Paper Discussion:
A Survey on Device-to-Device Communication in Cellular Networks


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Introduction

- Device-to-device (D2D) communications was initially proposed in cellular networks as a new paradigm for enhancing network performance.

- Motivation:
  - The emergence of new applications:
    - Content Distribution
    - Location-aware advertisement

- The initial studies showed:
  - D2D has advantages such as increased spectral efficiency and reduced communication delay.
  - D2D introduces complications in terms of interference control overhead and protocols that are still open research problems.

- The feasibility of D2D communications in Long-Term Evolution Advanced (LTE) is being studied by academia, industry, and standardization bodies.

- In this paper, the authors provide a taxonomy based on the D2D communicating spectrum and review the available literature extensively under the proposed taxonomy.

- The authors also provide new insights about research problems of D2D.
D2D definition

• D2D communication in cellular networks is defined as direct communication between two mobile users without traversing the Base Station (BS) or core network.
  • However, D2D communication is generally non-transparent to the cellular network.

✓ In a traditional cellular network, all communications must go through the BS even if both communicating parties are in range for D2D communication.
D2D Motivation

• New data intensive applications are emerging
  • e.g., proximity-aware services.

• 4G cellular Technologies (e.g., WiMAX and LTE-A) are still lagging behind mobile users’ booming data demand

• Researchers are seeking for new paradigms to revolutionize the traditional communication methods of cellular networks.
  • Device-to-Device (D2D) appears as one of such paradigms
Representative use-cases of D2D communications in cellular networks
In academia, D2D communication was first proposed in [3] to enable multihop relays in cellular networks.

Later the works in [4]–[8] investigated the potential of D2D communications for improving spectral efficiency of cellular networks.


Soon after, other potential D2D use-cases were introduced in the literature such as:

- multicasting [9], [10]
- peer-to-peer communication [11]
- video dissemination [5], [12]–[14],
- machine-to-machine (M2M) communication [15],
- cellular offloading [16]
Industry Initiatives

• The first attempt to implement D2D communication in a cellular network:
  • Qualcomm’s FlashLinQ [17]
  • PHY/MAC network architecture for D2D communications underlaying cellular networks.
  • FlashLinQ takes advantage of OFDM/OFDMA technologies and distributed scheduling to create an efficient method for timing synchronization, peer discovery, and link management in D2D-enabled cellular networks.

• 3GPP is also investigating D2D communications as **Proximity Services (ProSe)**.
  • The feasibility of ProSe and its use-cases in LTE are studied in [18]
  • The required architectural enhancements to accommodate such use cases are investigated in [19].

• ProSe is supposed to be included in 3GPP Release 12 as a public safety network feature with focus on one to many communications [19]

• A brief overview of standardization activities and the fundamentals of 3GPP ProSe can be found in [20]
D2D Communications: Inband x Outband

D2D communications

Inband D2D
- Underlay
- Overlay

Outband D2D
- Controlled
- Autonomous
D2D Communications: Inband x Outband

- Inband - on the cellular spectrum
  - The interference in the unlicensed is uncontrollable
- Outband - uses unlicensed spectrum
  - The precious cellular spectrum be not affected by D2D communications
D2D Communications: Inband x Outband

- **Inband - on the cellular spectrum**
  - **Underlay** - proposes to use the cellular spectrum for both D2D and cellular communications
    - The majority of the literature on D2D
    - Study the problem of interference mitigation between D2D and cellular communication [8], [21]–[28].
  - **Overlay** - propose to dedicate part of the cellular resources only to D2D communications
    - The precious cellular spectrum be not affected by D2D communications.
    - In order to avoid the aforementioned interference issue
    - Resource allocation gains utmost importance so that dedicated cellular resources be not wasted [29].

- **Outband D2D**
  - Controlled
  - Autonomous
D2D Communications: Inband x Outband

- Outband - unlicensed spectrum
  - **Controlled** - Coordination between radio interfaces controlled by the BS
  - **Autonomous** - Coordination between radio interfaces controlled by the users themselves

- Challenges in coordinating the communication over two different bands
  - Usually D2D communication happens on a second radio interface
    - e.g., WiFi Direct [30], ZigBee [43] and Bluetooth [31].

- Outband D2D investigate issues such as:
  - Power consumption [32]–[36]
  - Inter-technology architectural design.
D2D Communications: Inband x Outband
Related Topics: D2D versus MANET or CRN

- From an architectural perspective, D2D communications may look similar to Mobile Ad-hoc NETworks (MANET) and Cognitive Radio Networks (CRN).
- The key difference: The involvement of the cellular network in the control plane
- D2D communications in cellular network are expected to be overseen/controlled by a central entity
  - e.g., evolved Node B (eNB) – Base Station (BS).
- D2D users may act autonomously only when the cellular infrastructure is unavailable.
- The availability of a supervising/managing central entity in D2D communications resolves many existing challenges of MANET and CRN such as
  - white space detection
  - collision avoidance
  - synchronization.
- D2D communication is mainly used for single hop communications
  - it does not inherit the multihop routing problem of the MANET.
Related Topics: D2D x M2M

• M2M is the data communication between machines that does not necessarily need human interaction.
  • M2M communication [39]–[41] is another architecture that might benefit from D2D-like schemes.

• M2M focuses on data exchange among (numerous) nodes or between nodes and infrastructure
  • M2M does not have any requirements on the distances between the nodes.

• M2M is application-oriented and technology-independent

• D2D aims at proximity connectivity services and it is technology-dependent.
<table>
<thead>
<tr>
<th>Proposal</th>
<th>Analytical tools</th>
<th>Platform</th>
<th>Direction</th>
<th>Use-case</th>
<th>Evaluation</th>
<th>Achieved performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improving spectrum efficiency [7], [8], [23] [4], [26], [27], [44] [5], [45], [50], [29], [54], [70], [89]</td>
<td>- Chen-Stein method &lt;br&gt;- Zipf distribution &lt;br&gt;- Integer/linear programming &lt;br&gt;- Mixed integer nonlinear programming &lt;br&gt;- Convex optimization &lt;br&gt;- Bipartite Matching &lt;br&gt;- Kuhn-Munkres algorithm &lt;br&gt;- Han-Kobayashi &lt;br&gt;- Newton's method &lt;br&gt;- Lagrangian multipliers &lt;br&gt;- Graph theory &lt;br&gt;- Auction algorithm &lt;br&gt;- Particle swarm optimization</td>
<td>- WiMax &lt;br&gt;- CDMA &lt;br&gt;- LTE &lt;br&gt;- LTE-A</td>
<td>- Uplink &lt;br&gt;- Downlink &lt;br&gt;- Uplink/downlink</td>
<td>- Content distribution &lt;br&gt;- File sharing &lt;br&gt;- Video/file exchange</td>
<td>- Numerical simulation &lt;br&gt;- System-level simulation</td>
<td>- System throughput can be improved from 16% to 374% compared with conventional cellular networks under common scenarios &lt;br&gt;- Throughput can be improved up to 650% when D2D users are far away from the BS &lt;br&gt;- Number of admitted D2D users can be increased up to 30%</td>
</tr>
<tr>
<td>Improving power efficiency [56], [59] [61], [67]</td>
<td>- Heuristic algorithms &lt;br&gt;- Exhaustive search &lt;br&gt;- Linear programming</td>
<td>- LTE &lt;br&gt;- LTE-A &lt;br&gt;- OFDMA</td>
<td>- Uplink &lt;br&gt;- Downlink &lt;br&gt;- Uplink/downlink</td>
<td></td>
<td>- System-level simulation</td>
<td>- Power efficiency can be improved from 20% to 100% compared with conventional cellular networks</td>
</tr>
<tr>
<td>Improving performance with QoS/power constraints [63], [64] [65]–[68]</td>
<td>- Heuristic algorithms &lt;br&gt;- Bipartite Matching &lt;br&gt;- Kuhn-Munkres algorithm</td>
<td>- LTE &lt;br&gt;- LTE-A</td>
<td>- Uplink &lt;br&gt;- Downlink</td>
<td>- VOIP/FTP</td>
<td>- Numerical simulation &lt;br&gt;- System-level simulation</td>
<td>- From 15% to 70% throughput gain with QoS constraint &lt;br&gt;- From 45% to 500% sum-rate gain with QoS/power constraint</td>
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</table>
## Literature Summary: Inband – Underlaying (2/2)

<table>
<thead>
<tr>
<th>Proposal</th>
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<th>Evaluation</th>
<th>Achieved performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improving fairness [22]</td>
<td>Auction algorithm</td>
<td>LTE</td>
<td>Downlink</td>
<td>-System-level simulation</td>
<td>-A fairness index around 0.8</td>
<td>-Throughput of cell edge users can be improved up to 300%</td>
</tr>
<tr>
<td>Improving cellular coverage [75]</td>
<td>-LTE, -LTE-A</td>
<td></td>
<td>Uplink/downlink</td>
<td>-Numerical simulation</td>
<td></td>
<td>-Cell coverage is also enlarged up to 20%</td>
</tr>
<tr>
<td>Supporting setup of D2D [79]</td>
<td>Protocol</td>
<td>LTE-A</td>
<td>Uplink/downlink</td>
<td>-D2D link setup</td>
<td>-Numerical simulation</td>
<td>-Outage probability reduces by 99%</td>
</tr>
<tr>
<td>Increasing the number of concurrent D2D links [82]</td>
<td>Mixed-integer nonlinear programming, Hungarian algorithm, Heuristic algorithm</td>
<td>LTE</td>
<td>Uplink</td>
<td>-System-level simulation</td>
<td></td>
<td>-Number of admitted D2D links is increased up to 10% compared to random D2D link allocation</td>
</tr>
<tr>
<td>Offloading traffic [16]</td>
<td></td>
<td></td>
<td>Offloading traffic</td>
<td>-System-level simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improving performance of multicast [9, 90]</td>
<td>-LTE, -LTE-A</td>
<td></td>
<td>Uplink/downlink</td>
<td>-Numerical simulation</td>
<td></td>
<td>-Frame loss ratio of feedback is reduced by 80%</td>
</tr>
<tr>
<td>Proposal</td>
<td>Analytical tools</td>
<td>Platform</td>
<td>Direction</td>
<td>Use-case</td>
<td>Evaluation</td>
<td>Achieved performance</td>
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<td>--------------------------------------------------------------------------------------</td>
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<tr>
<td>Increasing energy efficiency [92]</td>
<td>-LTE</td>
<td>-Uplink</td>
<td>-</td>
<td>-Numerical</td>
<td>-Energy efficiency can be increased from 0.8 bps/Hz/mW to 20 bps/Hz/mW</td>
<td></td>
</tr>
<tr>
<td>Improving spectrum efficiency [14]</td>
<td>-Convex Optimization</td>
<td>-Uplink</td>
<td>-</td>
<td>-Numerical</td>
<td>-Cell throughput is improved by 40% over underlay mode</td>
<td></td>
</tr>
<tr>
<td>Improving performance of multicast [10]</td>
<td>-Downlink</td>
<td>-Video transmission</td>
<td>-</td>
<td>-Numerical</td>
<td>-90% gain in bandwidth compared to the method using only one retransmitter</td>
<td></td>
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</tbody>
</table>
## Literature Summary: Outband

<table>
<thead>
<tr>
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<th>Direction</th>
<th>Use-case</th>
<th>Evaluation</th>
<th>Achieved performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improving throughput of video distribution</td>
<td>- Game theory - Chen-Stein method</td>
<td>- LTE</td>
<td>- Downlink</td>
<td>- Content distribution</td>
<td>- Numerical simulation</td>
<td>- Video throughput is improved by up to two orders of magnitude</td>
</tr>
<tr>
<td>Reducing channel sensing overhead [95]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Throughput is improved by up to 25%</td>
</tr>
<tr>
<td>Improving throughput, energy efficiency, and</td>
<td>- Game theory - CDMA</td>
<td>- LTE</td>
<td>- Downlink</td>
<td>- Relaying - Video transmission</td>
<td>- Numerical simulation</td>
<td>- Throughput and energy efficiency are improved by 50% and 30% over classical Round Robin scheduler, respectively</td>
</tr>
<tr>
<td>fairness [32], [33], [99]</td>
<td></td>
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<tr>
<td>Designing a protocol for outband D2D</td>
<td>- LTE</td>
<td>- Downlink</td>
<td>- Relaying</td>
<td></td>
<td>- System-level simulation</td>
<td>- 50% delay improvement compared to Round Robin scheduler</td>
</tr>
<tr>
<td>communications [35]</td>
<td></td>
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<tr>
<td>Improving video transmission [96]</td>
<td>- LTE</td>
<td>- Downlink</td>
<td>- Video transmission</td>
<td>- System-level simulation</td>
<td></td>
<td>- Throughput is improved by 10000% and 1000% over conventional and coded broadcasting methods, respectively</td>
</tr>
<tr>
<td>Improving delay sensitive utility [98]</td>
<td>- Lyapunov optimization</td>
<td>- LTE</td>
<td>- Downlink</td>
<td>- Online gaming - Live video</td>
<td>- System-level simulation</td>
<td>- Average packet delay is reduced by up to 70% - Utility can be improved greatly</td>
</tr>
<tr>
<td>Reducing average file transfer delay [36]</td>
<td>- Dynamic programming - Heuristic algorithm - Distributed algorithm - Queueing theory</td>
<td>- LTE</td>
<td>- Downlink</td>
<td>- Web browsing - HTTP live streaming</td>
<td>- System-level simulation</td>
<td>- Average file transfer delay is reduced by up to 50% compared to methods without traffic spreading</td>
</tr>
</tbody>
</table>
Advantages and Disadvantages of Different types of D2D Communications

<table>
<thead>
<tr>
<th></th>
<th>Inband</th>
<th></th>
<th>Outband</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Underlay</td>
<td>Overlay</td>
<td>Controlled</td>
<td>Autonomous</td>
</tr>
<tr>
<td>Interference between D2D and cellular users</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Requires dedicated resources for D2D users</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Controlled interference environment</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Simultaneous D2D and cellular transmission</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Requires inter-platform coordination</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Requires devices with more than one radio interface</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Introduces extra complexity to scheduler</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
</tbody>
</table>
D2D Implementation Challenges in Real World

• *Interference Management*
• Power Allocation
• Resource Allocation
• Modulation Format
• Channel Measurement
• Energy Consumption
• HARQ (Hybrid automatic repeat request - hybrid ARQ or HARQ)
How Far is D2D From a Real World Implementation?

• The D2D communication is not mature yet

• There are various obstacles to implement D2D in cellular networks:
  • Telecom Operators
    • The operators are used to having control of their spectrum and the way it is used.
    • A successful D2D implementation should allow D2D communications in a manner that operators are not stripped off their power to control their network.
  • Technical Challenges
    • There are physical challenges such as suitable modulation format and CSI acquisition which should be addressed efficiently.
How Far is D2D From a Real World Implementation?

• However it is not only a new research topic:
  • 3GPP
    • It is already being studied in the 3GPP standardization body [18], [19].
    • 3GPP recently decided that the focus of D2D in LTE would be on public safety networks [20].
  • Qualcomm
    • Qualcomm has shown interest in this technology
    • They built a prototype for D2D communications in cellular network
    • The prototype can be used in different scenarios such as social networking, content sharing, and so on [111].

• The authors believe that D2D communications will become an essential part of cellular communications in the next few years.
Potential Future Work

• Theoretical Work:
  • The use of mathematical tools and optimization techniques in the state-of-the-art are very limited.
  • The current literature definitely lacks optimal mode selection techniques and interference and power control mechanisms.
  • The queue stability analysis using techniques such as stochastic Lyapunov optimization can be also an interesting issue to tackle.
  • This can be further extended to provide
    • throughput-based utility
    • throughput-power tradeoff
    • delay bounds
    • delay analysis.
Potential Future Work

• Architecture:
  • There is very little work explaining the required architecture in order to support D2D communications in cellular networks [5], [79].
  • It is interesting to further investigate on the capability of the current centralized cellular architecture to handle D2D procedures such as device discovery, D2D connection setup, cellular network registration process, interference control, resource allocation, security, and so on.
  • Software defined networking-oriented architectures soon will have to include D2D in the equation.
  • D2D needs to be studied in the more complex context of HetNets due to growing market interest for availability of multiple radio technologies deployed on mobile devices.
Potential Future Work

• Performance Analysis:
  • The majority of the available literature is based on numerical or home grown simulations.
    • Although these types of evaluation method are suitable for studying the potential gains, they are still far from reality due to simplified assumptions.
  • The authors believe a performance evaluation using the existing network simulators such as NS3 [106], OPNET [107], Omnet++ [108] or an experimental evaluation can help in revealing both real performance and new challenges of D2D communications in cellular networks

<table>
<thead>
<tr>
<th>Evaluation method</th>
<th>Related literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical simulation</td>
<td>[4], [5], [9], [12], [27], [45], [63], [104] [10], [15], [26], [44], [50], [66], [92], [105] [13], [21], [25], [29], [65], [67], [68], [74] [21], [54], [54], [64], [75], [75], [76]</td>
</tr>
<tr>
<td>System-level simulation</td>
<td>[6], [8], [26], [54], [61], [70], [89], [95] [16], [42], [49], [56], [59], [90], [96], [109] [36], [82], [98], [110]</td>
</tr>
<tr>
<td>Experiment</td>
<td>No experimental study</td>
</tr>
</tbody>
</table>
Conclusion

• The paper provides an extensive survey on the available literature on D2D communications in cellular networks.
• The authors categorized the available D2D literature into two major groups: inband and outband.
• The works under inband D2D were further divided into underlay and overlay.
• Outband D2D related literature was also sub-categorized as controlled and autonomous.
• Underlay D2D issues
  • Power control and interference management between D2D and cellular users.
• Overlay D2D
  • Does not have the interference issue because D2D and cellular resources do not overlap.
  • However, this approach allocates dedicated cellular resources to D2D users and has a lower spectral efficiency than underlay.
• Outband D2D
  • There is no interference and power control issue between D2D and cellular users.
  • Nevertheless, the interference level of the unlicensed spectrum is uncontrollable
  • Hence, QoS guaranteeing in highly saturated wireless areas is a challenging task.
• The survey showed that D2D communication in cellular networks is immature and there are still numerous open issues such as interference management, power control, etc.
• The authors also shed light on some possible research directions needed to improve the understanding of D2D potentialities for real world applications.
Obrigado!
Thanks!
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Extra
Outband D2D: Data flow between D2D users and the eNB (i.e., BS).
BS-transparent traffic spreading

(a) No traffic spreading; (b) Traffic spreading from $U_2$ to $U_1$. 
D2D device discovery and connection establishment procedure.
D2D architecture proposed in [101]

- The required architectural and protocol modification in the current cellular standards to adapt inband D2D communication [101].
- Adding a D2D server inside or outside the core network.
  - The main architectural modification
- In case the D2D server is placed outside the core network, it should have interfaces with:
  - Mobility Management Entity (MME)
  - Policy and Charging Rules Function (PCRF)
  - Peer D2D servers
  - Application servers.
- The D2D server is expected to handle functionalities such as:
  - Device identifier allocation
  - Call establishment
  - UE capability tracking
  - Service support
  - Mobility tracking.
- The authors also propose a protocol stack in which D2D pairs have extra:
  - PHY, MAC, Radio Link Control (RLC)
  - Packet Data Convergence Protocol (PDCP) layer for direct communication.
- This means that User Equipment (UE) retain their cellular connectivity while communicating over D2D link.
D2D Implementation Challenges in Real World

• **Interference Management:**
  • Under inband D2D communication, User Equipments (UEs) can reuse uplink/downlink resources in the same cell.
  • It is important to design the D2D mechanism in a manner that D2D users do not disrupt the cellular services.
  • Usually addressed by power and resource allocation schemes, although the characteristics of D2D interference are not well understood yet.

• **Power Allocation:**
  • In inband D2D, the transmission power should be properly regulated so that the D2D transmitter does not interfere with the cellular UE communication while maintaining the minimum SINR requirement of the D2D receiver.
  • In outband D2D, the interference between D2D and cellular user is not of concern.
    • Therefore, power allocation may seem irrelevant in outband D2D.
    • However, with increased occupancy of ISM bands, efficient power allocation becomes crucial for avoiding congestion, collision issues, and inter-system interference.
D2D Implementation Challenges in Real World

• Resource Allocation:
  • This is another important aspect of D2D communication specially for inband D2D.
  • Interference can be efficiently managed if the D2D users communicate over resource blocks that are not used by the nearby interfering cellular UEs.
  • Resource allocation for outband D2D simply consists in avoiding ISM bands which are currently used by other D2D users, WiFi hotspots, etc.

• Modulation Format:
  • This is one of the challenges which is rarely addressed by researchers.
  • The existing LTE UEs use an OFDMA receiver in downlink and a SC-FDMA for uplink transmission.
  • Thus, for using downlink (resp. uplink) resources, the D2D UE should be equipped with OFDMA transmitter (resp. SC-FDMA receiver) [20].
D2D Implementation Challenges in Real World

• Channel Measurement:
  • Accurate channel information is indispensable to perform efficient interference management, power allocation, and resource allocation.
  • Conventional cellular systems only need the downlink channel information from UEs and the uplink channel information is readily computed at the base station.
  • Unfortunately, D2D communication requires information on the channel gain between D2D pairs, the channel gain between D2D transmitter and cellular UE, and the channel gain between cellular transmitter and D2D receiver.
  • The exchange of such extra channel information can become an intolerable overhead to the system if the system needs instantaneous CSI feedback.
  • The trade-off between accuracy of CSI and its resulting overhead is to be further investigated.

• Energy Consumption:
  • D2D communication can potentially improve the energy efficiency of the UE.
    • However, this highly depends on the protocol designed for device discovery and D2D communication.
    • For example, if the protocol forces the UE to wake up very often to listen for pairing requests or to transmit the discovery messages frequently, the battery life of the UE may significantly reduces.
  • The trade-off between UE’s power consumption and discovery speed of the UEs should be better studied.
D2D Implementation Challenges in Real World

• HARQ:
  • Considering the complexity of interference management in D2D communication, HARQ appears to be a viable technique to increase the robustness.
  • HARQ can be sent either directly (i.e., from the D2D receiver to the transmitter) or indirectly (i.e., from the D2D receiver to the eNB, and from the eNB to the D2D transmitter) [20].
  • The direct mode poses less overhead to the eNB in comparison to indirect mode.
  • Moreover, benefits from the ACK/NACK messages arrive to the transmitter with shorter delay.
Analytical Tools used in the D2D Literature

<table>
<thead>
<tr>
<th>Tools</th>
<th>Related literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete Time Markov chain</td>
<td>[42]</td>
</tr>
<tr>
<td>Merge and split algorithm</td>
<td>[42]</td>
</tr>
<tr>
<td>Distributed algorithms</td>
<td>[36], [42], [82]</td>
</tr>
<tr>
<td>Coalitional game theory</td>
<td>[42]</td>
</tr>
<tr>
<td>Poisson point process</td>
<td>[104]</td>
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<tr>
<td>Queueing theory</td>
<td>[36]</td>
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<tr>
<td>Alzer’s inequality</td>
<td>[104]</td>
</tr>
<tr>
<td>Fubini’s theorem</td>
<td>[104]</td>
</tr>
<tr>
<td>Laplace transform</td>
<td>[104], [105]</td>
</tr>
<tr>
<td>Slivnyak’s theorem</td>
<td>[104]</td>
</tr>
<tr>
<td>Heuristic algorithm</td>
<td>[36], [56], [82]</td>
</tr>
<tr>
<td>Convex Optimization</td>
<td>[14], [89]</td>
</tr>
<tr>
<td>Chen-Stein Method</td>
<td>[13]</td>
</tr>
<tr>
<td>Maximum Weight Bipartite Matching</td>
<td>[63]</td>
</tr>
<tr>
<td>Kuhn-Munkres algorithm</td>
<td>[63]</td>
</tr>
<tr>
<td>Han-Kobayashi</td>
<td>[45]</td>
</tr>
<tr>
<td>Jensen’s Inequality</td>
<td>[105]</td>
</tr>
<tr>
<td>Mixed integer nonlinear programming</td>
<td>[70]</td>
</tr>
<tr>
<td>Integer programming</td>
<td>[66]</td>
</tr>
<tr>
<td>Linear programming</td>
<td>[61], [66]</td>
</tr>
<tr>
<td>Nonlinear programming</td>
<td>[82]</td>
</tr>
<tr>
<td>Dynamic programming</td>
<td>[36]</td>
</tr>
<tr>
<td>Newton’s method</td>
<td>[66]</td>
</tr>
<tr>
<td>Lagrangian multipliers</td>
<td>[66]</td>
</tr>
<tr>
<td>Graph theory</td>
<td>[25]</td>
</tr>
<tr>
<td>Auction algorithms</td>
<td>[22], [54]</td>
</tr>
<tr>
<td>Exhaustive search</td>
<td>[59]</td>
</tr>
<tr>
<td>Geometrical probability</td>
<td>[77]</td>
</tr>
<tr>
<td>Evolution theory</td>
<td>[74]</td>
</tr>
<tr>
<td>Particle swarm optimization</td>
<td>[64]</td>
</tr>
<tr>
<td>Sub-gradient algorithm</td>
<td>[65]</td>
</tr>
<tr>
<td>Hungarian algorithm</td>
<td>[82]</td>
</tr>
<tr>
<td>Lyapunov optimization</td>
<td>[98]</td>
</tr>
</tbody>
</table>
### Evaluation Methods in D2D Literature

<table>
<thead>
<tr>
<th>Evaluation method</th>
<th>Related literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical simulation</td>
<td>[4], [5], [9], [12], [27], [45], [63], [104],</td>
</tr>
<tr>
<td></td>
<td>[10], [15], [26], [44], [50], [66], [92], [105],</td>
</tr>
<tr>
<td></td>
<td>[13], [21], [25], [29], [65], [67], [68], [74],</td>
</tr>
<tr>
<td></td>
<td>[21], [54], [54], [64], [64], [75], [75], [76]</td>
</tr>
<tr>
<td>System-level simulation</td>
<td>[6], [8], [26], [54], [61], [70], [89], [95],</td>
</tr>
<tr>
<td></td>
<td>[16], [42], [49], [56], [59], [90], [96], [109]</td>
</tr>
<tr>
<td></td>
<td>[36], [82], [98], [110]</td>
</tr>
<tr>
<td>Experiment</td>
<td>No experimental study</td>
</tr>
</tbody>
</table>