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Mode Selection for 5G Heterogeneous and Opportunistic Networks

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ABSTRACT 5G and beyond networks will offer multiple communication modes including device-to-device and multi-hop cellular (or UE-to-network relay) communications. Several studies have shown that these modes can significantly improve the Quality of Service (QoS), the spectrum and energy efficiency, and the network capacity. Recent studies have demonstrated that further gains can be achieved when integrating demand-driven opportunistic networking into Multi-Hop Cellular Networks (MCN). In opportunistic MCN connections, devices can exploit the delay tolerance of many mobile data services to search for the most efficient connections between nodes. The availability of multiple communication modes requires mode selection schemes capable to decide the optimum mode for each transmission. Mode selection schemes have been previously proposed to account for the introduction of D2D and MCN. However, existing mode selection schemes cannot integrate opportunistic MCN connections into the selection process. This paper advances the state of the art by proposing the first mode selection scheme capable to integrate opportunistic MCN communications within 5G and beyond networks. The conducted analysis demonstrates the potential of opportunistic MCN communications, and the capability of the proposed mode selection scheme to select the most adequate communication mode.

INDEX TERMS 5G, mode selection, multi-hop cellular, opportunistic networking, UE-to-Network Relay, device-to-device, D2D, device-centric wireless networks.

I. INTRODUCTION

5G and beyond mobile networks must support the continuously increasing data traffic demand and the digitalization of key vertical sectors [1]. 5G networks mainly rely to date on infrastructure-centric solutions. These include the *softwarization* of networks and ultra-dense networks that deploy more infrastructure nodes closer to the end-user. These solutions can reduce the infrastructure cost per bit, add flexibility in the network management, and augment the network capacity. We are also witnessing a progressive migration of relevant network functions towards the edge [2]. This brings processing and intelligence closer to where the data is generated and consumed which helps reducing the latency. The European Technology Platform NetWorld2020 and the 5G Industry Association propose to further evolve this idea of decentralization in their Smart Networks vision for 5G and beyond networks. This vision is outlined in their strategic research agenda available in [3]. The Smart Networks vision outlines a roadmap where terminals or devices become a crucial part of future networks: "*not only should the terminal be able to fully exploit the new smartness of the network, but it should become, where suitable, an integral part of the realization of the latter, just like any other infrastructure resource*" [3]. This vision is fostered by the increasing computing, networking and situational-awareness capabilities of devices that can be used to support network functions. These devices include not only smartphones, but also other 5G-enabled devices, e.g. vehicles, machines or robots. This vision transforms smart devices into *prosumers* (producer & consumer) of wireless connectivity. Smart devices will actively participate in the network management through a carefully designed cooperation and coordination with the infrastructure. The realization of this new paradigm is supported by the development of D2D (Device-to-Device) and MCN (Multi-Hop Cellular Network) technologies. These technologies improve the spectral

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efficiency, the QoS (Quality of Service) and the energy efficiency [4]. Two devices in close proximity can directly communicate with each other using D2D. This helps to offload traffic from the cellular infrastructure. D2D communications can also increase the spectrum spatial reuse through carefully designed interference management techniques. In MCNs, mobile devices can connect to the cellular infrastructure using other devices as relays. MCNs improve the link budget by replacing long Non Line of Sight (NLOS) links with shorter links with improved link budgets. MCN was introduced in Release 13 of the 3GPP standards [5] where it is also referred to as UE (User Equipment)-to-network relay. MCN technologies represent an interesting option to connect and manage machine-type communication devices [6]. Previous studies have also demonstrated that MCNs can provide significant QoS, capacity and energy gains compared to conventional cellular communications [7].

Further gains can be obtained in 5G and beyond 5G networks using demand-driven opportunistic networking. Demand-driven opportunistic networking establishes connections between devices based on the efficiency of the possible connections [8]. Opportunistic networking was initially proposed for disconnected networks with intermittent connectivity. When a connection is lost, mobile devices store and carry the data until they find other nodes to forward the stored data [9]. Recent studies extend the concept of opportunistic networking to networks with full connectivity. In this case, connections between nodes are established when their efficiency is guaranteed. This concept is referred to as demand-driven opportunistic networking [10]. Demand-driven opportunistic networking exploits non-real-time traffic to search for the best connectivity opportunities. Devices can simultaneously encounter multiple connection options in urban scenarios. The dominance of video in the mobile data traffic[1] increases the potential of demand-driven opportunistic networking in 5G and beyond. Video streaming buffers data equivalent to a few tens of seconds of playback. Devices can use this playback time to search for the most efficient connections. Recent field trials have shown that the use of demand-driven opportunistic networking in MCNs can increase the cellular spectrum efficiency by a factor between 4.7 and 12 [10] compared to conventional single-hop cellular communications.

MCN and opportunistic MCN communications require relay nodes with good link budgets. Trying to establish these links entails certain risks if adequate relays cannot be found. Mode selection schemes are hence necessary to identify the optimum communication mode for each transmission [12]. These schemes are critical because if a mode is incorrectly selected the end-user QoS will be degraded and significant signaling overhead can be generated. Mode selection schemes have been proposed to select between cellular and D2D communications [13], or between cellular and MCN communications [12]. However, to the authors' knowledge, there is currently no mode selection scheme capable to integrate opportunistic MCN connections in the selection process. It should be noted that these connections have lower risks than MCN ones since devices can store and carry the information until finding adequate links to forward the information. This paper advances the state of the art by proposing the first mode selection scheme capable to include opportunistic MCN communications in the mode selection process. The designed mode selection scheme can select among: conventional cellular, MCN and opportunistic MCN communications. The proposed mode selection scheme also embeds in the selection process the decision about the number of hops for opportunistic MCN connections.

The main contributions of this paper are:

- The first mode selection scheme capable to integrate opportunistic MCN communications within 5G and beyond networks. The mode selection scheme is capable to select the most adequate communication mode among conventional cellular communications, MCN and opportunistic MCN.
- A probabilistic estimate of the benefits and risks of heterogeneous communication modes in 5G and beyond networks. These estimates drive the mode selection process that also takes into account the network conditions.
- The benefits and risks of each mode are estimated using information already available at the BS. This ensures that our proposed mode selection scheme does not introduce additional signaling overhead.
- The proposed mode selection scheme also identifies the number of hops that should be used in opportunistic MCN connections. This is important to accurately estimate the benefits and risks of opportunistic MCN connections considering the context conditions.
- The paper presents an in-depth analysis that demonstrates that opportunistic MCN communications can significantly improve the performance of future cellular networks. The conducted analysis also demonstrates that the proposed mode selection is capable to effectively integrate opportunistic MCN communications in heterogeneous 5G networks. This improves the throughput and capacity of networks, and reduces their energy consumption.

The rest of the paper is organized as follows. Section II reviews the related work. Section III presents the mode selection scheme proposed in this study. The scheme selects the most adequate communication mode based on the context conditions. The benefits and risks of each communication mode are quantified in Sections IV, V and VI. The performance achieved with the proposed mode selection scheme is evaluated in Section VII. Finally, Section VIII summarizes the main outcome of this study and concludes the paper.

[1]Cisco estimates that video traffic currently accounts for 64% of the mobile data traffic. It is estimated that this percentage will rise to 79% by 2022 [11].

II. RELATED WORK

The development of D2D and MCN within 5G has triggered research on the design of mode selection schemes. The contributions in [14] and [13] propose mode selection schemes that decide whether two users in proximity should communicate using a direct D2D or a conventional cellular connection. In [14], a UE selects the direct D2D link if the path-loss of the D2D link is lower than the path-loss of the UE-BS cellular link. Reference [14] analyzes the impact of path-loss measurement errors on the maximum effective communication capacity. Authors demonstrate that the effective capacity exponentially decreases with the errors. In [13], D2D communications can use dedicated or shared resources with other active cellular transmissions. The BS selects the communication mode and resources using information about the channel quality of all possible links between transmitters and receivers. Acquiring all this information has a non-negligible cost that could compromise the feasibility of the mode selection scheme. However, authors show that the selection process maximizes the total system throughput and reduces interference between UEs. Higher performance is usually achieved when D2D connections use dedicated resources. However, shared resources must be considered when the number of UEs increases.

MCN can significantly improve the end-user QoS, the network capacity and the energy efficiency [7]. However, trying to establish an MCN connection has the risk of not being able to find the adequate relay nodes to outperform conventional cellular communications. This risk can significantly impact the end-user QoS and generate unnecessary network signalling overhead. The integration of MCN in 5G and beyond networks requires then the design of mode selection schemes capable to account for both the benefits and risks of exploiting MCN connections. These benefits and risks are strongly conditioned by the context, e.g. by the density of nodes in the cell. Few studies tackle to date the mode selection problem when considering MCN connections. In [15], the authors propose a distance-based mode selection scheme that selects MCN links when the distance between the UE and the BS is larger than a predefined threshold. If the distance is shorter, conventional cellular connections are used. The authors proposed in [16] a mode selection scheme that computes the benefits and risks of each communication mode. The study was conducted considering conventional cellular and MCN communications as possible communication modes. The scheme selects the communication mode that better balances risks and benefits. The benefit refers to the QoS performance achieved with a given communication mode. Risks refer to the probability of not being able to achieve these expected benefits. This can occur for example if the MCN mode is selected and a relay node cannot be found at the start of the transmission. Reference [16] shows that the proposal based on benefits and risks outperforms the distance-based approach from [15].

Reference [12] proposes a mode selection scheme for scenarios where D2D links in an MCN connection share radio resources with cellular users. The scheme sequentially decides the channel allocation for D2D links, the transmission power, and finally the communication mode. This approach provides nodes with more accurate information about the performance that could be achieved with each communication mode. The results reported in [12] show that the proposed scheme can improve the quality of the cellular coverage. However, the study does not analyse the signalling overhead and potential delays resulting from the channel allocation and transmission power adjustments for all possible links. The transmission power is also considered in the mode selection proposal presented in [17]. The scheme selects the MCN connection for a given UE if the power consumed in the complete MCN link is lower than the power of a conventional cellular connection. The proposed scheme reduces power consumption and the outage probability. The authors evolve their proposal in [18] to consider caching enabled MCNs. In [18], content is distributed to certain UEs in a cell. UEs can choose between cellular, D2D and MCN connections when they want to download the content. The UE selects a D2D connection if the content is cached by a nearby UE. If not, the UE can select the MCN mode to download the content from the BS if it can find a relay UE within a given distance from the BS. If this is again not possible, the UE uses a conventional cellular connection to download the data from the BS. Similarly to other studies, [17] and [18] assume that UEs know the location of all UEs. However, the cost of collecting this information should not be overlooked.

Existing mode selection schemes choose between conventional cellular, D2D or MCN links. None of the existing proposals consider opportunistic MCN connections during the selection process despite their significant impact on QoS, energy efficiency and network capacity [8], [10]. This study advances then the state of the art by proposing the first mode selection scheme that considers opportunistic MCN connections as a candidate communication mode. The proposal is based on the authors' original BRISK scheme [16] that evaluates the benefits and risks of candidate communication modes in the selection process. This scheme is here extended to account for the possibility to utilize opportunistic MCN connections. To this aim, this study probabilistically estimates the benefits and risks of establishing opportunistic MH connections. These benefits and risks are computed based on the context conditions. The proposed mode selection scheme also identifies the number of hops that should be considered when selecting the opportunistic MCN mode.

III. MODE SELECTION

This work focuses on downlink (DL) transmissions where the end user is the destination node DN. We consider that the transmission from the BS to the DN can be done using three different communication modes: conventional single-hop cellular communications (referred to as SH), MCN communications (referred to as MH), or opportunistic

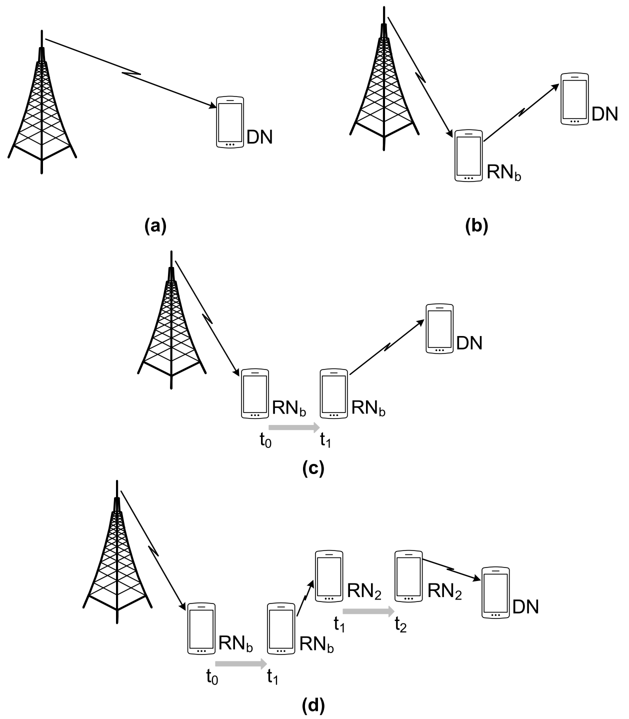

FIGURE 1. Illustration of communication modes. (a) SH communication; (b) MH communication; (c) 2-hop MH-OPP communication; (d) 3-hop MH-OPP communication.

MCN communications (referred to as MH-OPP).[2] These modes are illustrated in Fig. 1. SH corresponds to conventional cellular communications with a direct cellular connection from the BS to the DN (Fig. 1.a). In MH, the DN is connected to the BS through a relay node RN_b that acts as a bridge to the cellular infrastructure (Fig. 1.b). The BS-RN_b transmission starts at the beginning of the session. The RN_b-DN transmission is launched as soon as RN_b starts receiving data from the BS. The MH-OPP mode integrates opportunistic networking into MH connections. Fig. 1.c and Fig. 1.d represent the MH-OPP mode with two and three hops respectively. The figures illustrate how relay nodes can store and carry the information (e.g. from t_0 to t_1 in Fig. 1.c) until finding an adequate D2D link with another node. This study implements the concept of demand-driven opportunistic networking [10]. In this case, connections between nodes are established based on their capacity to support a requested service or network demand (e.g. ensuring a given throughput or spectrum efficiency). This approach exploits the delay tolerance that characterizes the dominant non-real-time mobile data traffic (e.g. video streaming) to find high quality connections between nodes. In this study, opportunistic connections are established based on their link quality so that the throughput experienced by the RN_b can be translated to the DN. To this aim, it is necessary that D2D connections ensure a throughput level at least as high as that experienced in the BS-RN_b cellular link. This puts a limit on the maximum distance between D2D nodes that are part of an MH-OPP connection.

The mode selection scheme proposed in this paper is an evolution of the BRISK (mode selection scheme based on Benefits and RISKs) scheme in [16] to integrate opportunistic MCN connections. The scheme selects the communication mode that better balances benefits and risks. The benefits quantify the QoS that a user could experience with a communication mode if the connection is established under the adequate conditions, e.g. if the adequate relays can be found in the case of MH or MH-OPP connections. Risks refer to the probability of not being able to achieve the expected benefits. This can occur for example if the MCN mode is selected and a relay node cannot be found at the start of the transmission. The mode selection scheme operates as follows:

$$m_i^* = \arg \max_{m \in \{SH, MH, n-MH\text{-}OPP\, \forall\, n \in \{2,\ldots,N\}\}} Q_m^i \tag{1}$$

where Q_m^i represents the QoS that a node DN_i could expect when using mode m. n represents the number of hops in a MH-OPP connection, and N is the maximum possible number of hops for this mode. The expected QoS is estimated taking into account the benefits and risks of each communication mode:

$$Q_m^i = Benefit_m^i \cdot \left(1 - Risk_m^i\right) \tag{2}$$

where $Benefit_m^i$ and $Risk_m^i$ represent the benefit and risk that a node DN_i could expect from the use of mode m.

The original BRISK scheme was designed to select between SH and MH connections. MH-OPP introduces the possibility for nodes to store and carry data until finding adequate relays. This reduces the pressure to find relays in real-time, and hence mitigates the challenges faced by MH. This study goes then a step further, and evolves BRISK to design the first mode selection scheme that integrates opportunistic MH communications into the mode selection process. The proposed scheme selects between SH, MH and MH-OPP connections. MH communications are limited in this study to two hops following [19]. This study showed that most MH benefits can be achieved with just 2 hops between source and destination (i.e. a cellular hop between the BS and the RN_b, and a D2D hop between the RN_b and the DN). In addition, it can be a challenge to maintain a real-time multi-hop connection with a large number of hops [20]. MH-OPP allow nodes to store and carry the information until finding adequate forwarding conditions. This study considers MH-OPP connections with either 2 or 3 hops in total. The proposed scheme embeds the decision about the number of hops in the MH-OPP mode in the selection process. This is actually critical for DL communications since the number of hops has an impact on the selection of the RN_b node. In particular, it has an impact on the area where the BS should search for the RN_b. The selection of the RN_b has in turn a direct impact on the throughput of the BS-RN_b cellular link, and consequently on the throughput of MH-OPP connections.

[2]We use opportunistic networking in the D2D links but not in the BS-RN cellular links.

The mode selection scheme requires quantifying the benefits and risks of each communication mode. These are defined in the following sections for the SH, MH and MH-OPP modes.

IV. SH COMMUNICATIONS

We consider that the cell coverage of a BS is divided into rings. A ring R is defined as the coverage area of a BS where a given Modulation and Coding Scheme (MCS) maximizes the throughput. The BS uses Signal to Noise Ratio (SNR) measurements and link adaptation schemes to select the MCS that maximizes the throughput for a given block error rate (BLER) threshold. To this end, the network uses look-up tables (LUTs) that quantify the BLER of each MCS as a function of the SNR. These LUTs help identify the MCS that maximizes the throughput for a given SNR value or range. Nodes located in rings closer to the BS experience better link quality conditions and can hence utilize MCSs with higher data rates. We utilize the notation $R' \succ R$ to indicate that a node located at R' uses a MCS that provides higher data rates than a node located at R. The throughput also depends on the number of radio resources s. We assume that all nodes located in the same ring R experience on average the same cellular throughput when assigned an equal number of radio resources s. We denote as $q(s, R)$ the cellular QoS that a node located in ring R can experience when assigned s radio resources. This QoS should reflect the user satisfaction level. This is challenging since satisfaction is subjective. In this study, we define $q(s, R)$ as a function of the cellular throughput experienced at the DN for SH connections and at the $\mathrm{RN_b}$ for MH and MH-OPP connections. We assume that $q(s, R)$ is equal to zero when the throughput is below th_{min}. $q(s, R)$ then grows linearly with the cellular throughput until a maximum value from which it asymptotically tends to 1. Other $q(s, R)$ functions could be defined, although this will not modify the conclusions of this study. In fact, this study conducts a comparative analysis for different communication modes, and the selected $q(s, R)$ function affects them equally.

The benefit that can be obtained when establishing an SH connection between the BS and a DN_i depends on the distance d_i between DN_i and the BS. d_i determines the ring R_i where the DN_i is located. It also depends on the number of assigned cellular radio resources s_i. The benefit for SH can be expressed as follows:

$$Benefit_{\mathrm{SH}}^{i}\left(s_i, d_i\right) \equiv q\left(s_i, R_i\right) \tag{3}$$

The BS can establish a SH connection with any node in its coverage area if there are sufficient cellular radio resources. The only risk associated to the use of the SH mode is then the unavailability of cellular radio resources. This risk is present for all modes, and will affect them equally in the mode selection process. This risk is then not taken into account, and the risk associated with the establishment of an SH connection is $Risk_{\mathrm{SH}}^{i}\left(d_i\right) = 0$. The expected SH performance can then be expressed as follows:

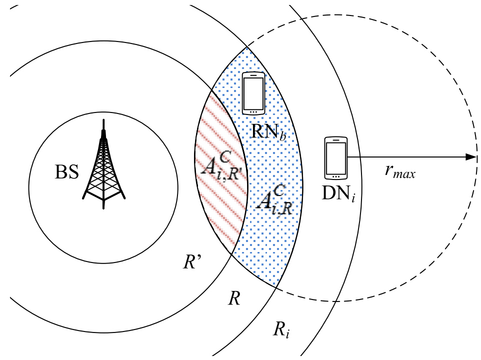

FIGURE 2. Conditions for an MH connection.

$$Q_{\mathrm{SH}}^{i}\left(s_i, d_i\right) = Benefit_{\mathrm{SH}}^{i}\left(s_i, d_i\right) \equiv q\left(s_i, R_i\right) \tag{4}$$

V. MH COMMUNICATIONS

In MH communications, the $\mathrm{RN_b}$ is selected at the start of the connection. The transmission from $\mathrm{RN_b}$ to DN starts as soon as $\mathrm{RN_b}$ receives data from the BS. We denote as R_i the ring where DN_i is located. DN_i can experience a higher performance with a MH connection than with a SH one if two conditions are satisfied. The first condition is that the RN must be located in a cellular ring R with higher data rates than R_i (i.e. $R \succ R_i$). Reference [21] showed that DN_i can experience the same performance as $\mathrm{RN_b}$ if the distance between $\mathrm{RN_b}$ and DN_i is below a maximum threshold r_{max}. The second condition is then that the distance between $\mathrm{RN_b}$ and DN_i must be smaller than r_{max}. MH connections can then outperform SH ones if the selected $\mathrm{RN_b}$ is located within an area A_i^C defined in (5). A_i^C is the union of the intersection areas $A_{i,R}^C$ between a circle $C(\mathrm{DN}_i, r_{max})$ centered in DN_i and with radius r_{max}, and the rings R that satisfy $R \succ R_i$ (see Fig. 2):

$$A_i^C = \bigcup_{R|R \succ R_i} A_{i,R}^C \tag{5}$$

$$A_{i,R}^C = R \cap C\left(\mathrm{DN}_i, r_{max}\right) \tag{6}$$

If a $\mathrm{RN_b}$ can be found in A_i^C, the MH benefit can be expressed as:

$$Benefit_{\mathrm{MH}}^{i}(s_i, d_i) = \frac{\sum_{R\,|R \succ R_i} \left(q(s_i, R) \cdot \mathrm{P_{RN}^{A}}(A_{i.R}^{C})\right)}{\sum_{R\,|R \succ R_i} \mathrm{P_{RN}^{A}}(A_{i.R}^{C})} \tag{7}$$

where $\mathrm{P_{RN}^{A}}\left(A_{i,R}^C\right)$ represents the probability of finding at least one $\mathrm{RN_b}$ within the area $A_{i,R}^C$. $q(s_i,R)$ represents the QoS of the BS-$\mathrm{RN_b}$ cellular link that is assigned s_i radio resources. $\mathrm{RN_b}$ is located in R. The benefit of MH is a function of d_i because the intersection area $A_{i,R}^C$ is a function of the location of DN_i.

An MH connection will not outperform a SH one if at least one of the two following conditions occurs: 1) the BS cannot find a RN_b in a ring R such that $R \succ R_i$, and 2) the distance between RN_b and DN_i is higher than r_{max}. The risk $Risk^i_{MH}$ resulting from establishing a MH connection between BS and DN_i can then be expressed as:

$$Risk^i_{MH}(d_i) = 1 - P^A_{RN}(A^C_i) \quad (8)$$

where $P^A_{RN}\left(A^C_i\right)$ is the probability of finding a RN_b within A^C_i. $Risk^i_{MH}$ is a function of d_i since d_i has an impact on the definition of A^C_i and hence on $P^A_{RN}\left(A^C_i\right)$. The expected QoS for MH connections $Q^i_{MH}(s_i, d_i)$ can then be computed as follows:

$$Q^i_{MH}(s_i, d_i) = \frac{\sum_{R|R \succ R_i} \left(q(s_i, R) \cdot P^A_{RN}(A^C_{i.R})\right)}{\sum_{R|R \succ R_i} P^A_{RN}(A^C_{i.R})} \cdot P^A_{RN}(A^C_i) \quad (9)$$

VI. OPPORTUNISTIC MH COMMUNICATIONS

MH-OPP communications can outperform SH and MH when some conditions are satisfied. These conditions depend on the number of hops n in the MH-OPP connection. Before identifying these conditions, it is necessary to define certain parameters and settings that are relevant to the operation of MH-OPP.

An MH-OPP connection with n hops from source to destination (referred to as n-MH-OPP) utilizes $n-1$ RNs (including the RN_b). We assume nodes move at an average speed v. RNs are numbered from RN_1 to RN_{n-1} based on their distance to the BS. RN_1 is the closest RN to the BS and acts as the RN_b. RN_{n-1} is the closest RN to the DN (Fig. 1.d). RN nodes can store and carry the data until finding adequate conditions to forward the data to other relay nodes. However, we must guarantee that the time needed to transmit all the data from the BS to the DN is below a maximum service-dependent deadline t_d. This time is equal to the sum of the time needed to complete the cellular (t_{cell}) and D2D (t_{D2D}) transmissions, and the time the data is stored and carried by the RNs. The maximum total time $t_{s\&c}$ that the data can be stored and carried by all the RNs is equal to:

$$t_{s\&c} = t_d - (n-1) \cdot t_{D2D} - t_{cell} \quad (10)$$

t_{D2D} is the ratio between the total amount of data to transmit and the throughput of the D2D link. The D2D throughput is obtained using the models in [21] and [8] (presented in Section VII.A), and assuming that D2D nodes are separated by a distance[3] equal to r_{max}. t_{cell} is estimated as the ratio between the total amount of data to transmit and the throughput of the cellular link. To compute t_{cell}, we consider that only the radio resources necessary to guarantee th_{min} are assigned. The assumptions considered to estimate t_{D2D} and t_{cell} represent a worst case scenario, and hence provide a conservative estimate of the benefits that can be obtained with MH-OPP.

[3] A higher distance would prevent transferring the QoS experienced at RN_b to the DN.

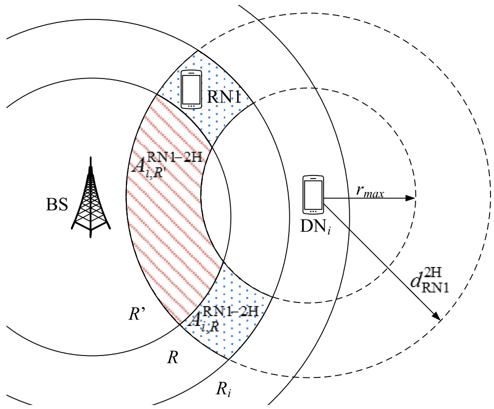

FIGURE 3. Illustration of A^{RN1-2H}_i RN1-2H for condition #2 that RNs must satisfy to establish an 2-MH-OPP connection.

RNs moving towards the DN are preferred to establish a downlink n-MH-OPP connection since they provide better forwarding opportunities. We define d^{nH}_{RNj} (with $j \in [1, n-1]$ and $n \in [2, N]$) as the maximum distance possible to establish $n-j$ D2D opportunistic links between RN_j and DN. This distance is equal to:

$$d^{nH}_{RNj} = r_{max} \cdot (n-j) + t_{s\&c} \cdot v \quad (11)$$

Eq. (11) establishes that RN_{n-1} must be at a distance from the DN equal or lower than r_{max} after $t_{s\&c}$ so that the end-to-end transmission successfully concludes before t_d. Establishing an n-MH-OPP connection with $n \geq 2$ requires then finding n-1 RNs that satisfy the following conditions:

1) RNs must be heading towards the DN.
2) The distance between RN_1 and DN_i must be lower than d^{nH}_{RN1} and higher than $d^{(n-1)H}_{RN1}$ if $n > 2$. It must also be higher than r_{max} if $n = 2$. This results in that the BS needs to find an RN in the area A^{RN1-nH}_i defined in (12). This area is the union of the areas $A^{RN1-nH}_{i,R}$ defined in (13) $\forall R \succ R_i$. $A^{RN1-nH}_{i,R}$ represents the intersection area between the ring R and a circle centered in DN_i with radius d^{nH}_{RN1} minus the area of a circle centered in DN_i and with radius equal to $d^{(n-1)H}_{RN1}$ for $n > 2$ and equal to r_{max} for $n = 2$. Fig. 3 illustrates an example of A^{RN1-2H}_i.

$$A^{RN1-nH}_i = \bigcup_{R|R \succ R_i} A^{RN1-nH}_{i,R} \quad (12)$$

$$A^{RN1-nH}_{i,R} = \begin{cases} R \cap \left(C(DN_i, d^{nH}_{RN1}) - C(DN_i, d^{(n-1)H}_{RN1})\right) & \text{if } n > 2 \\ R \cap \left(C(DN_i, d^{nH}_{RN1}) - C(DN_i, r_{max})\right) & \text{if } n = 2 \end{cases} \quad (13)$$

3) The distance between RN_j and DN_i for $j > 1$ must be lower than d^{nH}_{RNj}. The distance between any pair of relay nodes should not be higher than r_{max} so that the throughput experienced at RN_b can be transferred to

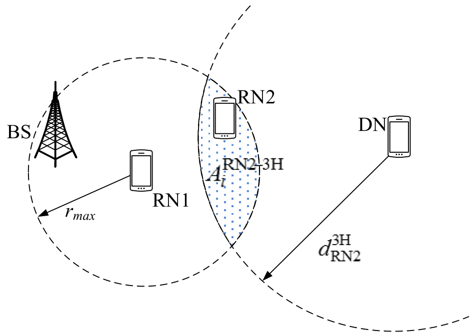

FIGURE 4. Illustration of $A_i^{\mathrm{RN2-3H}}$ RN2-3H for condition #3 that RNs must satisfy to establish an 3-MH-OPP connection.

the DN_i. It is then necessary that RN_j is located in an area $A_i^{\mathrm{RN}j-n\mathrm{H}}$ defined as:

$$A_i^{\mathrm{RN}j-n\mathrm{H}} = C\left(\mathrm{RN}_{j-1}, r_{max}\right) \cap C\left(\mathrm{DN}_i, d_{\mathrm{RN}j}^{n\mathrm{H}}\right) \quad (14)$$

$A_i^{\mathrm{RN}j-n\mathrm{H}}$ depends on the location of RN_{j-1} and DN_i. Fig. 4 illustrates an example of area $A_i^{\mathrm{RN2-3H}}$.

Taking into account the previous conditions, we can express the benefit of an n-MH-OPP connection as (15), as shown at the bottom of this page.

In (15), $q(s_i,R)$ represents the performance of the BS- $\mathrm{RN_b}$ cellular link when $\mathrm{RN_b}$ is located in R and the link has s_i radio resources. $\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1}-n\mathrm{H}})$ represents the probability of finding in $A_{i,R}^{\mathrm{RN1}-n\mathrm{H}}$ at least one RN moving towards DN_i. This RN will act as RN_b for the n-MH-OPP connection. $\mathrm{P}_{(n\text{-}1)\text{-D2D}}(\mathrm{DN}_i, A_{i,R}^{\mathrm{RN1}-n\mathrm{H}})$ represents the probability of establishing n-1 opportunistic D2D links between RN_b and DN_i when RN_b is located in $A_{i,R}^{\mathrm{RN1}-n\mathrm{H}}$. This probability depends on the probability of finding RNs that satisfy condition #3.

This study considers MH-OPP connections with n equal to 2 and 3 hops. The probability of establishing an opportunistic D2D link between DN_i and an $\mathrm{RN_b}$ located in the area $A_{i,R}^{\mathrm{RN1-2H}}$ is equal to 1 for 2-MH-OPP connections. This is the case because $A_{i,R}^{\mathrm{RN1-2H}}$ was calculated in (11) to guarantee that $\mathrm{RN_b}$ could establish a D2D link with DN_i within the service deadline. The benefit achieved with a 2-MH-OPP connection $Benefit_{2-\mathrm{MH-OPP}}^{i}$ is then computed as:

$$Benefit_{2-\mathrm{MH-OPP}}^{i}(s_i, d_i) = \frac{\sum_{R,R\succ R_i}\left(q(s_i,R)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{\mathrm{A}}(A_{i,R}^{\mathrm{RN1-2H}})\right)}{\sum_{R,R\succ R_i}\mathrm{P}_{\mathrm{RNtoDN}}^{\mathrm{A}}(A_{i,R}^{\mathrm{RN1-2H}})} \quad (16)$$

To compute the benefits achieved with a 3-MH-OPP connection, we compute the probability $\mathrm{P}_{2\text{-D2D}}(\mathrm{DN}_i \,|\, A_{i,R}^{\mathrm{RN1-3H}})$ of establishing 2 opportunistic D2D links between DN_i and an $\mathrm{RN_b}$ located in $A_{i,R}^{\mathrm{RN1-3H}}$. To this end, let's consider that the $\mathrm{RN_b}$ is located at a distance d_b from DN_i with a probability equal to $\mathrm{P}_{\mathrm{RN}}^{d}(d_b)$. The probability of establishing 2 opportunistic D2D links depends on the probability of finding at least one RN moving towards DN_i within the area $A_i^{\mathrm{RN2-3H}}$ defined in (13). $A_i^{\mathrm{RN2-3H}}$ is a function of the location of $\mathrm{RN_b}$ and DN_i. This probability is equal to $\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2-3H}})$. Finally, we need to consider all possible locations where $\mathrm{RN_b}$ can be located within $A_{i,R}^{\mathrm{RN1-3H}}$.$\mathrm{P}_{2\text{-D2D}}(\mathrm{DN}_i \,|\, A_{i,R}^{\mathrm{RN1-3H}})$ can then be computed as:

$$\mathrm{P}_{2\text{-D2D}}(\mathrm{DN}_i \,|\, A_{i,R}^{\mathrm{RN1-3H}}) = \frac{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2-3H}})\cdot \mathrm{d}d_b}{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{d}d_b} \quad (17)$$

where d_b^{min} and d_b^{max} are the largest and shortest possible distances between $\mathrm{RN_b}$ and DN_i when $\mathrm{RN_b}$ is located in $A_{i,R}^{\mathrm{RN1-3H}}$. These distances are defined as:

$$d_b^{min} = \max\left\{d_{\mathrm{RN}_1}^{2\mathrm{H}}, d_i - r_{outer}\right\} \quad (18)$$

$$d_b^{max} = \min\left\{d_{\mathrm{RN}_1}^{3\mathrm{H}}, d_i - r_{inner}\right\} \quad (19)$$

In (18) and (19), d_i is the distance between DN_i and the BS. r_{outer} and r_{inner} represent the outer and inner radius that define ring R. $Benefit_{3\text{-MH-OPP}}^{i}$ can then be estimated following (20), as shown at the bottom of this page.

Trying to establish an MH-OPP connection has the risk that we cannot find the RNs needed to guarantee that the

$$Benefit_{n-\mathrm{MH-OPP}}^{i}(s_i, d_i) = \frac{\sum_{R,R\succ R_i}\left(q(s_i,R)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1}-n\mathrm{H}})\cdot \mathrm{P}_{(n\text{-}1)\text{-D2D}}(\mathrm{DN}_i \,|\, A_{i,R}^{\mathrm{RN1}-n\mathrm{H}})\right)}{\sum_{R,R\succ R_i}\left(\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1}-n\mathrm{H}})\cdot \mathrm{P}_{(n\text{-}1)\text{-D2D}}(\mathrm{DN}_i \,|\, A_{i,R}^{\mathrm{RN1}-n\mathrm{H}})\right)} \quad (15)$$

$$Benefit_{3-\mathrm{MH-OPP}}^{i}(s_i, d_i) = \frac{\sum_{R,R\succ R_i}\left(q(s_i,R)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1-3H}})\cdot \frac{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2-3H}})\cdot \mathrm{d}d_b}{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{d}d_b}\right)}{\sum_{R,R\succ R_i}\left(\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1-3H}})\cdot \frac{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2-3H}})\cdot \mathrm{d}d_b}{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{d}d_b}\right)} \quad (20)$$

transmission finishes before t_d. An n-MH-OPP connection will not outperform a SH or MH connection if at least one of the two following conditions occurs:

1) The BS cannot find an $\mathrm{RN_b}$ moving towards the DN_i in a ring R such that $R \succ R_i$, and located at a distance from the DN_i comprised between $d_{\mathrm{RN1}}^{n\mathrm{H}}$ and $d_{\mathrm{RN1}}^{(n-1)\mathrm{H}}$ if $n > 2$, or between $d_{\mathrm{RN1}}^{n\mathrm{H}}$ and r_{max} if $n = 2$. These restrictions define the area $A_i^{\mathrm{RN1}-n\mathrm{H}}$(12) where we need to find $\mathrm{RN_b}$. The probability of not finding a RN within $A_i^{\mathrm{RN1}-n\mathrm{H}}$ is given by 1-$\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-n\mathrm{H}})$.
2) It is not possible to find RNs to establish n-1 opportunistic D2D links between RN_b and DN_i when RN_b is located in $A_i^{\mathrm{RN1}-n\mathrm{H}}$. This probability is equal to 1-$\mathrm{P}_{(n\text{-}1)\text{-D2D}}(\mathrm{DN}_i \,|A_i^{\mathrm{RN1}-n\mathrm{H}})$.

The risk $Risk_{n-\mathrm{MH-OPP}}^{i}$ resulting from establishing an n-MH-OPP connection can then be expressed as:

$$\begin{aligned} Risk_{n-\mathrm{MH-OPP}}^{i}(d_i) &= 1 - \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-n\mathrm{H}}) + \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-n\mathrm{H}}) \\ &\quad \cdot \left(1 - \mathrm{P}_{(n\text{-}1)\text{-D2D}}(\mathrm{DN}_i \,|A_i^{\mathrm{RN1}-n\mathrm{H}})\right) \end{aligned} \tag{21}$$

For a 2-MH-OPP connection, $\mathrm{P}_{1\text{-D2D}}(\mathrm{DN}_i \,|A_i^{\mathrm{RN1}-2\mathrm{H}})$ is equal to one. This is because $A_i^{\mathrm{RN1}-2\mathrm{H}}$ was defined so that a $\mathrm{RN_b}$ located within this area can establish a D2D link with DN_i before t_d. $Risk_{2-\mathrm{MH-OPP}}^{i}$ is then equal to:

$$Risk_{2-\mathrm{MH-OPP}}^{i}(d_i) = 1 - \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-2\mathrm{H}}) \tag{22}$$

For a 3-MH-OPP connection, we need to compute the probability of not being able to establish 2 opportunistic D2D links between the $\mathrm{RN_b}$ and DN_i when $\mathrm{RN_b}$ is in $A_i^{\mathrm{RN1}-3\mathrm{H}}$. This probability depends on the probability that we cannot find an adequate $\mathrm{RN_2}$ within $A_i^{\mathrm{RN2}-3\mathrm{H}}$. This probability is equal to 1-$\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2}-3\mathrm{H}})$. Similarly to (17), it is necessary to consider all possible positions of $\mathrm{RN_b}$ within $A_{i,R}^{\mathrm{RN1}-n\mathrm{H}}$. $Risk_{3-\mathrm{MH-OPP}}^{i}$ is then computed as:

$$\begin{aligned} Risk_{3\text{-}\mathrm{MH-OPP}}^{i}(d_i) &= 1 - \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-3\mathrm{H}}) + P_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-3\mathrm{H}}) \\ &\quad \cdot \frac{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot\left(1\text{-}\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2}-3\mathrm{H}})\right)\cdot \mathrm{d}d_b}{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{d}d_b} \end{aligned} \tag{23}$$

where d_b^{min} and d_b^{max} are the largest and shortest distances between $\mathrm{RN_b}$ and DN_i when $\mathrm{RN_b}$ is within $A_i^{\mathrm{RN1}-3\mathrm{H}}$. These distances are defined as:

$$d_b^{min} = d_{\mathrm{RN_1}}^{2\mathrm{H}} \tag{24}$$

$$d_b^{max} = d_{\mathrm{RN_1}}^{3\mathrm{H}} \tag{25}$$

Finally, we can computed the expected QoS performance for 2-MH-OPP and 3-MH-OPP connections as shown in (26) and (27), as shown at the bottom of this page, respectively.

VII. EVALUATION

A. SCENARIO AND MODELS

The proposed mode selection scheme is evaluated in a single cell scenario with 1 km radius. DN nodes request downloading a 20Mb file, and the deadline to download the file (t_d) is set equal to 60s [22]. Nodes are initially distributed in the cell following an homogeneous Poisson distribution with average node density ρ. Simulations have been conducted for average node density values equal to 5, 15, 25, 50, and 100 nodes/km; the scenarios are referred to as D1, D2, D3, D4 and D5 respectively. Nodes move across the cell at a constant pedestrian speed equal to 3 m/s and randomly select their direction. This mobility pattern results in a uniform distribution of nodes within the cell. The probability $\mathrm{P}_{\mathrm{RN}}^{A}(A)$ of finding at least one RN within an area A can then be computed following a Poisson distribution:

$$\mathrm{P}_{\mathrm{RN}}^{A}(A) = 1 - \exp(-\rho A) \tag{28}$$

$$Q_{2-\mathrm{MH-OPP}}^{i}(s_i, d_i) = \frac{\sum_{R,R\succ R_i}\left(q(s_i,R)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1}-2\mathrm{H}})\right)}{\sum_{R,R\succ R_i} \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1}-2\mathrm{H}})} \cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-2\mathrm{H}}) \tag{26}$$

$$\begin{aligned} Q_{3-\mathrm{MH-OPP}}^{i}(s_i, d_i) &= \frac{\sum_{R,R\succ R_i}\left(q(s_i,R)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1}-3\mathrm{H}})\cdot \frac{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RNtoDN}}^{d}(d_b)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2}-3\mathrm{H}})\cdot \mathrm{d}d_b}{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RNtoDN}}^{d}(d_b)\cdot \mathrm{d}d_b}\right)}{\sum_{R,R\succ R_i}\left(\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_{i,R}^{\mathrm{RN1}-3\mathrm{H}})\cdot \frac{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2}-3\mathrm{H}})\cdot \mathrm{d}d_b}{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{d}d_b}\right)} \\ &\quad \cdot \left\{ \mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-3\mathrm{H}}) - P_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN1}-3\mathrm{H}}) \cdot \frac{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot\left(1\text{-}\mathrm{P}_{\mathrm{RNtoDN}}^{A}(A_i^{\mathrm{RN2}-3\mathrm{H}})\right)\cdot \mathrm{d}d_b}{\int_{d_b^{min}}^{d_b^{max}} \mathrm{P}_{\mathrm{RN}}^{d}(d_b)\cdot \mathrm{d}d_b} \right\} \end{aligned} \tag{27}$$

TABLE 1. CQI, modulation and code rate.

CQI index	Modulation	Code Rate x 1024	Transmission rate (kbits/s/PRB)
1	QPSK	78	24.99
2	QPSK	120	38.45
3	QPSK	193	61.84
4	QPSK	308	98.69
5	QPSK	449	143.88
6	QPSK	602	192.90
7	16QAM	378	242.25
8	16QAM	490	314.03
9	16QAM	616	394.78
10	64QAM	466	447.97
11	64QAM	567	545.06
12	64QAM	666	640.23
13	64QAM	772	742.13
14	64QAM	873	839.22
15	64QAM	948	911.32

Cellular transmissions are modelled using the LTE (Long Term Evolution) radio interface with 5MHz.[4] These transmissions utilize one of the LTE Modulation and Coding Schemes (MCSs) associated to the 15 Channel Quality Indicator (CQI) values defined in 3GPP TS 36.213 [23]. These CQI values are shown in Table 1. The MCS is dynamically selected based on the distance between a cellular node and the BS. The cellular data rate (dr_{cel}) depends on the cell ring where the cellular node is located. Following [23], we consider that the MCS that guarantees a BLER below 10% is utilized in each ring. We compute the cellular th_{cel} as:

$$th_{cel} = dr_{cel}(d) \cdot (1 - BLER) \tag{29}$$

where $BLER$ is equal to 10%.

We consider out-of-band D2D transmissions using IEEE 802.11g at the 2.4GHz band. It should be noted that 3GPP considers both IEEE 802.11 and cellular technologies for D2D (or sidelink as referred to in 3GPP) communications [6]. The D2D transmissions are modelled following the IEEE 802.11g-based D2D throughput model reported in [8]:

$$th_{D2D} = dr_{D2D}(d) \cdot Eff \cdot (1 - PER_{D2D}(d)) \tag{30}$$

$dr_{D2D}(d)$ is the data rate of the IEEE 802.11g MCS[5] that is used in the D2D transmission. PER represents the experienced Packet Error Ratio experienced, and Eff is the channel efficiency. d represents the distance between the transmitter and the receiver. We consider that the MCS is dynamically selected to maximize the throughput based on the link quality conditions [21]. We use the model in [21] to compute the D2D data rate:

$$dr_{D2D}(d) = \begin{cases} 54 & \text{if } d < p_1 \\ \dfrac{54}{1/p_1 - 1/p_2} \cdot \left(\dfrac{1}{d} - \dfrac{1}{p_2}\right) & \text{if } p_1 \le d < p_2 \\ 0 & \text{if } p_2 \le d \end{cases} \tag{31}$$

p_1 and p_2 are fitting parameters, and are equal to 78.47 and 270.85 respectively [21]. We also utilize the empirical D2D PER model presented in [21]:

$$PER_{D2D}(d) = \frac{0.75}{1 + e^{0.019\cdot(d-115.15)}} \tag{32}$$

The channel efficiency Eff in (30) represents the effective time that the channel is used to transmit data. This time depends on the transmission time of data packets (t_d) and ACK packets (t_{ack}), the contention period (t_{cont}), and the inter-frame guard times (DIFS and SIFS):

$$Eff = \frac{t_d}{\text{DIFS} + t_{cont} + t_d + \text{SIFS} + t_{ack}} \tag{33}$$

Following [21], r_{max} has been set equal to 80m.

The energy consumed in D2D and cellular transmissions is estimated as:

$$E(d) = (p_r + p_t + P_T(d)) \cdot t_{Tx} \tag{34}$$

where p_t and p_r represent the power consumed in the transmitter and receiver electronics respectively. t_{Tx} is the transmission time. It is computed as the ratio between the data transmitted and the D2D or cellular throughput. $P_T(d)$ represents the transmission power. It is set to a value that guarantees that the receiver's signal power level P_R is equal to the threshold required for a successful communication between two nodes. The signal power at the receiver can be computed as $P_R = G_T + G_R + P_T - PL$, where G_T and G_R represent the transmitter and receiver antenna gains (here equal to 1), and PL the propagation loss. PL is modeled using the WINNER propagation model for urban scenarios [24]. Using this model, it is possible to estimate P_T as:

$$P_T(d) = \begin{cases} \dfrac{P_R \cdot 10^{4.1} \cdot (f/5)^2}{G_T \cdot G_R} \cdot d^{2.7} & \text{if } d < d_{bp} \\ \dfrac{P_R \cdot 10^{4.1} \cdot (f/5)^2}{G_T \cdot G_R \cdot d_{bp}^{1.73}} \cdot d^4 & \text{if } d \ge d_{bp} \end{cases} \tag{35}$$

In (31), $d_{bp} = 4 \cdot (h_T - 1) \cdot (h_R - 1)/\Lambda$ is the breakpoint distance. h_T and h_R are the transmitter and receiver antenna heights, and Λ is the carrier wavelength (all in meters). f is the carrier frequency in GHz.

The energy consumed in the process to store and carry data is modeled following [8].

B. PERFORMANCE

This section analyzes the performance achieved with the proposed mode selection scheme. The scheme is referred to as OPP in this section. The performance obtained with OPP

[4] A 5MHz channel is typically used in real deployments, but other configurations could be used without affecting the outcome and trends highlighted in this study.

[5] IEEE 802.11g defines twelve possible modulation and coding schemes that result in the data rates of 54, 48, 36, 24, 18, 12, 9, 6, 11, 5.5, 2, 1 Mbps.

TABLE 2. Percentage of completed downloads before the deadline.

Scenario	SH	NO-OPP	OPP
D1		82.52	82.52
D2		82.89	85.05
D3	82.52	84.95	87.21
D4		86.89	90.87
D5		87.82	94.84

TABLE 3. Percentage of downloads with each communication mode.

	SH			NO-OPP			OPP		
	SH	MH	MH-OPP	SH	MH	MH-OPP	SH	MH	MH-OPP
D1	100	-	-	100	0	-	100	0	0
D2	100	-	-	98.5	1.5	-	77.1	7.6	15.3
D3	100	-	-	83.0	17.0	-	38.9	18.3	42.8
D4	100	-	-	40.0	60.0	-	8.2	14.4	77.5
D5	100	-	-	19.6	80.4	-	9.4	3.9	86.8

is compared against that obtained with conventional cellular communications (referred to as SH) and with the scheme selecting only between the SH or MH modes (referred to as NO-OPP). In all cases, the MH mode is limited to 2 hops and the MH-OPP mode can operate with 2 or 3 hops. The number of hops is selected by the mode selection scheme based on the context conditions.

Table 2 shows the percentage of downloads that are completed within the established deadline. The table shows that the proposed scheme (OPP) outperforms SH and NO-OPP option for all scenarios except D1. D1 is characterized by a very low density of nodes. In this case, there are few opportunities to find adequate RNs, and OPP mostly selects the SH mode for the transmissions. This explains why OPP achieves the same performance as SH in D1. The gains obtained with OPP increase with the density of nodes. These gains result from the use of opportunistic MCN communications. This is highlighted in Table 3 that shows the percentage of downloads executed with each communication mode. Table 3 shows that OPP results in a large percentage of downloads executed with the MH-OPP scheme in most scenarios, and this percentage increases with the density of nodes. The MH-OPP mode establishes connections under good link quality conditions that ensure high data rates and an efficient use of the radio resources. The number of possible links increases with the density of nodes, and so does the usage of the MH-OPP mode. OPP is capable to detect the risks of trying to establish MH-OPP connections when the density of nodes is very low (D1). In this case, OPP selects the SH mode for all the downloads.

The gains obtained with the proposed mode selection scheme are further illustrated in Fig. 5 and Fig. 6. Fig. 5 depicts the average cellular throughput.[6] Fig. 6 shows

[6]Results for D1 are not shown since SH, NO-OPP and OPP achieve the same performance.

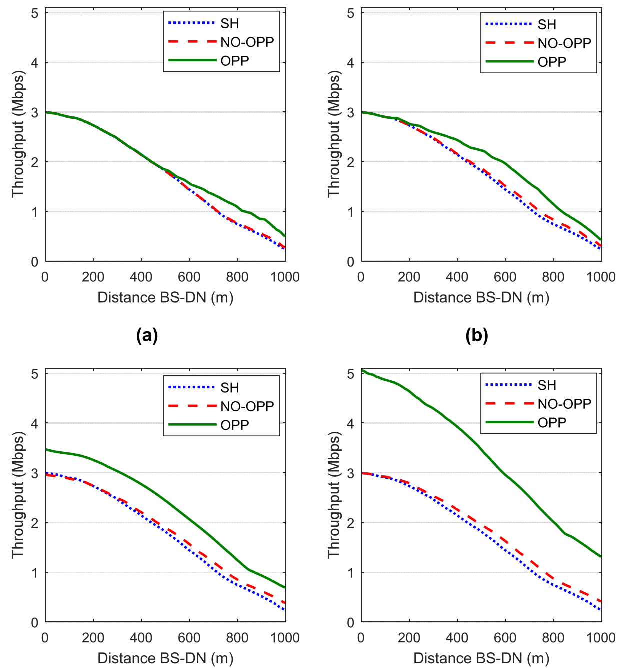

FIGURE 5. Average cellular throughput. (a) D2 scenario; (b) D3 scenario; (c) D4 scenario; (d) D5 scenario.

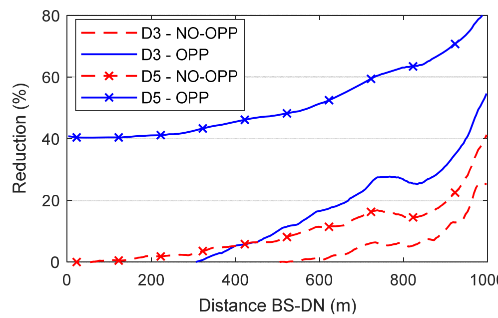

FIGURE 6. Reduction in the average cellular channel occupancy achieved with OPP and NO-OPP compared to SH.

the reduction in average cellular channel occupancy achieved with NO-OPP and OPP with respect to SH. The channel occupancy is defined as the total time during which cellular radio resources are used to download data. Fig. 5 shows that OPP improves the throughput experienced by DNs that are further away from the BS when the density of nodes is low (D2-D3). This is because these DNs experience the worst link level conditions with the BS, and hence strongly benefit from using the MH-OPP mode. OPP improves the cellular throughput for all DNs independently of their location when the density of nodes increases (Fig. 5.c and Fig. 5.d). High throughput levels reduce the duration of transmissions, and therefore the use of cellular radio resources (Fig. 6). This in turn has an impact on the cellular capacity since more nodes can be served with the same cellular radio resources. Fig. 5.d shows that the proposed scheme (OPP) increases on

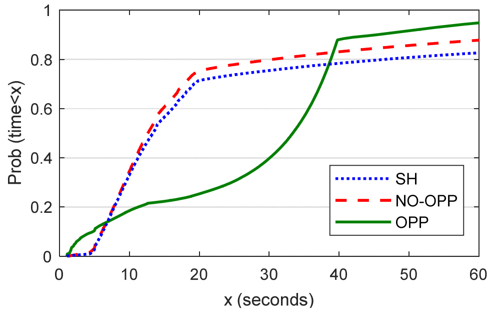

FIGURE 7. Cumulative distribution function (CDF) of the time needed to complete a download in D5.

average the cellular throughput compared to conventional cellular communications (SH) by 125%[7] in D5. NO-OPP only increases the throughput compared to SH by 12%. The higher throughput achieved with OPP reduces the average cellular channel occupancy compared to SH by more than 51% in D5. NO-OPP can only reduce the channel occupancy by 10% compared to SH. The gains obtained with OPP derive from the use of the MH-OPP communication mode (Table 3). This mode searches for relay nodes (RN) with good D2D link quality conditions. This guarantees high throughput values and an efficient use of the spectrum. Searching for the optimum D2D links increases the duration of the end-to-end transmissions (Fig. 7). However, Table 2 shows that OPP actually increases the percentage of downloads executed within the deadline. These results show that waiting for optimum conditions (within the service-dependent deadline) is better than starting transmissions as soon as connections are present. The use of the MH-OPP mode also improves the energy consumption. Fig. 8 compares the average energy consumed per download as a function of the distance between the BS and the DN. This energy is computed considering the energy consumed in the cellular and D2D transmissions, and in the store & carry process for MH-OPP communications. The results are shown for four different densities. Fig. 8 clearly demonstrates that the proposed scheme (OPP) significantly reduces the energy consumption. The gains achieved increase with the BS-DN distance and with the density of nodes. For example, OPP reduces the average total energy consumption by 5.7% compared to SH for distances up to 350m in D3. The reduction augments to 39.4% for distances higher than 350m. On the other hand, NO-OPP only reduces the average total energy consumption compared to SH by 0.5% and 6.6% respectively. The gains obtained with OPP significantly increase with the density of nodes in the scenario. For example, OPP reduces the energy consumption compared to SH by 71.4% in D5 (for distances higher than 350) and by 39.4% in D3. Higher energy reduction levels are observed when the density increases because OPP can establish more MH-OPP connections (Table 3) as there are more potential relay nodes.

[7]The gains increase to between 200% and 440% when DNs are located 800m to 1000m from the BS.

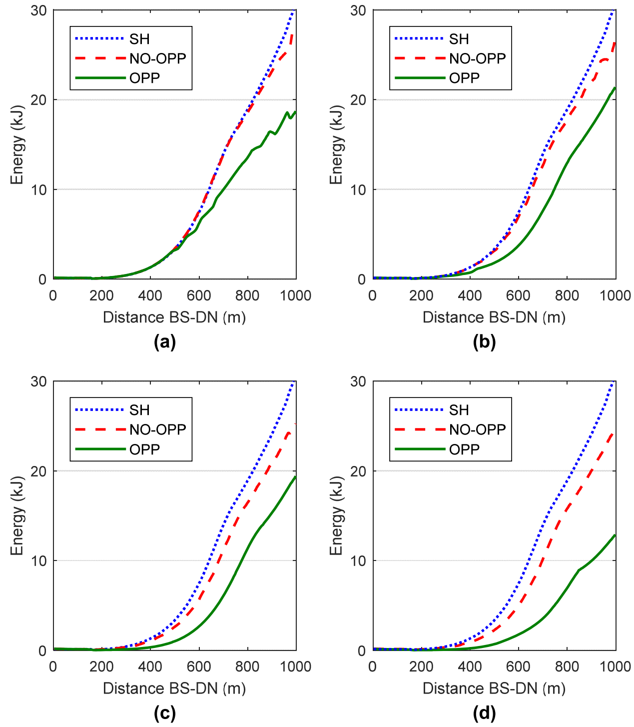

FIGURE 8. Average energy consumption per download as a function of the distance between the BS and the DN. (a) D2 scenario; (b) D3 scenario; (c) D4 scenario; (d) D5 scenario.

This allows establishing connections with better link quality conditions, and consequently increases the throughput, reduces the duration of transmissions and decreases the total energy consumption.[8] The average energy consumption gains achieved with OPP for DL communications are obtained at the cost of a slight increase in the energy consumed per node. This increase is the energy consumed by devices when they act as relays for other DL connections. We would though like to note that the energy consumed at the devices (RNs) per transmission is significantly smaller than the energy consumed in the BS-RN or BS-DN cellular transmissions.[9] This is the case because OPP searches for D2D links with good link quality conditions and hence low energy consumption. We would also like to emphasize that this study is focused on DL communications. Devices will save significant energy in their UL transmissions with OPP thanks to the use of MH and MH-OPP communications. These savings were demonstrated by the authors in [7] and [8]. Reference [7] showed that 2-hop MCN communications can reduce by 50% the total energy consumption for UL transmissions compared to conventional cellular communications. These gains consider the energy consumed at the source device and the relay nodes. Consequently, devices can achieve significant energy gains

[8]The energy consumed by the radio transmissions is significantly larger than the energy consumed during the store and carry processes.

[9]For example, a RN consumes 0.04kJ per download when using OPP under D4. However, OPP reduces the energy consumed in the cellular transmission (from BN to RN) to 4.65kJ per download compared to 6.08kJ with SH.

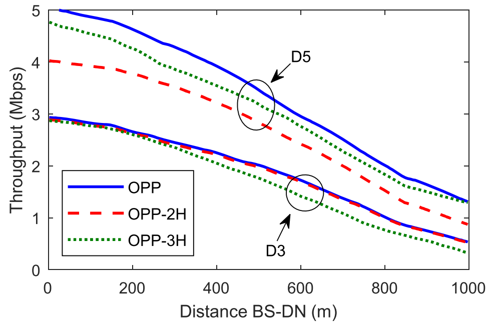

FIGURE 9. Average cellular throughput as a function of the BS-DN distance for different configurations of OPP.

in their UL transmissions. In [8], the authors analytically demonstrated that the integration of opportunistic networking and MCN communications can reduce the energy consumption by more than 90% compared to conventional UL cellular communications. This gain considers again the energy consumed at the source device and the relay nodes. The energy consumed per node for DL communications will hence be compensated by the savings achieved in UL transmissions.[10]

The proposed mode selection scheme (OPP) embeds the decision on the number of hops for MH-OPP connections in the mode selection process. This allows dynamically selecting the best MH-OPP configuration (i.e. with 2 or 3 hops) based on the context conditions. This is illustrated in Fig. 9, Table 4 and Fig. 10 that compare the performance obtained with OPP to that obtained when the MH-OPP mode can only operate with either 2 (OPP-2H) or 3 (OPP-3H) hops. Fig. 9 shows that OPP improves the average cellular throughput for all distances and densities of nodes. This is because OPP selects the configuration of MH-OPP connections that optimizes the cellular throughput based on the context conditions. Fig. 9 shows that a configuration of MH-OPP connections with only 2 hops achieves higher performance than a configuration with 3 hops under low densities. The trend is reversed for higher densities. Under low densities, the probability of finding adequate RN nodes is small. In this case, the risk of establishing MH-OPP connections increases with the number of hops. This risk decreases when the density of nodes increases. In this case, MH-OPP connections with 3 hops improve the performance since RN_b nodes closer to the BS can be selected. The trends observed in Fig. 9 are also reflected in Table 4 and Fig. 10. Table 4 shows that OPP achieves the highest percentage of completed downloads. Similarly, OPP reduces the total average energy consumption per download (Fig. 10).

C. COMPLEXITY AND SIGNALLING OVERHEAD

This section analyzes the complexity and signalling overhead of the proposed mode selection scheme. The scheme

[10]The throughput and energy consumption gains are clear incentives for nodes to cooperate and act as RN for other DNs under the adequate network conditions. Our proposed mode selection scheme (OPP) is capable to identify these conditions and select the most adequate communication mode.

TABLE 4. Percentage of completed downloads before the deadline for different configurations of OPP.

Scenario	OPP-2H	OPP	OPP-3H
D3	86.95	87.21	84.31
D4	90.43	90.87	88.35
D5	91.85	94.84	94.51

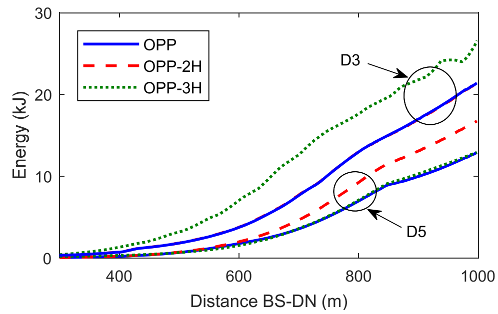

FIGURE 10. Average total energy consumed per download as a function of the BS-DN distance for different configurations of OPP.

probabilistically estimates the benefits, risks and expected performance of each communication mode (SH, MH and MH-OPP). The performance is estimated considering the context conditions of each DN. The proposed mode selection scheme selects for each DN the communication mode that provides the highest expected performance. Table 5 summarizes the complexity order of the processes carried out to estimate the benefits and risks for each communication mode. In Table 5, N_R represents the number of rings R defined in the cell. Table 5 shows that estimating the benefits of the MH and MH-OPP modes has the highest complexity order that is equal to $O(N_R)$ and is lineal with N_R. Following Table 5, it is possible to conclude that the complexity order of the mode selection scheme is equal to $O(N_{DN} \cdot N_R)$, where N_{DN} represents the number of DNs for which a mode selection decision has to be taken. The computational complexity of the proposed mode selection scheme is then linear with the number of DNs in the system, and with the number of rings R defined in the cell. The number N_R of rings is limited by the number of MCS used in the system; a typical value is between 10 and 15. We would also like to note that the number of rings in a cell is constant for a given deployment, and the complexity order of our proposed mode selection scheme can then be expressed as $O(N_{DN})$. To the author's knowledge, our proposed mode selection scheme is the first to consider opportunistic MCN communications. Its complexity is then compared as a reference with the proposal presented in [15]. This proposal only considers the SH and MH communication modes. The proposal in [15] selects the MCN link when the distance between a DN and the BS is larger than a pre-defined threshold. Otherwise, the proposal selects the SH mode. The computational complexity of the proposal in [15] is also linear with the number of DNs, i.e. $O(N_{DN})$. The complexity

TABLE 5. Computational complexity.

Calculation	Complexity order
$Benefit^{i}_{\mathrm{SH}}(s_i, d_i)$	O(1)
$Risk^{i}_{\mathrm{SH}}(d_i)$	O(1)
$Benefit^{i}_{\mathrm{MH}}(s_i, d_i)$	O(N_R)
$Risk^{i}_{\mathrm{MH}}(d_i)$	O(1)
$Benefit^{i}_{\mathrm{2\text{-}MH\text{-}OPP}}(s_i, d_i)$	O(N_R)
$Risk^{i}_{\mathrm{2\text{-}MH\text{-}OPP}}(d_i)$	O(1)
$Benefit^{i}_{\mathrm{3\text{-}MH\text{-}OPP}}(s_i, d_i)$	O(N_R)
$Risk^{i}_{\mathrm{3\text{-}MH\text{-}OPP}}(d_i)$	O(1)

of our proposal is then similar to existing mode selection schemes even if our scheme is the first to be able to integrate opportunistic MCN communications (this is not the case of [15]).

It is also important to highlight that the mode selection scheme proposed in this study utilizes information already available at the BS to select the most adequate communication mode. In particular, it uses the distance between DNs and the BS, and the density of nodes in the cell. The DN-BS distance can be currently estimated by BSs using the signal level received from a DN. Current cellular networks also already know the number of nodes per cell. Hence, the implementation of the proposed mode selection scheme does not introduce additional signaling overhead in the network. Other mode selection schemes that have been reported in the literature (e.g. [12] and [17]) require nodes to measure the signal level received from other potential RNs. In addition, nodes must share these measurements with the BS or other nodes. This approach results in a non-negligible signaling overhead. For example, let's consider that each DN has to report signal level measurements from N_{RN} potential relay nodes, and that 1 byte is sufficient to quantify each measurement. In this case, the overhead per cell is equal to $N_{DN} \cdot N_{RN}$ bytes.

VIII. CONCLUSION

This study has proposed and evaluated the first mode selection scheme that integrates opportunistic MCN communications in heterogeneous 5G networks. The proposed scheme selects the communication mode that achieves the best trade-off between benefits and risks. In particular, the proposed scheme can select between conventional single-hop cellular communications, multi-hop cellular communications, and opportunistic multi-hop cellular communications. The proposed scheme also embeds the decision on the optimum number of hops in the mode selection process. The performance of the proposed scheme has been compared to that obtained with conventional single-hop cellular communications and with multi-hop cellular communications. The obtained results have demonstrated that opportunistic MCN communications can significantly improve the performance of future 5G and beyond cellular networks. In addition, the study has demonstrated that the proposed mode selection scheme is capable to select the communication mode that maximizes the performance at all levels (successful downloads, throughput, capacity and energy consumption). The proposed mode selection scheme reduces the risks derived from the use of MCN communications while fully exploiting its advantages based on the context conditions. This is important to facilitate the introduction of MCN technologies into 5G and beyond networks.

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