services Department for six years. He has vast experience with cellular network infrastructure and all modern development platforms and languages. He has a certificate in ICONIX/SCRUM. He has also CCNET certified from CISCO. His research interests include mobile and wireless communications, next generation networks (5G) and device-to-device (D2D) communications, using artificial intelligence techniques.



CHRISTOPHOROS CHRISTOPHOROU received the B.Sc. degree in computer science, the M.Sc. degree in advanced computer technologies, and the Ph.D. degree in mobile/wireless networks from the University of Cyprus, in 2002, 2005, and 2011, respectively.

He has published over 35 papers in journals, scientific conferences, and book chapters. Since 2004, he has been involved initially as a Researcher and later as a Project Manager in different local (RPF-funded) and EU-funded research projects in the domain of AAL and Ageing Well, such as FRAIL, SUCCESS, MEMENTO, GrowMeUp, Miraculous-Life, SocialRobot, Co-Living, and AgeingWell and in the mobile and wireless networks domain, such as C-CAST, C-MOBILE, MOTIVE, and BBONE. His main research interests include telecommunications, networking, database management systems, social collaborative care networks, and information and communication technology (ICT) personalized solutions (for various sectors including the eHealth domain).

VASOS VASSILIOU (Senior Member, IEEE) is currently an Associate Professor with the Department of Computer Science, University of Cyprus, and the Co-Director of the Networks Research Laboratory (NetRL), UCY (founded by Prof. A. Pitsillides). Since November 2017, he has been the Group Leader at the Smart Networked Systems Research Group, RISE Center of Excellence on Interactive Media, Smart Systems and Emerging Technologies, Nicosia, Cyprus. He has also been appointed as the Senate of the University of Cyprus to the Board of Directors of CYNET, the National Research and Educational Network, where he serves as the Chair, since November 2016. He has more than 75 publications in academic journals, books, and international conferences, with more than 1300 citations. His research interests include protocol design and performance aspects of networks (fixed, mobile, and wireless), in particular mobility management, QoS adaptation and control, resource allocation techniques, wireless sensor networks, and the Internet of Things.

He is a Senior Member of the ACM, the Treasurer of the IEEE Cyprus Section, the Chair of the IEEE ComSoc Cyprus Chapter, part of the IBM Academic Initiative, and the Academic Advocate for the ISACA Cyprus Chapter. He is also on the Editorial Boards of the *Telecommunication Systems* journal (Springer) and the *Computer Networks* journal (Elsevier), among others. He has been a member of the TPC for about 100 international conferences in his field and acted as the chair of various committees in more than 15 conference organizations.

MARIOS LESTAS (Member, IEEE) received the B.A. and M.Eng. degrees in electrical and information engineering from the University of Cambridge U.K., in 2000, and the Ph.D. degree in electrical engineering from the University of Southern California, in 2006.

He is currently an Associate Professor at the Department of Electrical Engineering, Computer Engineering and Informatics, School of Engineering, Frederick University. He has participated in a number of projects funded by the Research Promotion Foundation and the EU. His research interests include application of non-linear control theory and optimization methods in intelligent networks, such as computer networks, transportation networks, power networks, molecular nano-networks, and metasurfaces. In the aforementioned networks, he has investigated issues pertinent to congestion control, information dissemination, network vulnerability, demand response, and more recently privacy and security.

ANDREAS PITSILLIDES (Senior Member, IEEE) was a Visiting Professor at the Department of Electrical and Electronic Engineering Science, University of Johannesburg, South Africa, from 2014 to 2017, and the School of Electrical and Information Engineering, University of the Witwatersrand (Wits), from 2017 to 2020. He is currently a Professor with the Department of Computer Science, University of Cyprus, the Co-Director of the Networks Research Laboratory (NetRL, http://www.NetRL.cs.ucy.ac.cy), and a Visiting Professor with the Department of Electrical and Electronic Engineering Science, University of Johannesburg, from 2021 to 2024. He has a particular interest in adapting tools from various fields of applied mathematics, such as adaptive non-linear control theory, computational intelligence, game theory, and complex systems and nature inspired techniques, to solve problems in communication networks. He has published over 350 refereed papers in flagship journals, such as IEEE, Elsevier, IFAC, Springer, international conferences, book chapters, and coauthored two books (one edited). He has participated as a principal or a co-principal investigator in over 40 European Commission and locally funded research projects with over 6.7 million Euro. His research interests include communication networks, software-defined metamaterials (hypersurfaces and reconfigurable intelligent surfaces), nanonetworks and the Internet of Things and the Web of Things, smart systems (smart grid), smart spaces (home and city), and e-health.

He received several awards, including best paper, presented keynotes, invited lectures at major research organizations, short courses at international conferences, and short courses to industry.