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Relay-Assisted D2D Underlay Cellular Network Analysis Using Stochastic Geometry: Overview and Future Directions

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ABSTRACT Device-to-Device (D2D) communication is one of the enabling technologies for meeting the capacity requirements of the fifth-generation wireless systems (5G). It has diverse applications in traffic offloading, disaster management and content sharing, to mention a few. The network coverage and capacity further improve when relays are introduced to D2D communication. However, the interference becomes more severe since these devices also share resources with the traditional cellular users in the underlay. To take the benefits and avert the drawbacks of this spectrum sharing scenario, analytical tools capable of revealing the mathematical relationships among pertinent network design parameters are needed. This brings stochastic geometry (SG) into the picture. With SG-based analyses, designers can model concepts to understand, provide insights, and address the problems of spectrum sharing in relay-assisted D2D communication. Some of the key metrics of particular interest to network designers are the transmission capacity and spectral efficiency of D2D communication, as they reveal the performance gains and quantify the level of interference within the network. These enable them to properly correlate relevant cause-and-effect relationships before wealth and time are invested in network implementation. Despite the studies on the analysis of relay-assisted D2D underlay cellular networks using SG in recent years, there is no available survey material where researchers can find models, assumptions, key results and derived lessons to further comprehend this area and open up new research lines. This motivates the presentation of this paper which in addition to the aforementioned, gives elaborate discussions on promising areas for future research with respect to the recent advancements in D2D communication and SG research.

INDEX TERMS D2D, energy efficiency, relay, spectral efficiency, stochastic geometry, survey, transmission capacity.

I. INTRODUCTION

Device-to-Device (D2D) communication underlay cellular network infrastructure is receiving a lot of attention recently [1]. This paradigm facilitates mutual communication between devices in proximity with little or no intervention of the base station (BS) [2]. D2D communication has been identified as a promising technology for increasing the network capacity as well as user experience [3]. Additionally, it is a major prospective technology for attaining energy efficiency in cellular networks [4]. In future fifth-generation cellular networks (5G), D2D communication is regarded as an enabling technology to achieve high spectral efficiency (SE) and ultra-densification [5]. Furthermore, it enhances network throughput and reduces delay [6]. However, a major challenge in D2D networks within a cellular architecture is

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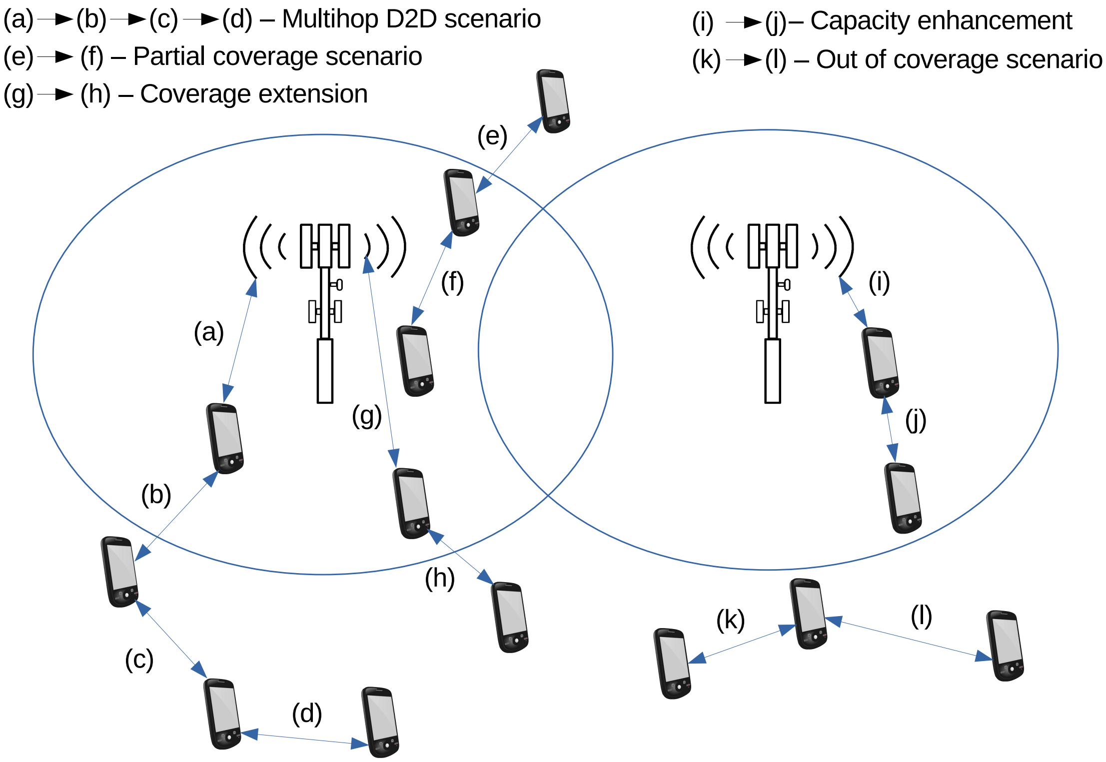

FIGURE 1. Typical relaying scenarios for relay-assisted D2D communication.

co-channel interference that occurs when the existing cellular transmissions interfere with D2D communications.

The application use-cases of D2D communication become more restricted when the source and destination devices are not in proximity [7]. Hence, a universal solution cannot be achieved by D2D communication without the intervention of relays [8]. For example, when D2D pairs are farther apart, the outage probabilities of D2D links will increase. Furthermore, nodes might not be able to reach other nodes due to constraints in transmit power [9] in a single hop. In such cases, most traditional interference management schemes such as power control may not work. This motivates the need to enhance the range of communication, thereby reducing the outage probability [10].

In relay-assisted D2D communication, the source and destination devices discover an idle node between them to establish mutual communication. The source node transmits data to the relay which decodes and forwards it to the destination node. Some typical relaying scenarios are illustrated in Fig. 1. Relay-assisted D2D communication has several use cases. According to [13], the ubiquity of D2D communication makes the incorporation of multihop D2D communication conceivable as a part of a future standard. This is because multihop D2D communication is not bounded to specific geographic locations like the traditional D2D communication.

Device relaying has several other benefits. It can inherently bring to light the potential of cooperative communication to meet the growing demand for higher data rates and capacity in 5G cellular systems [12]. The use of relays facilitates multihop transmission which improves spectral reuse within the network. Asides the potential of achieving higher data rates and improving the network capacity, there are also ‘promises’ of improved quality of service (QoS), and network load balancing. Also, relays can be used to improve network performance in poor coverage areas [11], such as places with damaged cellular infrastructure [13].

In view of the above significance of relays, this paper reviews the performance analysis of relay-assisted D2D communication in cellular networks. We concentrate on stochastic geometry (SG)-based analysis of the network as it has recently been proven to be effective for understanding interference in spectrum sharing networks. Furthermore, we discuss promising future directions that have emerged due to recent development in SG research, such as signal-to-interference ratio (SIR) meta-distribution, spatio-temporal interference correlation, and the use of generalized fading channels. Moreover, this paper also presents a number of research opportunities peculiar to relay-assisted D2D communication. Note that some of the future directions presented in this paper are also applicable to other wireless communication systems.

A. THE ROLE OF STOCHASTIC GEOMETRY IN NETWORK ANALYSIS

Stochastic geometry is a sophisticated tool from mathematics which gives insights into spatial averages taken over several

TABLE 1. Abbreviations and meanings.

Abbreviation	Meaning
3GPP	Third-generation partnership project
5G	Fifth-generation cellular network
ASR	Average sum rate
BS	Base station
CRN	Cognitive radio network
CUE	Cellular user equipment
D2D	Device-to-Device
DUE	D2D user equipment
FDAF	Full duplex amplify and forward
FDMA	Frequency division multiple access
IC	Interference cancellation
LOS	Line-of-sight
LTE	Long-term evolution
LTE-A	Long-term evolution advanced
PCP	Poisson cluster process
PDF	Probability density function
PPP	Poisson point process
QoS	Quality of service
RN	Relay node
SE	Spectral efficiency
SG	Stochastic geometry
SINR	Signal-to interference-plus-noise ratio
SIR	Signal-to-interference ratio
STP	Successful transmission probability
TDD	Time division duplexing
TC	Transmission capacity
UAV	Unmanned aerial vehicle
UE	User equipment

realizations for a large number of nodes at various locations. These insights could be in the form of outage probability, interference, data rate and signal-to-interference-plus-noise ratio (SINR) [14], [16]. SG can be employed to design spatial stochastic models for devices' locations.[1] Additionally, point processes can be generalized in two or three dimensions and indexed by time [15]. SG is meritorious as it can be used to characterize the SINR in cellular, sensor and adhoc networks. Traditional approaches in communication theory can not be easily deployed for that purpose as interference in such networks highly depends on the network geometry. Another reason is that these systems involve a high level of uncertainty. For instance, it is very hard for each node to know the location and predict the channel state of all other nodes [14]. Thus, statistical models depicting the relationship of devices in space using SG can be used to answer questions such as [15]:

- In the next decade, what effects will the large-scale deployment of unplanned infrastructure have on the spectrum and its users?
- What approach could be used to design wireless multi-hop networks which may involve mobility and randomly scattered users?
- How can the networks' throughput/capacity and connectivity/coverage be determined?

B. RELATED SURVEYS

This subsection briefly describes the contributions of related surveys/tutorials on SG for modelling various aspects of wireless communication. It is worth noting that D2D (and relay-assisted D2D) communication research using SG started becoming prominent after the first few surveys emerged.

Towards understanding the role of SG in modelling interference, Haenggi *et al.* [14] presented a seminal survey article on the use of SG and random graphs for the analysis of wireless networks in 2009. They expounded on SG based techniques such as point process, boolean model, percolation and connectivity. Insights were given into the history of SG, interference characterization and applications such as routing, secrecy, information propagation as well as point processes with fading.

In 2010, Andrews *et al.* [15] presented an entry-level tutorial illustrating the use of spatial models and relevant analytical techniques for wireless networks design. They derived metrics such as coverage and connectivity, throughput and end-to-end rate in wireless networks. The role of SINR and its constituent parameters and 'building blocks' were discussed. Furthermore, applications of spatial models to adhoc networks, femtocells and cognitive radio were also examined.

By 2013, Elsawy *et al.* [16] comprehensively surveyed and classified SG models in literature for single, multi-tier and cognitive cellular networks. The authors presented a novel taxonomy of the techniques used by researchers in SG to analyze the network performance with examples and references. Furthermore, baseline SG models and the use of SG for modelling technologies such as MIMO were also opened up. No discussion on the modelling of D2D communication using SG appeared in the paper.

In 2016, Andrews *et al.* [17] presented a primer on modelling and analyzing cellular networks using SG. They introduced point processes and tools for calculating the coverage probability metric showing their applications in both downlink (single/multi-tier) and uplink scenarios. Later in the year, Elsawy *et al.* [18] presented a tutorial on this subject including an exact baseband interference characterization and analysis of error rate in cellular networks. A unified approach for analyzing several pertinent metrics such as outage probability, error probability, and the ergodic rate was given. The paper described the significance of SG to D2D research briefly.

From the aforementioned, we observe a clear gap in the existing literature on the detailed exposition on SG models, methods and metrics for relay-assisted D2D communication studied in the last few years. A comparison of these previous surveys in Table 2 shows that a survey discussing SG-based analysis for D2D is absent in the literature, let alone relay-assisted D2D communication which is the focus of this paper.

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[1] Network designers can perform interference characterization using such models and provide insights into the network performance in different physical conditions based on diverse metrics.

TABLE 2. Related surveys on SG and their focus.

	Aspects	References				
		Haenggi *et al.* [14]	Andrews *et al.* [15]	Elsawy *et al.* [16]	Andrews *et al.* [17]	Elsawy *et al.* [18]
Analysis	Background on PPP	✓	✓		✓	✓
	Interference characterization/Outage		✓		✓	
	Techniques for Analysis			✓		
	Downlink Analysis				✓	
	Uplink Analysis				✓	
	Scaling laws	✓				
Performance Metrics	Connectivity					
	Coverage		✓		✓	
	Capacity	✓				
	Outage probability	✓			✓	✓
	Transmission Capacity	✓	✓			
	Ergodic capacity					✓
	Connectivity	✓				
	Percolation	✓				
	Symbol error probability					✓
	Pairwise error probability					✓
	Throughput		✓			
Applications	Single cell networks			✓	✓	✓
	Heterogeneous Networks			✓	✓	✓
	Cognitive Networks			✓	✓	
	MIMO			✓	✓	✓
	mmWave				✓	
	General	✓				
Modeling aspects	Biasing and load balancing			✓	✓	✓
	Spectrum Allocation			✓		
	Frequency-reuse			✓		✓
	PPP approximation					✓
	Error Analysis					✓
	Ergodic rate analysis					✓
	Gaussian Signalling Approx.					✓

C. MOTIVATION

Within the last decade, the stringent QoS requirements posed by future generation networks coupled with the data-hungry applications continue to push experts towards developing innovative technologies to accommodate 5G network requirements. Paradigms such as heterogeneous networks, ultra-dense networks, cloud radio access networks (C-RANs) and edge computing have emerged. Amongst such paradigms is D2D which facilitates the communication of devices without traversing the cellular BS. This differentiates it from traditional cellular communication. Not only has much been envisioned concerning technologies, but modelling techniques have also received a share of researchers ingenuity and novelty. New techniques in optimization, game theory and particularly SG arrive prestigious publication venues time after time.

Looking from the perspectives of technologies and techniques described above, we realize that relay-assisted D2D has positioned itself as a potential approach to tackle some of the traditional challenges of D2D communication such as coverage. Also, efforts have been made to model and unveil its performance in diverse application use cases and physical layer configurations using mathematical tools such as SG. However, as much as spectrum sharing systems have been researched using SG, there is no survey on relay-assisted D2D communication till now (see Table 2 and Fig. 2). In this regard, we study the models and assumptions on this subject and derive research-based lessons from this area. We thought this is not sufficient since much is yet to be tapped from the research of other spectrum sharing systems. So we critically derive lessons from other wireless systems in terms of models and techniques.

Furthermore, we tried to answer new questions that arise as the standardization of this (relay-assisted D2D) technology might be very close. For example, what are the common techniques and approaches currently used? What are the recent trends that would likely receive a large share of researchers time in years to come? Besides, we look into some of the integrand technologies which D2D could also ‘sail over’ to ‘give birth’ to the future 5G network where user demands are tactfully satisfied using the best of technologies now available and envisioned. In this respect, we explore several new SG-based domains and aspects relating to relay-assisted D2D communication. This paper also reveals some of the current models, findings, and future directions in this regard.

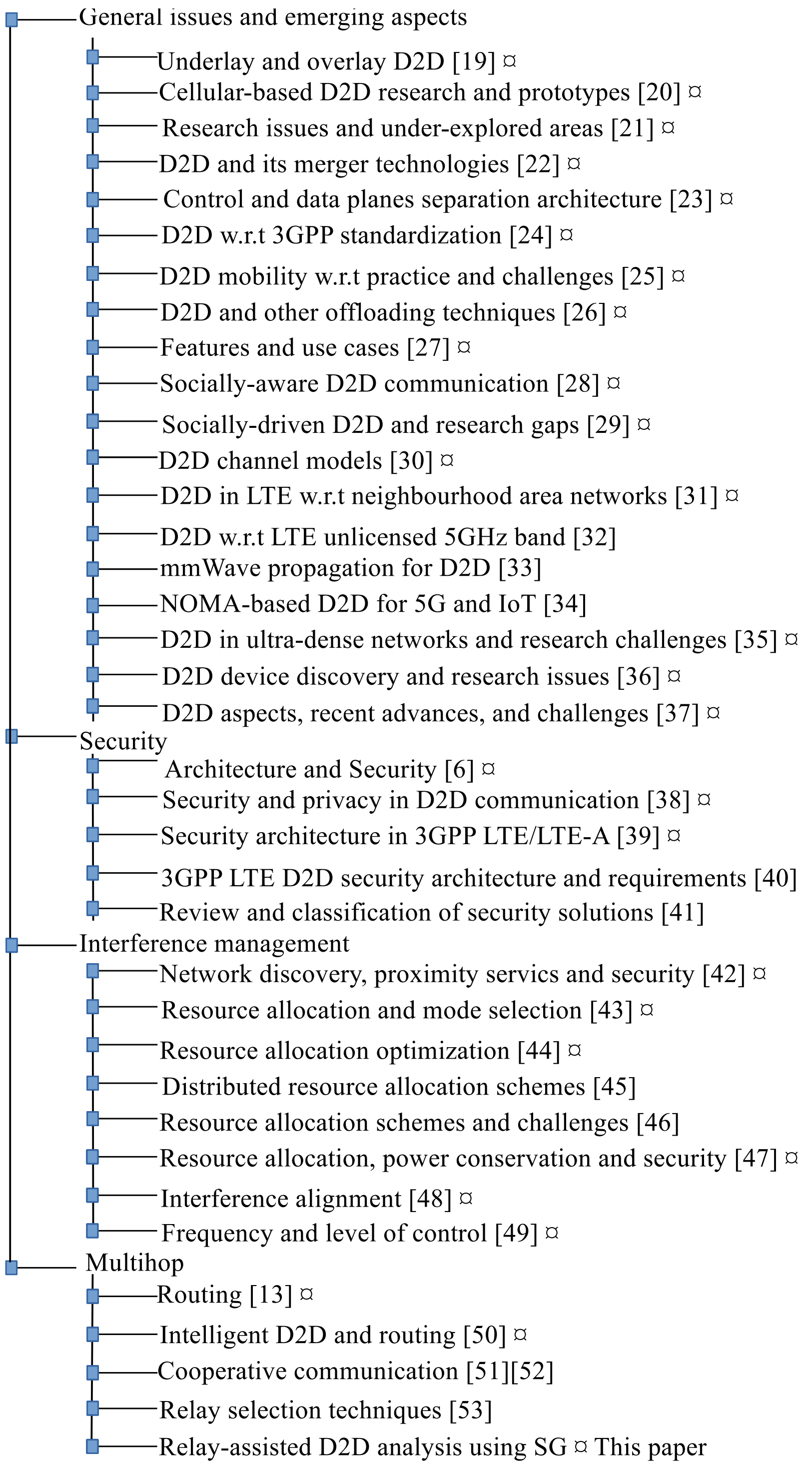

FIGURE 2. Taxonomy of D2D surveys. ⋄ indicates journal publication.

D. CONTRIBUTIONS

In this paper, we present the following contributions:

- Classification and discussion of existing literature on relay-assisted D2D communication network performance using SG in the context of metrics such as transmission capacity (TC) and SE.
- Derivation of lessons from reviewed literature and other spectrum sharing systems to guide readers to potential areas for future considerations.
- Exposition on open areas through the recent breakthrough in SG research as well as developments in D2D, relay-assisted D2D, and wireless communications

in general. Emerging research areas like SIR meta-distribution, where SG is highly propitious are identified.

The rest of this paper is organized as follows: Section II introduces D2D communication modes and spectrum sharing for relay-assisted D2D networks. It also explains some relevant performance metrics used in SG-based analysis of relay-assisted D2D networks. One of the most commonly studied metric, transmission capacity, is further discussed in Section III. Section IV reviews other performance metrics in SG-based analyses of relay-assisted D2D such as spectral efficiency, transmission rate, and service probability. Section V presents the potential areas for future work and further directions on relay-assisted D2D communication. Section VI concludes this paper. Table 1 provides the meanings of abbreviations used in this paper.

II. RELAY-ASSISTED D2D SPECTRUM SHARING MODELS AND RELEVANT PERFORMANCE METRICS

This section first introduces the D2D communication modes. Afterward, spectrum sharing models in relay-assisted D2D networks and some performance metrics studied in the network analysis are discussed.

A. D2D COMMUNICATION MODES

Considering how user devices can access the licensed or unlicensed spectrum, D2D communication can be classified into in-band (licensed) and out-band (unlicensed).[2] The in-band D2D can be further categorized into underlay and overlay modes (see Fig. 3). In the underlay mode, devices use the same spectrum for cellular and D2D communication i.e., they share the same radio resources. One motivation for the consideration of inband D2D communication is that the licensed spectrum has a considerable level of control compared with the unlicensed band [6]. Asides this, [6], [19], [55] highlighted a number of benefits which include improved spectral efficiency due to the exploitation of spatial diversity. Also, cellular devices can support inband D2D since the cellular frequency will be utilized. Furthermore, resource allocation techniques can be easily deployed to manage the network's QoS.

Despite these benefits, inband D2D communication has its own drawbacks [43], [55]. A typical challenge in underlay D2D is interference which could be addressed when proper power control and interference management techniques are considered. However, these may require very complex resource allocation techniques [19]. In the overlay mode, D2D uses a dedicated spectrum orthogonal to that of cellular communication. However, the cellular resources could be underutilized as a typical user cannot perform simultaneous cellular and D2D transmission. The use of the overlay mode may poorly affect the QoS due to a high level of unmanaged interference resulting from other wireless technologies sharing the same spectrum [1], [55]. This interference cannot be controlled by the BS. Thus the underlay D2D is more popular [19] and as such, it is the focus of this paper.

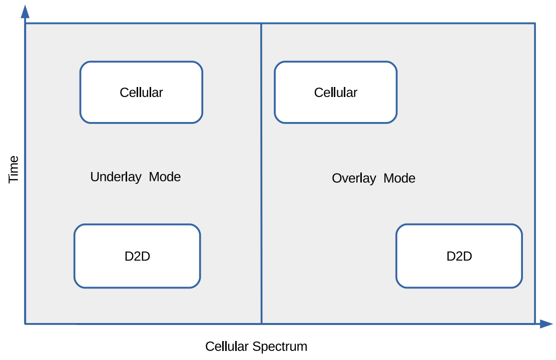

FIGURE 3. **In-band D2D spectrum sharing modes.**

Considering relay-assisted D2D communication, user devices can function in one of three modes: a cellular mode where they function as traditional CUEs, D2D mode where they communicate in a D2D fashion, and relay mode where they relay data for other devices.

B. SPECTRUM SHARING IN RELAY-ASSISTED D2D NETWORKS

In the quest for effective utilization of the scarce cellular network resources, it is imperative that the wireless channel is shared efficiently [56]. Spectrum sharing occurs when users/radio communication systems use the same spectrum resource. Sharing could occur in frequency, time and place (space) [57]. A fundamental component which affects spectrum sharing systems is the device density. In a dense relay-assisted D2D communication network, the chance of a more efficient spatial re-use is higher since the spectrum will be 'heavily' used by these systems across the entire network. Note that for effective network performance, the QoS requirements of participating systems have to be met [58]. In this regard, the level of reliability in terms of success probability for specific data rates has to be given proper consideration.

On the other hand, the demand for spectral resources in dense relay-assisted D2D networks becomes higher. Also, such scenarios experience more interference which significantly affects network performance. The level of interference dictates what type of resource allocation mechanisms, mode control, and power control is required to guarantee the target SINR thresholds for different systems within the network. Thus, a deeper understanding of the effect of device density, as well as other design parameters on the network, is crucial.

There are several models for spectrum sharing in relay-assisted D2D networks consisting of cellular devices, D2D devices, and relay nodes. A pictorial view of a typical network model where idle D2D devices can function as relay nodes is shown in Fig. 4. The next subsection describes key performance metrics used in this context.

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[2] In out-band D2D communication, the interference from D2D to eNodeB-UE is absent [54] as the frequency spectrum used by D2D does not overlap with the cellular spectrum [19].

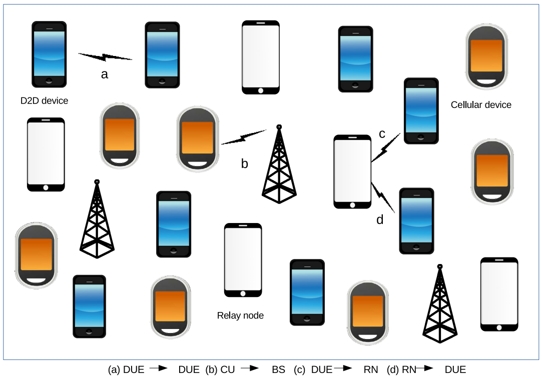

FIGURE 4. A pictorial view of a typical network model involving cellular, D2D, and relay nodes.

TABLE 3. Notations and meanings.

Notation	Meaning
λ_c	Density of CUEs
λ_d	Density of DUEs
λ_u	Density of UEs
λ_r	Density of RNs
λ_{BS}	Density of BSs
Φ_c	Homogeneous PPP of CUEs
Φ_d	Homogeneous PPP of DUEs
Φ_u	Homogeneous PPP of UEs
Φ_r	Homogeneous PPP of RNs
P_c	Cellular transmit power
P_d	DUE transmit power
P_r	RN transmit power
P_{re}	RN existence probability
T_c	CUE SIR threshold
T_d	DUE SIR threshold
T_r	RN SIR threshold
α	Path loss coefficient
R	D2D Link distance
d_{n0}	Expectation of D2D Link distance
ρ	Power allocation coefficient

C. PERFORMANCE METRICS

Some performance metrics used in the literature to evaluate relay-assisted D2D networks are described below. For simplicity, we have excluded mathematical definitions for these metrics. Interested readers could refer to the references cited for these definitions. The notations used in this paper are defined in Table 3.

1) TRANSMISSION CAPACITY

This refers to the number of successful transmissions which take place per unit area in a network, given a constraint in the outage probability [59]. TC measures the intensity of transmissions in space. It is motivated by fixing the outage probability to achieve a proper characterization of network performance. TC metric was initially developed for the analysis of spread spectrum in adhoc networks. It has found a lot of applications in wireless networks (specifically in decentralized networks which are difficult to characterize) since then. TC has been studied with respect to systems such as interference cancellation (IC) [60]–[62]; scheduling and power control [63], [64]; cognitive radio network (CRN) [65]–[67]; frequency spread spectrum [68]–[70]; as well as multiple antennas [59], [71]–[73]. Section III reviews literature on TC analysis of D2D and relay-assisted D2D communication using SG.

2) SPECTRUM-SHARING TRANSMISSION CAPACITY

As compared with TC which is an indication of the maximum number of successful transmissions [62], [68], spectrum-sharing TC applies to several systems with an arbitrary spatial density set within a range, where all outage probability constraints are to be satisfied. In this case, it refers to the number of successful transmissions [62].

3) ACHIEVABLE TRANSMISSION CAPACITY

For spectrum sharing systems, the achievable TC can be used to verify the impact of the secondary systems spatial density on the network capacity. Contrary to the TC, the achievable TC should satisfy the outage probabilities of all systems.[3] It thus includes the power ratio of coexisting systems as well as their multiple outage probability constraints [74]. Moreover, this is considered with respect to Shannon's formula. In other words, the spectrum sharing transmission capacity is multiplied by $\log(1+T_n)$ where T_n is the target SINR threshold of system n (see [10] for example).

4) AREA SPECTRAL EFFICIENCY

Area spectral efficiency quantifies the SE of cellular systems having a variable rate transmission. It can be referred to as the summation of the highest average data rates for a unit bandwidth, in a unit area supported by a cell's BS [75]. This definition encapsulates the trade-off between the SE for the cellular system, user link, and the quality of the communication link provided to users. Subsection IV-A discusses some of the works that studied SE in relay-assisted D2D communication using SG.

Next, we examine relevant literature considering SG-based analysis for evaluating relay-assisted D2D underlay cellular system performance. We present a classification of the reviewed literature based on their performance metric and assumptions as shown in Fig. 5.

III. TRANSMISSION CAPACITY ANALYSIS

As stated in the previous section, transmission capacity is a fundamental performance metric that has frequently appeared in SG-based D2D communication research. In this section, we review relevant works that used SG for TC analysis of D2D communication with and without relays. Lessons learned from the review are discussed and some open issues are highlighted.

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[3] In other words, primary and secondary systems in the context of CRNs.

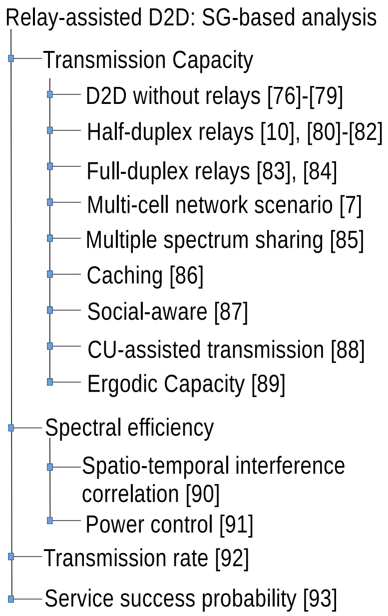

FIGURE 5. Taxonomy of reviewed literature on relay-assisted D2D underlay cellular networks based on performance metrics (layer 1), assumptions and models (layer 2) used.

A. TC ANALYSIS OF D2D COMMUNICATION WITHOUT RELAYS

D2D communication can provide higher capacity in terms of sum rate and increased throughput when compared with the traditional cellular communication [95], [96]. In this subsection, we briefly discuss methods and findings of relevant SG research that have studied TC metric of D2D communication without relays. Table 4 highlights some of their key aspects.

A premier investigation on the extent to which capacity improvement can be achieved in cellular systems when D2D modes are used is presented in [94]. The authors determined how device user density impacts the network's capacity. In this regard, the optimal density of D2D users that maximize the capacity of D2D-enhanced networks was derived. To provide insights necessary for adequate resource allocation and QoS enhancement in D2D networks, Kachouh *et al.* [76] investigated different aspects of LTE-based D2D communication using a convex-concave computational optimization technique to derive optimal ratio of transmit power. They recorded that an optimal power allocation solution exists for D2D which maximizes the global capacity of the Long-term evolution (LTE) network.

Lin *et al.* [79] studied how a typical device should choose its communication with a co-device or BS. They proposed a hybrid and tractable network model where mobile nodes were modelled using the Poisson point process (PPP) and the base stations were placed based on a hexagonal grid model. They assumed channel inversion power control where the transmit power of a cellular or D2D user, $P_i = L_i^{\alpha}$. L_i denotes the length of radio links. They also assumed that the average received power is 1 due to channel inversion. This implies that a proportionality coefficient ϕ (where $\phi \ll 1$) exists which maps the transmit power of user equipments, P_i to an actual transmit power $\widetilde{P}_i$. Their findings show that a trade-off exists between the spectrum access factor and D2D mode selection threshold for choosing either direct link communication or traditional cellular communication.

TABLE 4. Key aspects of the reviewed literature on capacity analysis of D2D communication without relays.

	Aspects	References				
		[76]	[94]	[77]	[78]	[79]
Optimization	Transmit power ratio	✓				
	Power allocation ratio				✓	
	Capacity optimization	✓	✓	✓		
	Transmission density			✓	✓	
	D2D mode			✓	✓	
	D2D density					✓
Modelling	OP threshold			✓	✓	✓
	ST Probability		✓	✓	✓	
	Poisson Point Process		✓	✓	✓	
	Channel Inversion					✓
	Spectrum access factor					✓
	Single-cell scenario	✓	✓			
	Multi-cell scenario		✓			

B. TC ANALYSIS OF RELAY-ASSISTED D2D COMMUNICATION

In this subsection, we review relevant works that used SG for TC analysis of D2D communication with a focus on relay-assisted D2D underlay cellular network. We describe a typical spectrum sharing model for the reviewed articles and highlight their key aspects in Table 5.

C. REFERENCE MODEL

This model (see Fig. 6) uses the generalized successful transmission probability (STP) for all links within the network and assumes that devices have the same transmission power for equal transmit distances. Also, D2D users are distributed based on PPP. The representation of devices is similar to that in Fig. 4. The generalized form of this model was presented by Lee *et al.* [58] as an extension to the TC metric proposed by Weber *et al.* [59] for spectrum sharing systems. It has been widely used in research such as [10], [80]–[82], [88], [97]. For 'n' spectrum sharing systems, the SIR at a typical receiver in system n is given as

$$\mathrm{SIR}_n = \frac{P_n \delta_{n0} d_{n0}^{-\eta}}{\sum_{\forall j \in \{n\}} I_j}, \tag{1}$$

where $I_j = (\frac{P_j}{P_n}) \sum_{k \in \Psi_j} \delta_{jk} |X_{jk}|^{-\eta}$.

δ_{jk} and X_{jk} refer to the Rayleigh fading coefficient and the distance to interfering node from the origin k, ($k \in \Psi_j$) in S_j, $j \in \{c, d, r\}$, respectively.[4] Similarly, δ_{n0} and d_{n0} are the Rayleigh fading coefficient of the reference transmitter to the typical receiver and their mutual distance, respectively. In other to have reliable data transmission, the systems SIR must satisfy the minimum SIR requirement i.e., $\mathrm{SIR}_n \geq \theta_n$, where θ_n is the SIR threshold of system S_n.

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[4] c, d, r denote cellular, D2D, and relay user equipment, respectively.

TABLE 5. Key aspects of the reviewed literature on capacity analysis of relay-assisted D2D communication.

	Aspects	References									
		[80]	[81]	[10]	[82]	[88]	[83]	[87]	[85]	[84]	[86]
Optimization	Optimal relay users distribution			✓							
	D2D system optimization				✓						
	Optimal capacity								✓	✓	
	Optimal transmit power				✓						
	Optimal relay selection strategy								✓		
	Optimal transmit power ratio			✓	✓						
Assumptions	Poisson point process	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Random relay Selection	✓	✓			✓					
	Nearest relay Selection										✓
	Random relay distribution			✓	✓						
	Full duplex relays						✓			✓	
	Rayleigh fading	✓	✓	✓	✓						✓
	Nakagami-m fading							✓			
	Direct link communication option	✓	✓	✓	✓						✓
	Constant data rate assumption			✓							
Unique Aspect	Distance expectation	✓	✓								
	Achievable TC			✓	✓						
	Two relay hops	✓									✓
	Single-cell scenario								✓		
	Multiple relay hops			✓	✓						
	Caching strategy										✓
	Social-aware							✓			
	Spectrum Management				✓						
	Successful transmission probabilities	✓	✓	✓							✓
	Closed form expression	✓	✓	✓	✓						

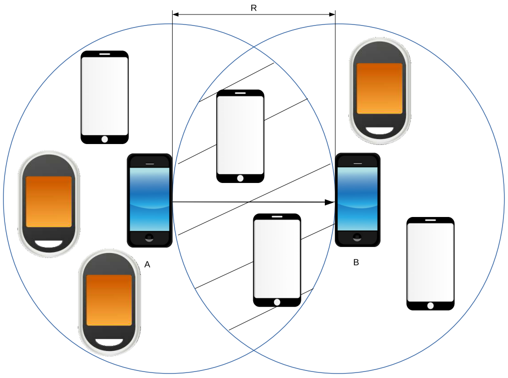

FIGURE 6. A reference model that shows relay nodes in the intersection region between two D2D users.

The STP used in this model is given in Lemma 1 in the appendix where it is narrowed down to three ($n = 3$) systems (i.e., cellular devices, D2D devices and relays) suitable for the relay-assisted D2D framework as deployed in [80], [81], [83].

D. RELATED LITERATURE

1) HALF-DUPLEX RELAYS

Using the above model, [80] studied the TC of relay-assisted D2D communication in underlay mode with respect to transmission link distance. This was extended in [81] to both underlay and overlay modes. The authors used two relaying approaches (i.e., relay only, and either relay or direct link) to enhance the performance of D2D communication. They presented closed-form expressions for the TC of D2D communication, derived capacity gains, and also considered variable D2D link distance (which is more practical) based on these modes. Wen *et al.* [82] studied a multihop D2D network by analyzing the achievable TC over Rayleigh fading channel. The probability density function (PDF) of SINR in the spectrum sharing network was formulated. An important assumption made is that the distance traversed by relay transmissions decreases with the increase in the number of hops. Their study reveals that the power ratio of the cellular and D2D system can influence the interference level and system capacity.

Lin *et al.* [10] investigate relay-assisted D2D communication to solve the problem of an increase in outage probability which occurs when D2D pairs are far apart. In the model, an idle UE is used to establish a link for communication between the source UE and destination UE as shown in Fig. 7 where $\frac{R^2}{2} + 2r_h^2 = r_1^2 + r_2^2$. With an assumption of decode and forward relay protocol, the outage probability is given as

$$P_r^o = 1 - P\{\gamma_1 > \gamma_d\}P\{\gamma_2 > \gamma_d\}, \tag{2}$$

where P_r^o is the D2D outage probability, γ_1 is the target SINR of the first hop and γ_2 is the target SINR of the second hop. Similarly, γ_d is the target D2D SINR. Having assumed a

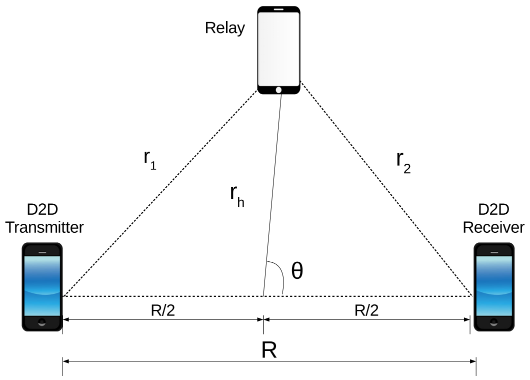

FIGURE 7. **The topology of relay-assisted D2D communication.**

random distribution of RNs, the authors analyze the optimal relay users distribution, PDF of the optimal relay users' position and optimal ratio of transmit power in terms of cellular and D2D users' densities. These results were used to present a theoretical analysis of the achievable TC of the network. They conclude that when the "wireless environment" is poor (particularly when users are densely distributed and the mutual distances between devices in D2D pairs extend), the achievable TC of D2D network can be enhanced by relay-assisted transmission.

2) FULL-DUPLEX RELAYS

Although half-duplex relaying is considered a very practical system [98], it is inefficient with regards to resource utilization since relays cannot transmit and receive on the same channel [99]. The authors in [83] considered full duplex amplify and forward (FDAF) relay nodes to assist cellular and D2D communication. These relays can transmit and retransmit signals thereby improving the network coverage and SE, amplifying the signal power, and achieving lower delay within the system. Devices can either communicate directly or through the FDAF relays. CUE, DUE and RNs were modelled as a PPP and D2D users share the uplink with cellular users. The paper analyzed the coverage probability and TC for both cellular and D2D links in this context. The results indicate that both coverage and capacity of cellular and D2D links are affected by parameters such as the RN density, mutual distance of D2D pair and D2D density. Although the introduction of FDAF within this framework is quite unique, the scenario can be adapted to social-aware relaying where devices require incentives that motivate them to relay. Furthermore, the use of full duplex relays can be studied under generalized fading channels since Rayleigh fading was assumed in the paper.

Delgado and Labeau [84] investigated the issues of fairness and network capacity in mobile relay-enhanced cellular networks. Under the presumption that the channel capacity at the center is usually greater than that of the cell edge, they studied the use of full duplex relays by investigating how fairness and overall network capacity can be maximized. A greedy algorithm selects the RNs which increases the channel capacity at the cell edge and reduces the transmission power consumption by 80%. The algorithm also improves the Jain fairness and average network capacity by 8% and 20%, respectively. However, the investigation in this paper is restricted to a single cell scenario.

3) MULTI-CELL NETWORK SCENARIO

Feng *et al.* [7] consider a tractable model for heterogeneous multi-cell network where idle UEs can function as RNs with interference and spatial distribution taken into account. To achieve this, they derive a closed-form expression for the coverage probability using three different location-aware relay selection schemes: all relay selection, where all the idle UEs can function as potential relays; sectorized relay selection, where the selected relay-to-destination distance is shorter than the source-to-destination distance; and distance-based relay selection, where the source can obtain its distance to relay nodes using GPS or the Received Signal Strength Indication. Therefore, only idle nodes within a specified radius can be selected. Results show that relay-assisted transmission can improve D2D network performance in terms of both TC and coverage probability. Also, distance-based relay selection provides the highest D2D TC and maintains the coverage probability compared to the all relay selection mechanism. Thus, it was concluded that the distance-based scheme was the best for cooperative D2D communication which underlays cellular networks.

4) MULTIPLE SPECTRUM SHARING

Lin *et al.* [85] investigated the achievable TC for D2D communication in both underlay and overlay direct and relay-assisted D2D modes. They analyzed an optimal selection approach between single and multiple sharing methods. Using the constraint of minimum energy consumption, the optimal relay selection strategy in terms of relay-assisted D2D communication was obtained. Results showed that the proposed optimal relay selection strategy lowers the energy consumption of relay-assisted D2D communication in underlay mode.

5) CACHING

The aim of caching popular files in a D2D group is to reduce the burden of the BS. This is achievable since the files requested can be catered for by the D2D links. Although the BS burden is relieved, it has to cache all the files as the D2D caching group refreshes at intervals of time. As such D2D communication would also share channel resources with cellular links and the interference that results from several D2D links would impact the quality of cellular links. To address this, Fan *et al.* [86] fix a threshold SINR at the BS so that the quality of cellular links can be guaranteed. They provide a mathematical model for the network capacity of cellular, D2D and relay links, and propose a distributed caching strategy where the most popular files within a D2D group are cached to improve the performance of the network in terms of capacity. This is based on the rationale that the popularity

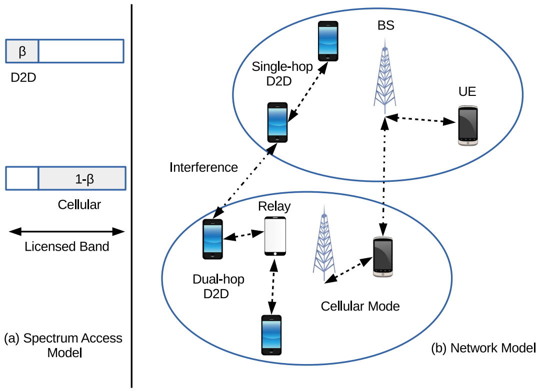

FIGURE 8. The system model and spectrum access scheme for [87].

of a file indicates its level of demand by mobile devices. The popularity of given k files is expressed as

$$q_i = \frac{\frac{1}{i^\gamma}}{\sum_{j=1}^{k} \frac{1}{j^\gamma}} \tag{3}$$

where q_i is the probability that the ith file is requested by a typical user. $1 \le \text{i} \le k$ and $1 \le \text{j} \le \text{k}$, $q_1 \le q_2 \le \cdots \le q_k$. It is assumed that a relay link is used when the distance between the requesting user and the BS is greater than a distance threshold. Numerical simulations were used to show that the proposed architecture significantly improves the network capacity.

6) SOCIAL-AWARE

Establishing relay links can be very challenging as RNs may not be willing to relay data for other users due to their selfish nature [87]. A typical relay user might wonder: "what benefit does one get by relaying data for an unknown user?" This is an aspect with little attention in SG-literature. Considering the above, Chun *et al.* [87] incorporated this social aspect of D2D nodes into the relay-assisted D2D framework and modelled the decision on being a relay node using the 'social comparison' presented in [100]. They allocated a specific portion β of the spectrum to D2D communication, while the complementary portion $1 - \beta$ is allocated to the cellular spectrum (where $0 \le \beta \le 1$ as shown in Fig. 8). Specifically, the authors formulated and characterized a donation game with the likeliness that devices would cooperate within an evolutionary framework. They studied a practical case where the cooperation probability is less than 100% cooperation (i.e the ideal case) and observed a lower TC and higher outage probability in the non-ideal case. Although after an adequate number of evolutionary generations, the cooperation probability evolved and the transmission performance approaches that of the full cooperation. This reveals that scenarios exist where device cooperation can evolve with time without any central enforcement.

7) CU-ASSISTED TRANSMISSION

In [88], the authors analyzed D2D TC when the cellular users allocate a certain portion of their power to assist in mutual D2D communication while keeping the quality of their own cellular transmissions intact. Under this assumption, if a number of available cellular users exist within the communication range of D2D devices, a cellular device is selected randomly in every time slot to assist the D2D transmission using time division duplex (TDD). The transmission power of the assisting cellular user is modelled as ρP_c, where P_c is the transmit power of the cellular user and $0 \le \rho \le 1$. Also, the expectation of the distance between the cellular user and D2D receiver (see Fig. 9) is given as $\frac{2}{3}R$, where R is the maximum communication range of D2D link. The average number of D2D users requiring the assistance of one cellular user is $\lambda_1 \pi R^2$, where λ_1 is the density of D2D users. Thus, the assisting cellular user uses $(1 - \lambda_1 \pi R^2 \tau) P_c$ to 'keep' its cellular transmission.

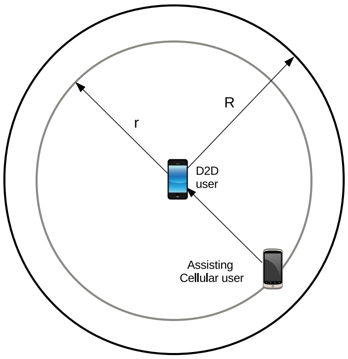

FIGURE 9. Model of D2D communication assisted by cellular users [88] © IEEE.

8) ERGODIC CAPACITY

In D2D underlay networks, [89] studied the trade-offs between ergodic capacity and power consumption to discover whether the merits of D2D underlay surpass its demerits when integral system aspects are considered under Rician fading assumption. These aspects include cellular BS density, DUE transmit power and device density. With the assumption that the D2D pairs are randomly distributed, the authors derived the ergodic capacity of the device and cellular users in closed form and further investigated the device density and transmit power required to achieve minimal energy consumption. The ergodic capacity was maximized using a two-stage scheme. This led to the presentation of a D2D framework for demonstrating the expedient system parameters to obtain the highest capacity gains. An interesting aspect of this work is that the ergodic capacity was evaluated considering the D2D distance as a random quantity i.e., not fixed, which is more practical. Note that, when the location of D2D transmit users were assumed to be dynamic, such users were deemed to move with the same velocity.

E. LESSONS LEARNED

Here, we derive lessons from the literature examined in this section. Insights are also drawn from some other networks, such as CRN which is an emerging merger technology with D2D communication.

From the literature, it was learned that both SG and optimization tools can be combined to effectively model, analyze and derive optimal values for relevant parameters and metrics in a relay-assisted D2D network. For instance, parameters such as global capacity, selection constraint for D2D pairs and spectrum sharing mechanisms can all be optimized. We note that the proposed optimization should depend on the nature and number of parameters to be optimized within the network. The assumption of a random selection of relays to forward data between D2D pairs in [80], [81] may not capture the variety of use-cases of D2D communication which might require different packet forwarding schemes (e.g., mission-critical applications). Hence, other relay node distribution should be considered with application target in mind. Similar to point processes having varying suitability based on medium access protocol or target application, appropriate and optimal relay selection strategies are also required.

The PPP is a common assumption which has been widely used in the study of D2D systems. It is important to cite that other point processes are more practical in scenarios where devices are not randomly scattered within the studied regions. Examples of such are: the Poisson Cluster Process (PCP) [101], [102], combination of PCP and Poisson Hole Process [103], binomial point process [104] and the Thomas cluster process [105] (which is useful for modelling content placement) [106].

Caching is a typical practical use-case of relay-assisted D2D communication which has the potential of improving the network performance. More research findings would be required to reveal the impact of different realistic assumptions for channel fading and constraints since caching is one of the potential applications of D2D communication.

The amalgamation of cognitive radio with D2D communication has a number of prospects. For instance, the use of cognitive D2D reduces the challenge of allocating frequencies by the operator. Furthermore, proper interference management and resource utilization can be achieved [22]. Looking into existing work on the TC of cognitive radio systems, we can take a few lessons such as the inclusion of parameters like medium access probability as used in [107]. For instance, the achievable TC can be studied under diverse medium access schemes as presented in [108], while taking the outage constraints of both cellular and D2D systems into consideration. Another lesson is the investigation of TC considering other forms of fading such as block fading channels.[5] The TC can be maximized with constraints in parameters such as transmit power and density.

With regards to TC in other spectrum sharing systems using SG, (1) the trade-offs between the TC of cellular and D2D systems with different transmission range and power can be investigated for energy harvesting relay-assisted D2D (see [110] for an example in overlaid wireless adhoc networks). Recently, more literature have appeared for realistic non-linear energy harvesting models deployable in this context. (2) The impact of parameters such as mutual distance between transmitters and receivers, BS density and successive interference cancellation can be investigated (see [67] for the case of cellular and mobile adhoc networks) in the context of relay-assisted D2D communication. (3) For cellular networks having guard zones to protect their QoS (e.g., [111]), relays could be used outside these zones to facilitate D2D communication. It is also possible to consider cellular users at the edge of these zones to relay data for other D2D devices. Secrecy performance in mmWave-based relay-assisted D2D networks with blockages is another future direction.

Note that a very common assumption in SG literature is the consideration of specific physical layer configurations such as a particular path-loss condition (e.g., $\alpha = 4$) and assumption of fixed distances between the transmit-receive pairs. In reality, such assumptions are restrictive [112] and do not provide comprehensive analytical insights into the performance of diverse real-world scenarios. Asides the random relay selection which is quite common in literature, other applicable relay forwarding schemes could be motivated. Recently, the mean distance between the nearest and farthest RNs to the source was derived in the context of cognitive wireless sensor networks (see the Appendix of [113]).

IV. SPECTRAL EFFICIENCY ANALYSIS AND OTHER METRICS

Stochastic geometry analyses have proven successful in giving analytically tractable expressions and the relationship between parameters which affect the cellular network performance. Asides the capacity analysis discussed in the previous section, other SG-based performance analyses such as SE, average transmission rate and power control for relay-assisted D2D communication are discussed in this section. The lessons learned and issues relating to energy-efficiency are also discussed. A highlight of some key aspects of the reviewed articles is presented in Table 6.

A. SPECTRAL EFFICIENCY ANALYSIS OF RELAY-ASSISTED D2D COMMUNICATION

In this subsection, we discuss some of the works that studied SE in the context of relay-assisted D2D communication using SG and describe a typical spectrum sharing model for the articles reviewed.

B. REFERENCE MODEL

In this model, the BS is modelled as a PPP with intensity λ_{BS}. D2D users are modelled as a PPP (Φ_d) thinned from the universal set (Φ_u with intensity λ_u) which includes cellular and D2D users. The UEs could either be active (belonging to Φ_u with intensity λ_u) or inactive (belonging to $\widetilde{\Phi}_u$ with

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[5] In cognitive radio systems, [109] studied the outage capacity and ergodic capacity of secondary users in a block fading channel environment.

TABLE 6. Key aspects of the reviewed literature on other performance analyses of relay-assisted D2D communication.

	Aspects	References						
		[97]	[89]	[4]	[91]	[90]	[92]	[93]
Optimization	Derivative-based algorithm	✓						
	Ergodic capacity power-aware optimization		✓					
	Power control optimization				✓			
	Energy efficiency maximization	✓		✓	✓			
Assumptions	Closest RN to transmitter selection					✓	✓	
	Relaying through idle-users						✓	
	Partial decode-and-forward						✓	
	Power control			✓	✓			
	Out-of-cell interference consideration						✓	
	Frequency Division Duplexing							✓
Objectives	Coverage extension							✓
	Spectral-efficiency analysis					✓		
	Energy-efficiency analysis	✓		✓				
	Protect cellular transmission					✓		
	Evaluation of Average transmission rate						✓	
Modeling	Evaluation using 3GPP parameters							✓
	Interference modelling using Gamma distribution						✓	
	Mission-critical application							✓
	Poisson point process	✓	✓	✓	✓	✓	✓	✓
Unique Aspects	Rician fading		✓					
	Layer 3 relays				✓			
	Spatially correlated interference					✓		
	Monte-Carlo simulation			✓	✓			
	Interference suppression	✓			✓			
	Spectrum partition factor					✓		
	Closed-form expressions		✓	✓				
	Energy savings via Relays			✓				
	Ergodic capacity vs. power trade-off		✓					

intensity $\widetilde{\lambda}_u$). For simplicity of representation, assume that a tagged BS covers an area approximated by a circular disk with radius $A(k, R_{BS})$ which is based on the approximation on a disk of radius R_{BS} centered at the typical BS k. The Bernoulli random variable model is shown in Eq. (4) below.

$$\Pr\left(\sim \mathrm{a}\right) = \frac{\widetilde{\lambda}_u}{\lambda_u + \widetilde{\lambda}_u}. \tag{4}$$

Note that the intensity of relay users is $\lambda_R = \widetilde{\lambda}_u$ and it is implicitly assumed that inactive users can function as relay nodes for D2D communication. The topology in Fig. 10 is assumed to be semi-static i.e., remains the same for a long period of time. Given that the set of D2D devices is obtained from thinning PPP for the total number of users, the intensity of D2D users is thus $\lambda_d = q\lambda_u$, where $q = \Pr\left(N_r = 0\right)\Pr\left(\mathrm{SINR}_{t,d} \geq \theta_D\right) + \Pr\left(N_r \geq 1\right)\Pr\left(\mathrm{SINR}_{t,r} \geq \theta_D, \mathrm{SINR}_{r,t} \geq \theta_D\right)$. $\mathrm{SINR}_{t,d}$, $\mathrm{SINR}_{t,r}$ and $\mathrm{SINR}_{r,d}$ represent the SINR threshold between the transmitting node and destination node, source node and RN, and RN and destination node, respectively [90]. All devices can be assumed to have a constant transmit power or channel inversion power control could be used. This model has been used in [90] and a similar model was used in [114].

C. RELATED LITERATURE

1) SPATIO-TEMPORAL INTERFERENCE CORRELATION

Temporal and spatial correlations occur in a wireless system where the transmitting set changes at every time slot (due to the medium access scheme/scheduler). The transmitting nodes at different time slots are usually chosen from a set having the same source of randomness [115]. The phenomenon where interference is correlated may make the performance of wireless communication systems degrade significantly in a spatial and temporal manner [116]. Interference correlation is either studied on the basis of static network or networks with finite mobility. Specifically, as the level of mobility tends to infinity, the interference is decorrelated across space and time [117]. Thus in real-world settings where topology changes occur less frequently as compared to packet retransmission and fading fluctuations, spatio-temporal correlation comes into the picture as the performance of active links are location dependent. As a result, the SIR seen by close receivers leads to spatially correlated SIRs [118].

In this respect, Atat *et al.* [90] study the spatial-temporal correlation between interference at the RN and destination device in relay-assisted D2D networks using the reference model in Fig. 10. Considering the correlation of aggregate interference at RNs (see Fig. 11), they investigated the SE

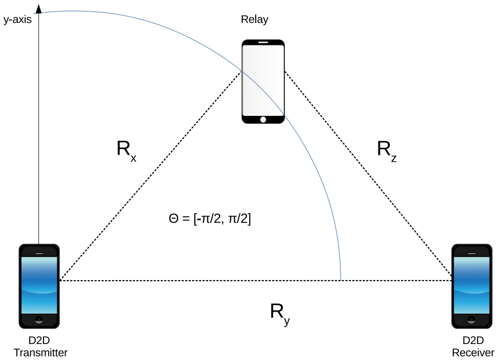

FIGURE 10. A reference model with relay nodes distributed within angle $\Theta = \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ [90] © IEEE.

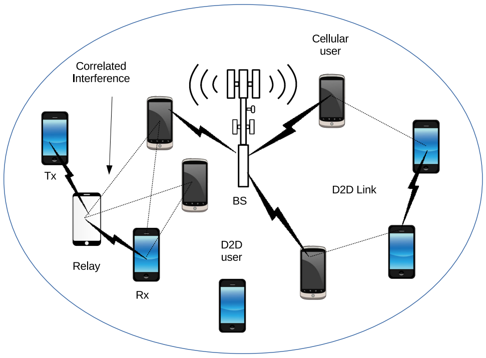

FIGURE 11. Network model showing spatio-temporal correlation of interference between communication links in a relay-assisted D2D network [90] © IEEE.

of relay-assisted D2D communication. A tractable analytical framework was presented to statistically analyze the performance of relay-assisted D2D networks. This accounts for the SE characterization of both cellular and D2D links. The framework gives insights into the achievable spectral efficiency gains when relays are deployed.

2) POWER CONTROL

This is crucial for the efficient use of energy and coordinating interference in wireless network [3]. It is essential for attaining the target SINR of the receiver. Also, the transmit range of devices depends on the transmission power which impacts the network throughput and connectivity. When transmit power of devices are reduced, the interference experienced by other 'ongoing' transmissions can be reduced. Therefore, this promotes more concurrent transmissions within the network [119]. Power control is a well-studied approach for managing the interference when D2D devices coexist with cellular devices. This helps to ensure that they do not interfere with traditional cellular communication [82].

On this subject, [91] proposed a power control scheme aimed at mitigating and suppressing interference between D2D and cellular communication to improve the SE and throughput performance. For simplicity, they considered a single-cell scenario having three layer-3 RNs with fixed locations as shown in Fig. 12. In this model, one cellular user and D2D transmitters simultaneously share the resources in the uplink. The RNs transmitting to D2D receivers utilize the same uplink resources. Using the relay assistance, the authors showed an improvement in the coverage probability of the cellular link when devices are far apart. The research examines cellular users that are uniformly located within the coverage region of the BS. Future work can study the use of such fixed layer-3 relaying scheme in a multi-cell environment which takes interference of other cells into account. However, this has to be motivated by applicable real-world scenarios since specifying a fixed number of relays appears restrictive and may need to be generalized. Furthermore, the spatio-temporal correlation of interference can be considered at the relays and receiving devices.

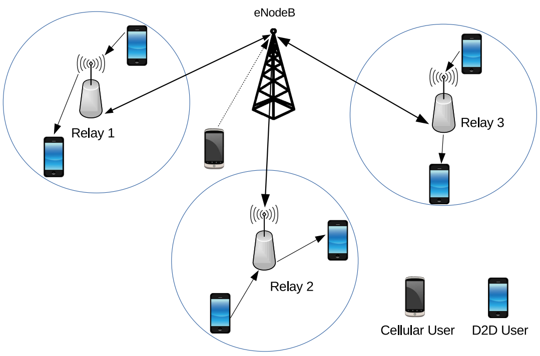

FIGURE 12. Network model showing fixed layer 3 relays [91] © IEEE.

D. TRANSMISSION RATE AND SERVICE SUCCESS PROBABILITY

This subsection reviews SG research on metrics such as coverage, throughput and transmission rate, in the context of relay-assisted D2D communication. We note that some of the articles reviewed here also studied other metrics.

1) TRANSMISSION RATE

A pioneering effort that analyzed user-assisted relaying in network-wide context is [92]. The authors studied partial decode and forward user-assisted relaying in the cellular uplink. In the scenario investigated, an active user relays data through the nearest idle user whenever D2D communication is enabled between two UEs in proximity. The proposed cooperation policies cater for fast, slow and hybrid fading channels. Analytical results were compared with the ideal situation when nodes have perfect information about the channel state. Their findings indicate that per-user transmission rate can be improved significantly using user-assisted relaying regardless of the out-of-cell interference. Transmission rate gain was also shown to increase with higher idle UE density and more preponderant in the case when active users are closer to the cell edge.

2) SERVICE SUCCESS PROBABILITY

The authors in [93] quantify the cellular network performance in terms of service success probability during network infrastructure breakdown such as when a natural disaster occurs. They modelled the link-level cellular service probability considering both successful uplink and downlink performances as $P_c = P_{UL}P_{DL}$, where P_{UL} and P_{DL} are the uplink and downlink success probabilities, respectively. The network level-performance of a single-hop relay network was derived as $\varrho_1 = \varrho_o + Q_1 - \varrho_o Q_1$, where Q_1 is the performance of the one-hop relay link (without the direct link) and ϱ_o is the average link-level success probability for the cellular link. For an nth relaying chain, the network-level performance ϱ_n is related to the the $(n-1)$th relaying chain network-level performance ϱ_{n-1} and the 'chained D2D chain performance' Q_n is as shown in Eq. (5).

$$\begin{aligned} \varrho_n &= \varrho_{n-1} + Q_n - \varrho_{n-1}Q_n \\ &= \varrho_{n-1} + \varrho_o Q_o^n - \varrho_{n-1}\varrho_o Q_o^n. \end{aligned} \tag{5}$$

After disaster occurrence, the BS was modelled with a thinning factor having a new resulting density $(1-\eta)\lambda_{BS}$, where $\eta \in [0, 1]$ is a proposed damage ratio which indicates the percentage of 'phased out BS' with respect to the total number of BS. Analytically, the authors evaluated the effect of D2D relaying to alleviate damages in such scenarios as $\varrho_n - \varrho_0$. Attempts were made to answer the following questions.

- How much alleviation can be achieved when D2D technology is introduced to the disaster scenarios?
- How can the network-level service success probability be described when chain relaying is used to extend cellular coverage?
- What insights can be deduced when disaster propagation scenarios are considered?

Results show that a buffer of 50-70% can be attained when a single hop relay is deployed for D2D communication.

E. LESSONS LEARNED

Spatial and temporal correlation of interference is a fundamental aspect of wireless communication scenarios with static, quasi-static or finite mobility. However, the performance analysis of relay-assisted D2D which considers spatio-temporal interference correlation is quite recent. This can be included in the fine-grained SG-based analysis of network models incorporating D2D communication in future works. From this review, we observed that analytical methods are mainly used within this domain to study network performance. Monte-Carlo simulations are also used (in some cases) to verify the correctness of the analytical results.

One of the key peculiarities of D2D communication is its applicability in critical scenarios where traditional cellular communication may not be effective, such as the event of natural disasters. SG can be deployed to provide insights into the network performance and relay link gains for such a scenario. It is worth noting that UAVs can also facilitate communication among devices during disasters. In addition to the aforementioned, power control is essential to meet the QoS requirement of the cellular network. In this respect, SG models have appeared in D2D and relay-assisted D2D literature to study this phenomenon in a tractable manner.

Similar to some works on TC discussed in Section III, optimization can be used with SG to evaluate the energy-efficiency of D2D communication. This tool has been used to study energy efficiency in multiple bands and reduce the overall network power consumption (see [97]). From our survey, we note that the Rayleigh assumption is the most common assumption used in SG-based investigations of relay-assisted D2D in the literature. A similar observation was made by Elsawy *et al.* [16]. The authors noted that this is due to the tractability and simplicity associated with the Rayleigh fading assumption.

Looking into the SG-based analysis in other wireless systems, several interference distributions can be analyzed (see [120]) to determine the desirable characteristics of spectrum sharing systems involving cellular, D2D, and relay nodes. Comparisons of the capacity and capacity gain of the relay-assisted D2D network can be made under various fading distributions similar to [121]. Fairness coexistence constraint [58] could be studied in the context of relay-assisted D2D communication considering the optimal transmit power and spatial densities in such scenarios. UAVs can also be incorporated into such models. However, this would require the consideration of a 3D model.

In recent years mobile technology has evolved from the usual call and text messages services to multimedia sharing. To improve the SE of cellular networks and facilitate multimedia sharing, D2D communication has proven to be very useful [122]. The current multimedia content-sharing applications consume battery. Also, the coexistence of D2D devices brings about interference to the cellular system [3], [97]. These indicate the need for energy-efficient D2D communication. The use of RNs to assist D2D communications can improve the energy-efficiency. However, the trade-offs between the transmit powers of D2D and RNs should be investigated in diverse network scenarios and application use-cases.

The consideration of inter-cell interference in relay-assisted D2D-enabled networks is another area for future work. Typical related work in this regard for Frequency division multiple access (FDMA) cellular network assisted by relays is given in [123]. It is important to bear in mind that the study of relay-assisted D2D communication for mmWave networks is still an emerging research direction. Future work could also study the impact of power control on the outage probability of cellular systems in the context of relay-assisted D2D in mmWave bands. Furthermore, the benefit of using relays (mobile and static) especially at the cell edge to improve the quality of cellular communication is worth giving further consideration.

Another aspect that has received much attention in SG-based research for relay-assisted wireless systems is relay selection [124]–[130]. In this regard, several relay selection schemes have been proposed. Also, attention has been given to the use of mobile relays (see [84], [128], [131]) which include both terrestrial and airborne Unmanned Aerial Vehicles (UAVs). Opportunities include proposing architectures for several use cases such as disaster management and crowdsourcing (e.g., how UAV-assisted D2D communication can be used in such scenarios). In a multihop scenario, if a typical receiving device is not within the range of the sending device, a nearby UAV can receive the data and send to the most appropriate device closer to a destination device towards the control center for appropriate actions and rescue operations. These relays could also be equipped with energy harvesting capabilities. Also, optimal relay selection algorithms for these scenarios would be sought after in such research. The impact of various relay positioning should also be investigated.

V. FURTHER DIRECTIONS ON RELAY-ASSISTED D2D COMMUNICATION

Following the review above, we present future directions related to the study of relay-assisted D2D communication using SG tools as shown in Fig. 13. Some of these directions could also be jointly investigated for D2D communications.

A. RELAY-ASSISTED D2D FOR CACHING

One of the key benefits of D2D communication is its potential to offload traffic from the BS. Particularly, this becomes very important when users are demanding for popular files such as multimedia content. In such cases, the traditional BS may not be able to cater for such overwhelming demand. Caching files at a nearer device is one of the key solutions to this problem. Devices could easily retrieve cached files from another device via D2D links. Besides alleviating the traffic load at the backhaul, this has the potential to reduce the delay in the delivery of such files and facilitate quick access to multimedia content [132]–[134].

An interesting pattern in our age is the rate at which popular content gets viewed, disseminated and downloaded. In YouTube, for example, a published video can have one million views and thousands of downloads within a short period of time. Imagine the amount of traffic that would be directed at such content. To handle such traffic bursts, a bright idea is to cache those files within the reach of users so that they can have it downloaded or viewed without placing any burden on the backhaul. However, D2D devices also have their constraint in terms of memory and the distance at which they can be effectively functional. This brings in the use of relays [132], to retrieve cached files from nearby users. Note that several objectives of interest in cache-enabled D2D communication relate to optimizing content placement [135]. In this context, relays can be deployed to manage this problem by facilitating communication between the requester of content and the devices in which they are cached.

Using network coding-based caching policies improves cellular network performance when compared with traditional caching techniques. This is because a linear combination of file chunks can be stored in the cache of the BS which yields a more effective performance [136]. It is also imperative to mention that cellular and D2D connections can cooperatively be used to retrieve missing content as a result of packet loss using network coding [137]. Moreover, energy harvesting relays can be used to achieve cooperative communication in a two-way network-coded network as studied in [138]. The approach was not considered for content caching, therefore, it opens opportunities for network coding-based relay-assisted cache-enabled D2D communication. Network coding can also be used to guarantee successful delivery probability using broadcast [139] that is useful in the context of sharing cached files requested by a group of users. Note that the above works ([136]–[139]) are typical examples of the deployment of SG tools to study the network coding phenomenon in diverse scenarios (among which is caching).

The use of SG tools to study relay-assisted caching and content placement is an emerging area with few published findings. It brings many forms of point processes into consideration since caching architecture depends on the node distributions within the application area. Furthermore, selecting the appropriate RN to achieve reduced delay and better performance can be fused into proposed frameworks in this domain. Proper mode selection for DUEs and CUEs should also be considered to satisfy the requests of devices requiring cached files. Summarily, SG can provide analytical tools robust to give insights into several questions related to D2D and relay-assisted D2D caching in 5G wireless networks.

B. TWO-WAY RELAYING

Two-way relaying is another promising direction which has been hardly explored in the context of D2D communication using SG. In two-way relay channels, nodes can exchange data concurrently using one or more relays [140]. The benefit of this is that it can achieve two-fold SE [141] and the communication is bidirectional i.e., as the source device sends data to the destination device, the destination device has data to send to the source device [140], [141]. This assumption is practical since it can be found in uplink and downlink cellular communication as well as packet acknowledgment [140]. Thus it is considerable in D2D communication especially when control messages would have to be sent between devices using relays.

The drawback of this approach is managing self-interference, synchronizing source nodes, and channel estimation [141]. Existing research on traditional two-way relaying include [142], [143]. It is important to bear in mind that when the transmitters are PPP distributed, the bidirectional interference becomes correlated and this is quite challenging to compute [144]. In recent times, some analytical efforts such as [90] have been directed towards spatio-temporal interference correlation in D2D networks. Two-way relaying can also be studied in the context of energy harvesting (see [145]–[152]) and wireless power transfer (see [153]–[157]).

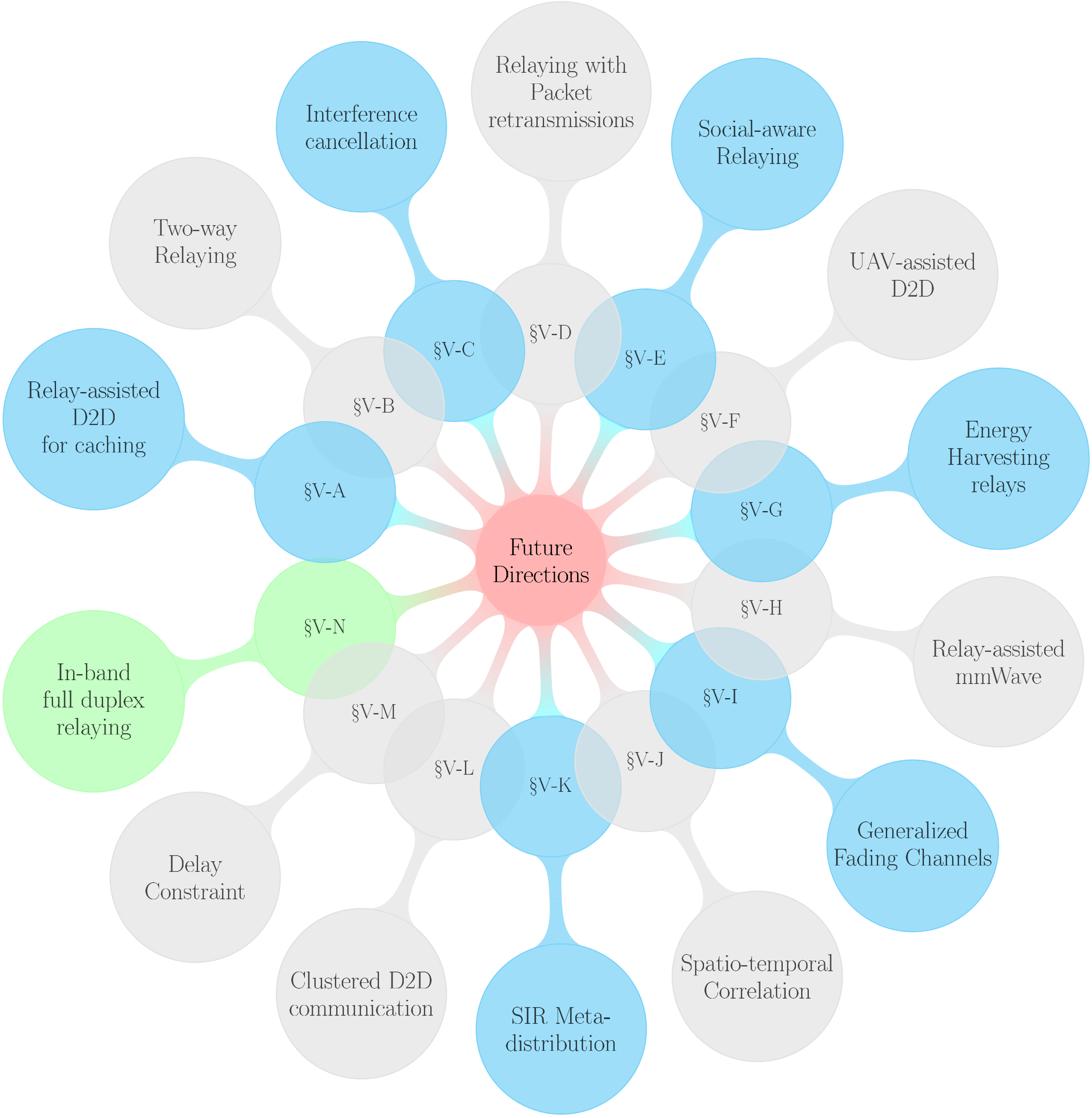

FIGURE 13. Organization of the further directions on relay-assisted D2D communication presented in this paper.

C. INTERFERENCE CANCELLATION

One of the main limitations of the cellular network performance is interference caused by 'human designed' devices [158]. When DUEs and relays share the spectrum with cellular users, this interference further aggravates. Similarly, in a scenario with dense network infrastructure there exist an advantage of improved signal power (and signal strength) which comes at the cost of an almost equal increase in interference, thereby limiting the SE gains. Two major techniques used to tackle interference are interference avoidance/coordination and interference cancellation. The former may not be as competitive as the latter when spectrum utilization is taken to account. This is because interference cancellation facilitates an aggressive spectrum reuse [159]. Thus, IC is a typical approach to mitigating interference in wireless networks where the desired information is demodulated and (or) decoded. The interference from the received signal is then canceled using this information in conjunction with channel estimates. A challenge, however, is providing accurate models to reconstruct the signals as well as model what such signals had 'experienced' when passing through the channel [158].

Parallel and successive IC are the practical techniques of IC [158]. To the best of our knowledge, no research has modelled parallel interference cancellation using SG. Also, IC is yet to be studied for relay-assisted D2D communication using SG, let alone a scenario where some devices can harvest energy and others can cancel interference.[6] SG tools would help present further research insights in this domain since it has reached an appreciable level of maturity in deriving both closed-form expression as well as tight upper and lower bounds on key metrics in the network. IC can also be studied with respect to content caching for diverse caching policies. In such scenarios, interference cancellation coefficients (see [62]) may be infused into the analysis. Additionally, several technologies such as machine-to-machine communications could co-exist with relay-assisted D2D communication. This would require network performance characterization and proper IC measures.

D. RELAYING WITH PACKET RETRANSMISSIONS

The inclusion of packet retransmission into SG-based D2D underlay cellular networks has been considered by Cardieri and Brito [160]. This opens a promising direction since the assumption of packet retransmission can improve the performance of the network.

There is no doubt that when relays are used to transfer data from the source to destination device and packets are retransmitted, more interference exists within the network. Managing such interference while enjoying the benefits of packet retransmission is thus an open issue. A key parameter in this regard is the packet arrival probability as deployed in [160]. The TC expression in such scenarios could also be determined. Such models can be studied in the context of energy-harvesting relays.

E. SOCIALLY-AWARE RELAYING

From our survey, we discovered that only [161] studied socially-aware relay-assisted D2D communication using SG. A recent research in M2M communication ([162]) analyzed the kth community. This paradigm (i.e., socially aware D2D) brings the realistic involvement of people and mobile devices into picture [163] and thus could depict a more practical scenario of D2D communication which involves human-held devices. Furthermore, socially aware-D2D communication can be used to achieve improved system performance [164].

From a social perspective, not all devices would be willing to function as relays. For instance, a D2D user may decide not to relay data for another user when they are strangers to each other. Although the use of incentives has been studied recently, it is more natural that users are willing to relay data for other users when they both exist in the same physical and social domain (e.g., students' acquaintances in a classroom). Amongst others, social attributes include users mutual interest and background [165]. In this respect, social ties can be used to improve the performance of cooperative D2D communication [166]. These should be considered in the investigation of relay-assisted D2D communication.

Asides the aforementioned, the consideration of trust which has recently attracted researchers interest [167] is a potential direction in socially-aware relay-assisted D2D communication. Trusts could be assigned values [168] where the willingness to cooperate is modelled as a value between 0 and 1. In this case, a trust level of 0 implies distrust and reluctance to cooperate while 1 is an indication of a high level of trust and willingness to cooperate. Another recently studied direction with regards to trust-aware relay selection is the consideration of a buffer-aided scheme [167], where relays can store data in buffers. Transmission of the stored data can be deferred to the time when the links are significantly strong. The consideration of buffers is a promising direction in the analysis of SG-based relay-assisted D2D communication because it combines queuing theory and SG which researchers have found very beneficial. However, it is important to note that packet queuing delays should be kept minimal. This requires that buffers should be maintained for a very short time [167]. Interference management within such framework and metrics such as energy-efficiency can be studied in future works.

F. UAV-ASSISTED D2D COMMUNICATION

The deployment of UAVs for information transfer has become one of the most recent research directions in wireless communications. This is because UAVs bring a new dimension to the existing cellular communication framework where flying drones can increase the coverage and capacity of the network. Specifically, the cellular infrastructure benefits from their flexibility, mobility and adaptive altitude. These make this technology highly propitious for public safety and emergency applications, especially when the terrestrial network is not fully operational or experiences a damage [169]. Asides its potential to provide connectivity, this solution could also be cost-effective [170] in critical applications and can also be 'swiftly-deployed' [171]. Besides, flying drones could be used to offload the traffic at the BS [170].

In an emergency response application (where D2D is helpful), UAV-relaying might provide connectivity between users (or groups) distant from each other especially when these users/groups cannot effectively communicate directly [171]. Hotspots, such as a university campus, can benefit improved throughput through UAVs [172]. Very recently, SG-based UAV models have begun to receive research attention [173]–[175]. Specifically for D2D communication, the coexistence of UAVs will bring in many challenges with regards to interference management in various UAV trajectories. Developing optimal UAV trajectories to improve energy efficiency as well as analyzing TC of UAV-assisted D2D communication are areas for future consideration.

Quite possibly, UAVs may deputize a malfunctioning BS or assist a macrocell when the radio access network or core

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[6] Note that in most cases, the energy harvesting efficiency is less than one.

network is congested [176]. The peculiarities of clustered D2D served by UAVs hovering above cluster centers should be taken into account. For example, instead of considering static clusters [177], dynamic clusters having mobility can be studied. Also, for a multiple UAV scenario, UAV height may be assumed to follow a particular distribution as compared to having equal height. UAV-assisted D2D with respect to mmWave and sub-6GHz band are conceivable. In the course of modelling terrestrial communication, a more generalized fading channel may be used as compared to the common Rayleigh fading assumption. Rigorous downlink and uplink analysis can be studied with respect to power control, optimal height and energy harvesting UAV-assisted D2D where DUEs harvest from UAVs. Non-linear energy harvesting models are considerable in such scenarios.

G. ENERGY HARVESTING RELAYS

A promising solution for the future highly dense heterogeneous networks is wireless powered communication. This paradigm has diverse practical applications [178]. Looking into the prospects and expectations of future D2D applications, we can see that D2D devices would consume more energy during their course of operation. Although mobile users currently charge their devices, the increased workload on these devices would require alternative energy sources to complement their batteries. Therefore, it is imperative to ensure that relays are equipped with an alternative energy source. Otherwise, users would feel reluctant to relay data for others (except when there are social ties or strong incentives). One way to achieve energy-efficiency and increased throughput is energy harvesting. The objective is to prolong the battery life of devices while harvesting from sources like solar, thermal, wind, ambient RF signals, etc.

The opportunities in this area using SG include proposing architectures involving any of the socially-aware characteristics, caching files at energy-harvesting relays, UAV-assisted file transmission (such as broadcasting a file among devices with common interest within a geographic region), etc. Furthermore, metrics such as outage probability, SE and TC could all be studied using the framework. As energy harvesting relays can harvest energy from access points (see [179] for example), future work can present SG models studying the scenario where D2D devices harvest from a combination of any of cellular devices, IoT devices and UAVs. This requires the derivation of the associated energy harvesting success probability[7] and appropriate point processes for these devices. Particularly, a 3D point process would be required for flying UAVs. In addition to the trade-offs between energy harvesting and transmission time, the impact of channel inversion power control and spatio-temporal correlation of interference should be given due attention.

Note that many of the works (such as [179]–[181]) that studied relay-assisted communication in heterogeneous networks and cognitive radio using SG have deployed linear energy harvesting model as compared to the model with a 'variable conversion efficiency [182]'. The latter is more realistic and was used by Mekikis *et al.* [112] in the context of wireless sensor networks. Recently, more models have appeared in literature which can be adapted to relay-assisted D2D communication. Specifically, curve fitting could be used for existing measurement results on hardware circuits for energy-harvesting which match the specification of a typical D2D device. This can be adopted to the network analysis in contrast to the linear model.

H. RELAY-ASSISTED MILLIMETER-WAVE

The global shortage of bandwidth for mobile broadband data access makes mmWave communication a promising technology for future generation cellular networks. Millimeter-wave is attractive considering its high bandwidth and reduced antenna size which enable a large number of antennas within a small space. These bring prospects for technologies such as massive MIMO [183]. However, mmWave has poor diffraction potential and is susceptible to blockages due to penetration loss. As a result, mmWave mainly relies on line-of-sight (LOS) transmission which makes high path loss, atmospheric absorption, high noise power and sensitivity typical challenges of mmWave communication. These factors impair its signals and thus lead to inadequate network coverage [183]–[185]. Note that although mmWave helps to 'achieve' a lower interference due to directionality, there would be degradation in the desired signal quality due to blockage [183]. When there is no blockage, transmission can occur directly between source and destination nodes without the help of relays [186].

To reap the benefits of mmWave technology while curtailing its major challenges, the use of relays is highly propitious [184]. Research in this area is quite sparse and only very few investigations have been made using SG. Perhaps, the first systematic performance evaluation on D2D relay-assisted mmWave cellular communication is presented in [184] where the authors study a dual hop D2D relaying scheme and develop a model for the coverage probability in the downlink. In this context, further SG research could account for blockages experienced in diverse scenarios with interfering nodes, beamforming, LOS and non-LOS propagations. The gains in coverage, capacity, and SE can be considered in such cases. Furthermore, studied models could put socially-awareness and ambient RF harvesting into consideration.

Transmit power and distance-based path loss that affect mmWave-based network performance can be studied for relay-assisted mmWave-based D2D communication. mmWave-based cellular networks can further improve the performance of cache-enabled D2D communication due to the high bandwidth availability [187]. This is very promising for sharing very large files since the constraints in bandwidth is less compared to using microwave frequencies. The use of relays would further help to improve coverage in such

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[7] Energy threshold beyond which devices can relay data after harvesting sufficient energy.

scenarios when contents are to be requested from devices which are far away, or when there is a blockage that prevents proper LOS transmission.

The secrecy capacity of social-aware mmWave-based energy harvesting relay-assisted D2D communication is another future direction which can be studied for different spatial node configuration motivated by suitable application scenarios. Existing analysis on secrecy in the context of D2D communication using SG [188]–[190] was not performed in the context of relay-assisted D2D communication let alone with respect to mmWave-based frequency bands and social awareness.

I. GENERALIZED FADING CHANNELS

D2D communication has become a key component of 5G networks by enabling the mutual connection between devices. Similarly, it helps to improve the network throughput, however, this comes at the cost of interference with cellular and other D2D users. This is because the physical channel is affected by factors which impact the communication quality (for instance, the propagation characteristics of the physical channel vary and as such, conventional fading models may not be sufficient for modelling) [191]. The operation of 5G will create various link requirements and the need for wireless devices to function over a wide variety of channels ranging from LOS to non-LOS, indoor to outdoor, homogeneous diffuse scattering to those with clustering of scattered multipath waves. Most works on SG-analysis for wireless networks focused on Rayleigh fading distribution as the typical small-scale fading model due to its simplicity [161]. However, Rayleigh fading distribution is very particular and thus may not capture new real-world fading environments with a wide variety of usage scenarios and link requirements [192].

Several models have been used to study other distributions involving large-scale shadowing effects, random shadowing and general fading distributions.[8] A recent study of D2D communication under generalized fading channels including Rayleigh, Rice, Hoyt, Nakagami-m and one-sided Gaussian models is presented in [191]. However, there is still much to be done with regards to studying relay-assisted D2D communication in terms of TC and other metrics like local delay under generalized fading channels. Similarly, the study of $(\kappa - \mu)$ shadowing is considered an attractive option which captures several real-world applications including D2D communication [161]. For other 'non-Rayleigh' fading distributions, closed-form expressions which do not require a complex numerical evaluation are desired [192].

J. SPATIO-TEMPORAL CORRELATION

A quick occurrence of retransmission after a transmission failure is likely to fail another time if a certain receiver has a temporal interference correlation. In vehicular networks where broadcast communication occurs and interference is highly spatial-temporally correlated, there could be a high correlation of outage within a dense cluster which leads to poor performance in terms of information dissemination [116]. This should be put into consideration when modelling D2D communication for vehicular networks involving such broadcast messages. Note that in the context of retransmissions and packet forwarding/routing, the spatial and temporal correlation of interference also makes the outage spatio-temporally correlated [115]. Traditional SG approaches aimed at presenting a *first-order* analysis confined to a single point of observation and usually a single-time frequency resource 'slice', are not sufficient to characterize the spatio-temporal correlation of the performance of a randomly chosen user. A joint analysis of observations from two spatial positions/locations is required *and/or* different 'time-frequency resource slices' [117].

Spatio-temporal correlation in cellular networks is challenging since the policy for BS association has to be considered. In such cases, interference cannot be modeled as infinite homogeneous PPP like adhoc networks [117]. The relationship between correlation distance and correlation of interference as well as the impact of node mobility on correlated shadowing environment was just recently reported in [116]. It is important to study the connection between correlation distance of shadowing and the temporal correlation of interference. Only a few research considered spatially correlated shadowing although many have studied the impact of correlation of node location/traffic. Slow fading is spatially correlated on a scale of 50-200m due to blockage and reflection in transmission channels [116]. Recently, the spatio-temporal correlation of interference was studied for the internet of things where queuing theory was merged with SG [193]. Also, [194] studied spatio-temporal correlation of interference for cooperative retransmission in massive machine type communication. The energy efficiency and TC of spectrum sharing environments for D2D underlaying cellular networks with spatially correlated interference are open for analysis.

Interference correlation can be studied with respect to the coexistence of D2D and other enabling technologies for 5G communication networks such as non-orthogonal multiple access (NOMA) [195]. NOMA involves the cooperative transmission and as such opens up room for the consideration of the interference correlation among receivers in the network. However, we recall that, spatio-temporal interference correlation is often neglected in classical SG literature [196]. NOMA has been studied using SG in diverse scenarios and network configurations such as Poisson networks [197], [198], UAVs [199], [200], caching [201], cognitive radio networks [202], half/full duplex [203], multi-cell mmwave [204], and for D2D communication using tools from SG [196], [205], [206]. Recently, [207] studied meta-distribution and spatio-temporal correlation in heterogeneous networks. Although meta-distribution (see Sec. V-K) has been studied in NOMA [198], [208], it is yet to be studied for relay assisted D2D communication to the best of our knowledge. Wireless energy transfer may further enhance such models.

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[8] See [161] for critical discussion on their strengths and weaknesses.

K. SIR META DISTRIBUTION

Meta-distribution [209] is a new research area which deploys SG. It is the derivation of conditional SIR distribution when the location of wireless nodes are given. This metric gives in-depth information about how the success probability in each link within the network is distributed [210]. It gives a higher level of significance than the traditional success probability which averages over the meta distribution of the entire network [209]. Thus questions relating to the distributions of the per-link success probability for each network realization and the fraction of users which can achieve the desired link reliability at a given SIR threshold can be answered [211]. Moreover, moments of meta distribution, mean local delay, beta approximation of meta distribution and variance of conditional success probability can be derived [211].

Not long ago, meta distribution has been used to study some of the aspects where traditional SG models have been deployed such as BS cooperation [212], interference cancellation [159], power control [211] and mmWave-based D2D networks [213]. A new notion of capacity i.e., spatial outage capacity [214] has been developed using the meta distribution. In the same vein, this can be investigated along with mean local delay for relay-assisted D2D communication. Furthermore, energy harvesting models could also be added to provide further insights and enrich such models. Meta distribution of SIR considering a social-aware D2D framework and successive interference cancellation can also be studied in future works.

L. CLUSTERED D2D COMMUNICATION

Content sharing is one of the applications of D2D communication where a device can download a file and share with other devices within its proximity. This may not be accurately modeled using the traditional PPP model hence [105] studied the use of PCP for D2D networks. PCP is more realistic when the clustering effect of device location is taken into account [215]. Asides content-centric networks, applications involving clustered networks include C-RANs (where transmitters are connected to the backhaul), mmWave, indoor scenarios and adhoc networks which involves nodes distributed within a finite region. In such scenarios, a device typically has a nearby device to communicate with directly [216].

Further research could investigate PCP-modelled D2D networks for the spectrum sharing TC and EE. Similarly, relays can be deployed within the PCP model where the devices distributing content can use the relays to connect to devices which are farther away within the cluster.[9] Furthermore, to model devices close to each other and depict the spatial separation between D2D and cellular users by using exclusion zones, a hybrid of PCP and Poisson Hole Process (PHP) has been studied in [103]. The energy gains and TC achieved using this model can be further investigated. These models could be studied with power control for D2D communication.

Note that the statistical dissimilarity of finite point process from different locations makes it very challenging to model finite single-cluster networks [216].

M. DELAY CONSTRAINT

Delay is a crucial performance metric in delay-sensitive cellular network applications like multimedia and internet-voice applications [217]. It is a major component of mobile traffic streaming services (voice over internet protocol/video conferencing) and elastic traffic services (such as web browsing and file transfer). The former is delay-sensitive but loss-tolerant while the latter is delay-tolerant but loss-sensitive. The third emerging class has a relaxed delay constraint and flexible traffic volume. This applies in proactive caching systems where content is pushed and cached in closer proximity to the end users. This kind of traffic could be referred to as *ultra-elastic* [218]. Forms of delay in a wireless network include transmission delay (the time spent on successful data transmission) and queuing delay (the waiting time in one or more service queues). A local delay is a form of transmission delay which could give a picture of the lower bound of the overall system delay. When the local delay is infinite, users do not get any useful service [219].

In this direction, [217] recently investigated D2D performance with delay constraint for energy consumption, STP, and TC. Future work could investigate relay-assisted D2D communication with delay constraint. Other point processes such as PCP could also be studied for their delay constraints. Following recent investigations, the interference characterization of D2D transmitters in a clustered framework with delay constraint could be studied [220]. Loss sensitive traffic should be analytically characterized as used in [218]. SG and queuing theory are promising approaches to capture this in a tractable manner [218].

N. IN-BAND FULL DUPLEX RELAYING

In the context of wireless networks, the word ‘duplex’ is meant to imply the ability of two systems to mutually communicate with each other. Duplexing modes are basically half duplex or full duplex. In the former devices cannot transmit and receive simultaneously which makes it easy to implement. It is thus the most commonly used duplexing technique [221]. The latter implies that devices can simultaneously transmit and receive data. This could either be out-band where each mobile/BS transmits and receives data using orthogonal resources or in-band where simultaneous transmission and reception can occur at each wireless terminal over the same frequency band. In theory, in-band full duplex has the potential to double the spectral efficiency of half-duplex. Some other benefits of in-band full duplex are its ability to double the ergodic capacity, reduce feedback and end-to-end delays. However, the challenges it faces include self-interference, imperfect interference cancellation (as self-interference cannot be perfectly canceled), increased inter-user interference, increased consumed power and complexity [222]. Although the existing 4G deploys

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[9] In such cases direct transmission may be feasible, however, relays might provide better performance gains.

half-duplex TDD and frequency division duplexing, a number of authors (e.g., [222], [223]) have emphasized the feasibility of full-duplex communication for 5G wireless systems.

One might wonder – what are the implications of half-duplex and full-duplex relaying? Half duplex implies an inefficient utilization of system resources since an extra dedicated time/frequency slot is required for relaying. This makes full duplex appealing. However, it is essential to design small-sized devices which can operate on full duplex and also ensure efficient channel modelling and estimation, effective cross-layer/joint resource management and proper interference management. The accumulated performance loss is also lower in full duplex D2D [224]. Asides improved spectral efficiency, D2D devices can leverage the short link communication to exploit full duplex communication i.e., with a lower transmit power, it is possible to alleviate self-interference [225].

To manage self-interference in full duplex relays, it is important to have sufficient separation in terms of frequency resources between transmitters, receivers and relays [141]. Reducing co-channel interference while optimizing the system performance can be achieved through power control, link adaptation, beamforming, and scheduling [225]. There is a possibility of an adaptive scheme in the context of D2D [226] and relay-assisted D2D [225]. UEs in the former (D2D without relays) or RNs in the latter (relay-assisted D2D) could choose between full duplex and half duplex modes. However, this requires proper mode selection schemes for devices (or relays) to choose when it is best to function in half or full duplex modes. There is much to be done when stochastic geometry comes into the picture.

Even as researchers like [224], [227], [228] have presented models studying throughput and interference in full-duplex D2D communication, efforts are required to investigate the mode selection using full duplex relays. Further questions in this regard are: when is it most suitable to use full duplex relays? At what distance threshold and transmit power (either fixed or power control) is it most appropriate for half/full duplex devices to deploy full duplex RNs when considering an acceptable level of interference protection for cellular users? From [225] we could further ask: in multi-tier and clustered scenarios, how can the impact of self-interference be reduced? How can we deploy antenna array and beamforming to improve the ability to isolate self-interference for full duplex relays? All these should be researched putting proper self-interference cancellation in mind. We believe from the maturity of current research, the tools of SG can be used to reveal insights into some of these questions.

VI. SUMMARY AND CONCLUSION

This paper identifies some of the key analytical models in relay-assisted D2D communication using tools from SG. Related literature on the transmission capacities of D2D and relay-assisted D2D communication were examined and compared based on their unique features and assumptions. Besides, insights were drawn from transmission capacity analysis of other spectrum sharing networks. Furthermore, the impacts of parameters such as transmit power, device density, and link distances were studied. It was observed that some of the existing works in this area have assumed equal transmit power for transmitting devices and a random relay selection mechanism. This leaves room for more investigations using power control and other relay selection mechanisms. Additionally, energy harvesting can be included in such models to power energy-constrained relay nodes.

After discussing the capacity analysis of D2D and relay-assisted D2D, the paper overviews other performance metrics in the SG-framework with application use cases such as disaster management. It further discusses other areas to be explored such as the study of UAV-assisted D2D communication while deriving lessons from other spectrum sharing networks. These include the consideration of fairness coefficient constraint, inter-cell interference, SINR and SIR characterization for relay-assisted D2D communication. Threshold-based scheduling and power control are other areas where SG is applicable in the analysis of D2D-enabled cellular networks. The impact of fading on the network capacity, tight bounds on the SIR distribution, and outage probability can be derived in such scenarios.

Moreover, other point processes applicable to scenarios which cannot be best described using the popular PPP model can be studied. In this respect, some of the derived expressions for the characterization of such models in other wireless communication literature may be deployed. Be informed that research deploying artificial intelligence to derive new point processes is on-going and would likely receive its share of researchers time in the coming years. Finally, this survey insights future work for relay-assisted D2D communication by identifying unexplored and under-explored areas. Some of the most recent trends in SG research such as spatio-temporal correlation, delay constraint and SIR Meta distributions were also highlighted. Other future areas for consideration include the SINR characterization in cognitive-based D2D communication and the study of interference cancellation in the context of relay-assisted D2D communication. This paper is a comprehensive eye-opener into the subject of relay-assisted D2D communication with exposition into its diverse opportunities based on recent developments in wireless networks, D2D communication, and SG research.

APPENDIX

USEFUL LEMMAS FOR RELAY-ASSISTED D2D ANALYSIS

A. LEMMA 1

For a typical receiver in systems $S_n, n \in \{c, d, r\}$, the general form of the STP should satisfy

$$\Pr\left(\mathrm{SIR}_n \geq \theta_n\right) = e^{-C_\alpha \theta_n^{\frac{2}{\eta}} d_{n0}^2 \sum_{j\in\{c,d,r\}} \lambda_j \left(\frac{P_j}{P_n}\right)^{\frac{2}{\eta}}}, \tag{6}$$

where $C_\alpha = \pi\Gamma(1+\frac{2}{\eta})\Gamma(1-\frac{2}{\eta})$.

The SIR at the receiver is as shown in Eq. (1) where $n \in \{c, d, r\}$. Using the model in Fig. 6, the following

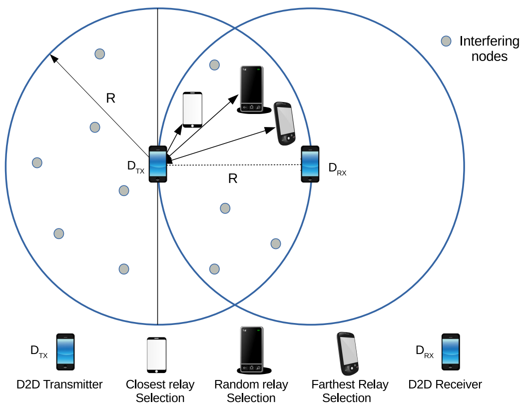

FIGURE 14. **Some typical relay selection scenarios.**

assumptions should be made before giving further detail on d_{n0}.

1) NODE DISTRIBUTION

The relay nodes have to be distributed based on a particular underlaying pattern e.g., uniform, cluster, random, etc. For two dimensional networks, node distribution can be in the form of underlaying point process e.g., PPP, Poisson cluster process, Thomas Cluster Process, Binomial point Process, Matern Cluster Process, etc.

2) RELAY NODE SELECTION

There are many characterized relay selection schemes in the literature (see [56], [229]–[232]). These schemes have their trade-offs in terms of spatial reuse, forward progress, and energy-efficiency. Here, we focus on three main characterized selection schemes: the closest relay to the source, random relay selection and farthest relay towards a destination.

When it is assumed that relays with density λ_r are randomly located within a disk centered at a D2D user having radius R (the maximum distance allowable between a D2D pair in Fig. 10), with an isotropic direction and Rayleigh distributed distance (i.e., placed according to a 2-D Gaussian distribution [79]), the pdf is given as [90]:

$$f_R(r_x) = \frac{2\pi\lambda_r}{1-e^{-\pi\lambda_r R^2}} r_x e^{-\lambda_r \pi r_x^2}, \quad 0 \le r_x \le R. \tag{7}$$

This is based on selecting the closest relay to the transmitter. When a relay is randomly and independently placed around the transmitting device in a isotropic manner using a Rayleigh distributed distance without restrictions on the maximum distance, the pdf is given as [79]:

$$f_R(r_x) = 2\pi\lambda_r R^2 r_x e^{-\lambda_r \pi r_x^2}, \quad r_x \ge 0. \tag{8}$$

Given that $\ominus$ is uniformly distributed between $\left[\frac{-\pi}{2}, \frac{\pi}{2}\right]$, the distribution of R_z in Fig. 10 is given below [90].

$$f_{R_Z}(r_z) = \frac{2r_z}{\pi R^2}, \quad 0 \le r_z \le \sqrt{\pi}R. \tag{9}$$

3) DISTANCE DISTRIBUTION

The distance between transmitter and receiver for each hop in a relay-assisted D2D network highly depends on how the relay device is chosen [233] (See Fig. 14). For the forwarding scheme, where the farthest relay to a destination within a transmission range[10] R is selected, the distance between a transmitter and receiver pair is denoted as r_{FR}. Its distribution is expressed in Eq. (10). Note that this forwarding scheme selects the node which maximizes the progress to the destination device in multihop networks.

$$f_{r_{FR}}(r) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{\lambda r e^{-\lambda R^2\left(cos^{-1}[\frac{r}{R}cos\theta]-\frac{r}{R}cos\theta\sqrt{1-(\frac{r}{R}cos\theta)^2}\right)}}{1-e^{-\lambda\pi R^2/2}} d\theta, \quad 0 \le r \le R. \tag{10}$$

See proof in [231, Appendix A] and background detail in [229, Pg. 40].

As for the nearest relay selection strategy (where the nearest relay in the forward direction is selected to forward data), let the transmit-receive distance be denoted as r_{NR}. The distance distribution is given in Eq. (11).

$$f_{r_{NR}}(r) = \frac{\lambda\pi r e^{-\lambda\pi r^2}}{1-e^{-\lambda\pi R^2/2}}, \quad 0 \le r \le R. \tag{11}$$

For the proof, see [229, Pg. 39] and [231].

For the case when a relay is randomly selected to forward data with the transmit-receive distance r_{RND}, its distribution is given in Eq. (12).

$$f_{r_{RND}}(r) = \frac{2r}{R^2}, \quad 0 \le r \le R. \tag{12}$$

This distribution is the most commonly used in literature.

4) EXPECTED DISTANCE

Thus to define d_n in our considered scenario, we use the expectation of the relay-link distance. For randomly selected RNs distributed based on PPP in the hatched region of Fig. 6, the expectation is given below [81].

$$E(r) = \tau R, \tag{13}$$

where $\tau = (4\pi - 36\sqrt{3} + 64)\Big/(12\pi - 9\sqrt{3})$ and $E(r)$ is the expectation of the relay distance.

As mentioned earlier, this expectation is dependent on the distribution of RNs and relay selection scheme chosen. The last component which would impact on the STP of individual links within the network is the duplexing mode as this affects the density of active devices within the network. For TDD, only half of the devices would be active at each point in time.

From Eq. (6), we can see that the parameter d_{n0} cannot be a fixed value since we are dealing with spatial averages. One way to deal with this is to use the expectation of the distance distribution assumed. This is also associated with the RN selection technique and its distribution function. However,

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[10] or average transmission range in CSMA-based networks. See [231].

this is just an approximation as a spatial distribution of nodes has been assumed using a point process. Furthermore, the use of an expectation captures the notion of a 'snapshot in time' of point processes.

Going back to Eq. (6) with the assumption of a random relay selection, the probability that a relay node would exist within the intersection region in Fig. 6 based on our PPP assumption is given in Lemma 2.

B. LEMMA 2

From Fig. 6, the RN existence probability (Pr_e) is given as

$$P_{re} = 1 - e^{-\lambda_r(\frac{2\pi}{3}-\frac{\sqrt{3}}{2})R^2}, \tag{14}$$

where the area of the hatched intersection region is based on the area of intersection of two equal circles i.e., $\chi = r^2\left(\frac{2\pi}{3}-\frac{\sqrt{3}}{2}\right)$. The proof is given in [80], [81]. In TDD network, the density of active users is given as $\frac{1}{2}\lambda_d P_{re}$ [80], [81]. A more generalized approach to finding the density of active links is given in [230, Equation 12].

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