Device to Device Communications Architectures and Cross-Layer Evaluation Frameworks

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Summary

The paper focuses on Device-to-device (D2D) Architectures evaluation frameworks. D2D communication and discovery can improve spectrum usage efficiency and optimize the tradeoffs between throughput and energy consumption. The target operation modes involve both indirect communication between two nodes via a base station or the direct communication among proximal nodes, enabling use cases that can support communications out of cellular coverage, as well as low end-end delay requirements. The paper will present the architectural evolution of D2D networks within 3GPP standardization and will highlight key network functionalities and signaling protocols. It will also identify key analytical and simulation models that can be used to assess the performance and energy efficiency of resource allocation strategies, and it will present a suitable cross-layer integrated framework.
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Key words:
D2D communications, 5G, ProSe , C-V2X, resource scheduling, power control.

1. Introduction

The evolution of mobile communication networks and services demonstrates a dramatic increase in the number of connected people and machines that use the wireless networking opportunities for increasingly sophisticated applications. Extending the use of wireless networks to things and machines leads to scaled up specifications for accommodating massive numbers of devices having a diverse range of functionalities, from sending short packet measurements up to collaborating with other proximal devices for performing complicated computation tasks. The heterogeneous wireless networks that support such complicated populations of nodes and applications will also have to follow a 5G service-oriented architecture consisting of specific software-defined network slices that focus on the requirements of corresponding vertical applications, in order to address the various requirements of the underlying use cases in a modular and scalable way.

Within this 5G architectural framework there is an increased need to revisit the wireless connectivity options that can be used by each network node/device in order to optimize the radio resource usage and to ensure that network capacity as well as service requirements are met. Beyond the traditional star topology connectivity options, consisting of direct links between a base station and the mobile nodes within a cell, the option of having direct connections among proximal nodes can definitely provide benefits in specific cases such as localized group communications, especially in cases where the base station cannot service the mobile nodes (i.e., in cases of network overload, network outages, infrastructure loss etc.). Also, device to device communication may be used for applications requiring distributed-edge networking and computation among groups of neighboring nodes, especially in cases of ultra low delay requirements as is the case for Ultra-Reliable Low-Latency Communication (URLLC) that applies to fast moving vehicles in platoon formations. It is therefore of high interest to explore the increasing capabilities that are provided in establishing device-device links within 5G architectures and to identify key aspects that have to be addressed when designing specific mobile network services.

The paper is structured in the following way: The next section provides a comprehensive coverage of key use cases and also pf the evolving standardization in device-device communications within standardization bodies such as 3GPP. Then, section 3 presents key analytical models for assessing the performance and energy efficiency of D2D resource allocation mechanisms. Section 4 then presents a cross-layer framework considering key analytical and simulation models, and provides supporting assessment performance results, followed by section 5 that shows a

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simulation modeling approach for assessing key metrics related to the signaling exchange among nodes in D2D communications. Finally, section 6 provides the paper conclusions.

2. Key use cases and architectures for LTE and 5G D2D

A. Key Initial Use Cases

Device to Device communications have been of interest to the 3GPP standardization from the onset of Release 12. The basic idea was to enable the communication of two devices within a cell, either directly or indirectly via the serving base station. Proximity-based Services (ProSe) are supported by D2D discovery and D2D communication and are linked to LTE Direct for using licensed spectrum in peer-peer communications, either within or beyond cellular LTE coverage areas [1]. In both cases the control signaling is being performed by the base station, whereas the actual data traffic can be either routed via the base station or can be directly exchanged between the devices via a direct D2D link.

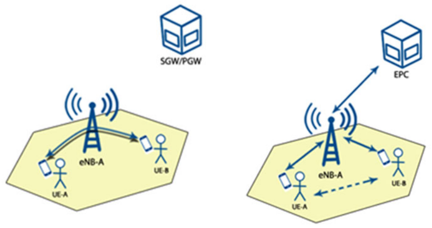

Fig. 1 LTE ProSe services: Network Connectivity among two proximal devices.

When two users (UE-A and UE-B) are in close proximity with each other, they could be able to use direct or local path. One such use case is shown in Figure 2, where the UEs are served by two different eNBs, yet they fulfilled some criteria that enabled them to directly communicate with each other.

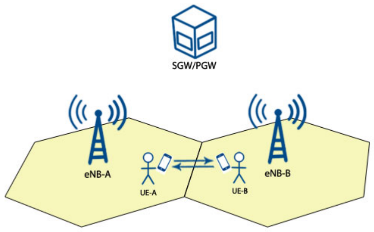

Fig. 2: Direct communication between two UEs

Another case is shown in Figure 3 where UEs are communicating with each other through a local path via eNB without the need for any third party. In this case both UEs have to be served by the same eNB.

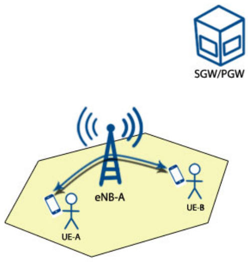

Fig. 3: Local routing communication between UEs served by one eNB

For the aforementioned ProSe communication use cases different control paths may possibly apply. The system should control all the attributes of the communication path such as resource allocation, power control, authorization and security. For the peer-peer direct communication between two UEs served by the same eNB, control information is exchanged between UE, eNB and EPC as shown in Figure 4.

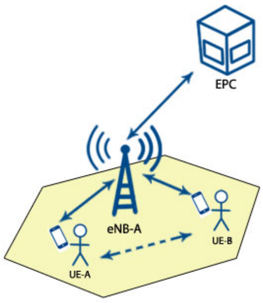

Fig. 4: ProSe controlled path for communication of UEs served by same eNB

When two UEs served by two different adjacent eNBs are involved in ProSe Communication, the control information is exchanged UE, eNB and the EPC as shown in Figure 5.

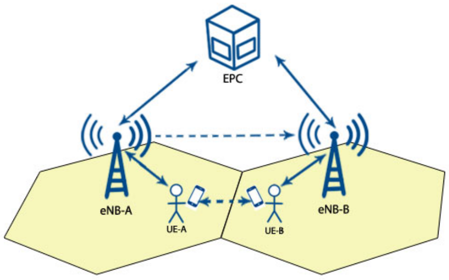

Fig. 5: ProSe controlled path for communication of UEs served by different eNBs

On the other hand, in case there is no network available, such as would be the use of public safety radio for emergency situation where there is no operational wireless network infrastructure, the corresponding resource controller can directly control the communication of UEs as shown in Figure 6. It can manage the allocation of radio resources for the ProSe communication so they could start communicating directly.

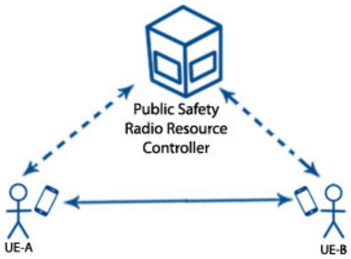

Fig. 6: Public safety ProSe communication for UEs without network support

B. Standardized D2D Architectures

The 3GPP ProSe includes several functionalities: device discovery at the EPC-level, support of EPC enabling devices to directly discover one another and communicate via WLAN, and communications using devices as relays.

Figure 7 shows an abstract illustration of the non-roaming architecture, based on the architecture depicted in the updated standardization document [2].

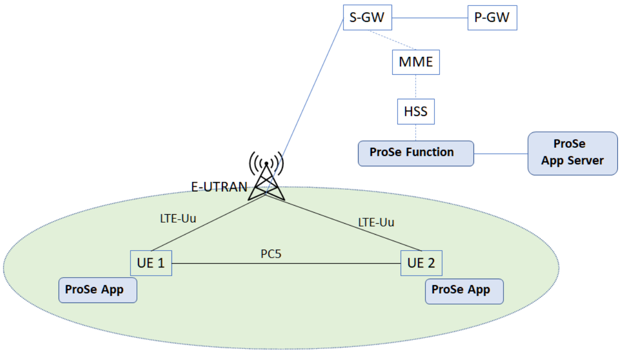

Fig. 7 High Level Architecture for the LTE ProSe services.

The main elements enabling Proximity Services are the following:

(i) ProSe App: The ProSe application that runs on each UE device enabling Proximity services.
(ii) ProSe App Server: The ProSe Application Server has the role of storing all required information regarding the users (IDs, related metadata, restricted codes, etc.) that assist in device discovery in order to initiate device-device communications.
(iii) ProSe Function: It has the following roles: providing the user equipment the required settings for directly discovering and communicating with other users, opening Prose Direct Discovery for the allocation and the processing of the matching between each application ID and code pair, exploiting specific user information that is available in the Home Subscriber Server (HSS) in order to ensure the exchange of discovery signaling in the wireless and wired part of the network topology. Additional functionalities include authorizing and configuring the user equipment for performing discovery via Wireless LAN and communications with the assistance of the Evolved Packet Core. The ProSe Function may support "on demand" announcing requested by the user based on operator policies and covers the required mechanisms for charging and securing the D2D links. When two UEs want to start communicating with each other in a direct or a local path, they need to set up the communication path starting with discovering the UEs available. Next, they have to find their mutual locations and to check if they match proximity criteria (such as being served by the same cell, eNB and MME or not). Figure 8 depicts this setup procedure.

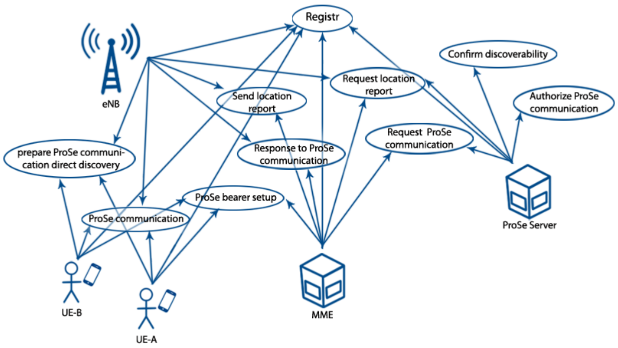

Fig. 8 ProSe Discovery and communication setup procedure

In the evolution towards V2X networks and services the abovementioned architecture has been updated and presented in the 3GPP standardization document [3], an abstract figure of which is illustrated in Figure 9.

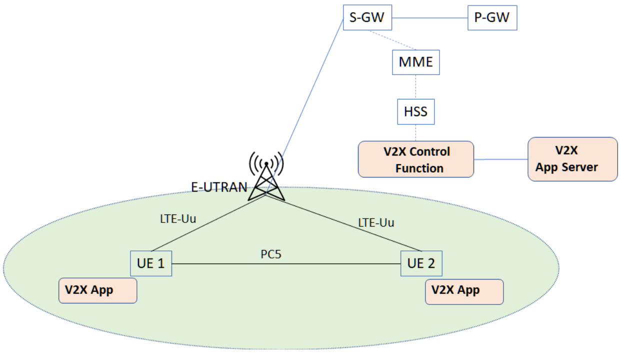

Fig. 9 High Level Architecture for the LTE V2X services.

The V2X architectural components that were existing in the previous 3GPP releases (such as MME, HSS, SGW, PGW) include the additional V2X Control and V2X Application Server functionalities.

The V2X (logical) Control function provides the UE with V2X enabler parameters. The App Server communicates with the V2X application and is in charge of setting up the appropriate Multicast/Broadcast Service, supporting also the use of Mobile Edge Computing (MEC) capabilities.

The main elements for providing V2X services are the following:

(i) V2X App: The V2X application runs on each UE to enable V2V and V2I services.

(ii) V2X App Server: The V2X Application Server supports mainly capabilities such as reception of unicast information transmitted from the user equipment, the delivery of information to a user in specific coverage locations either using unicast or multicast modes (via Multimedia Broadcasting Multicasting Service exploiting the user's location information) and the parameter provision for V2X communication via the PC5 interface, both to the V2X Control Functionality to the user equipment [4].

(iii) The V2X logical Control Functionality manages the individual network mechanisms to V2X communications. It provides the user equipment with the required V2X settings such as PLMN-specific parameter sets and also parameter sets that are necessary for V2X communications in cases of the user equipment being not served by E-UTRAN.

Additionally, 3GPP standardization has developed the architecture for providing V2X communication, namely V2X communication via PC5 and Uu operation modes that can be used by the user equipment in an independent manner in the transmit and receive directions.

V2X communications via PC5 operation mode are supported in LTE and/or NR.

V2X communications over Uu reference point are supported by E-UTRA connected to 5GC and/or NR connected to 5GC. In this release, V2X communication over Uu reference point is only unicast.

Figure 10 shows the non-roaming 5G System architecture for V2X communication via PC5 as well as Uu reference points, based on the architecture presented in [5].

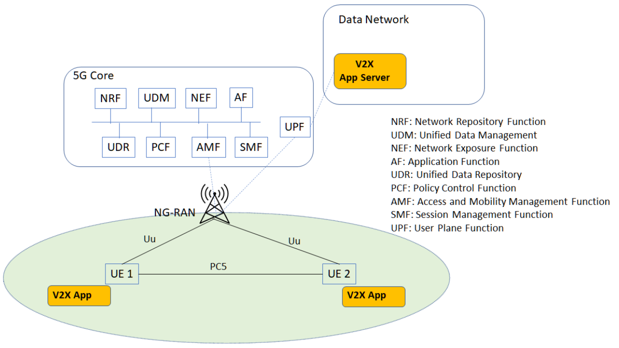

Fig. 10 5G V2X communication high level architecture

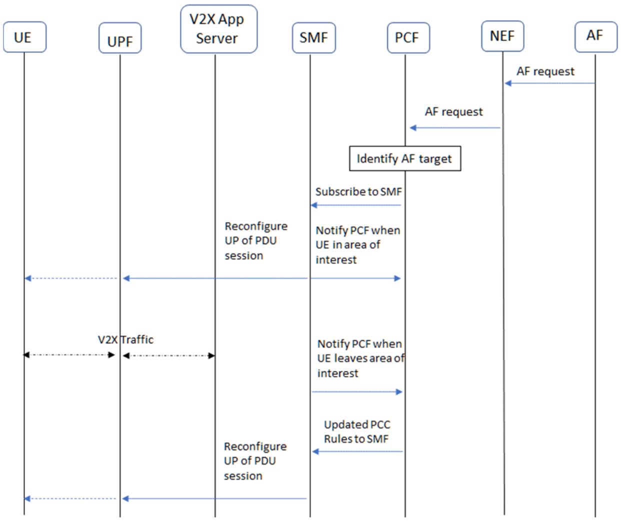

Fig. 11 High level Message Sequence for regulating traffic flow in mobile edge computing scenario.

From the depicted network functions, the Access and Mobility Management Function (AMF) handles important Radio Resource Management functionalities such as user registration, connection, and mobility management, whereas the Session Management Function deals with session establishment, modification and release [6].

The signaling chart in Figure 11 depicts the message exchange between the abovementioned functions for traffic flow routing in an edge computing scenario, as depicted in an illustration included in [7]. The objective is to prepare the network functions for supporting a UE entering an area of interest and to route the traffic corresponding to the UE located locally to and from the V2X App Server related to the specific area where the UE is located.

The legacy LTE Uu employs an eNodeB to act as a relay between mobile nodes, and the sidelink PC5 is used for direct connection between the mobile nodes, with resource scheduling either assisted by the eNodeB (Mode 3) or performed autonomously by the mobile nodes (Mode 4).

The new architectural enhancements are accompanied by a new QoS flow-based mechanism that matches specific QoS parameters (such as Guaranteed Bit Rate, PC5 QoS identifiers, delay budgets, priority levels, packet error rates etc.). The reliability and latency requirements that are addressed by the new standard extensions involve end-end latency values ranging from 5-10 msec, reliability between 99.99% and 99.999% and vehicle distances between 50-1000 m [8]. Furthermore, ETSI standardization activities in Co-operative Intelligent Transportation Systems (C-ITS) have introduced the ITS-G5 architecture and a communication protocol stack on top of the IEEE and LTE PHY and MAC layers with the following main functionalities: (i) Decentralized Congestion Control (DCC) [9], (ii) Cooperative Awareness Messaging (CAM), (iii) Decentralized Environmental Notification Messaging (DENM), and (iv) GeoNetworking (GN) [10]

3. Analytical models for D2D resource allocation

Various works related to Resource Allocation in vehicular communication systems have been presented in literature in the case of C-V2X LTE, the work [11] provides a survey of representative techniques focusing on different resource sharing principles among cellular and vehicular users (overlay, underlay) and also assuming various capabilities in terms of power control, resource block sharing and clustering. In [12] the authors presented a resource management scheme for V2X communications that was related to the distances between vehicular nodes and pedestrians and calculated the required power allocation per resource block based on reinforcement learning. In the work [13] the authors proposed energy consumption models for D2D communications, including 5G LTE and WiFi air interfaces. These models are useful for assessing the energy consumption in both end devices and the base station, assuming different cell sizes, D2D topologies and resource allocation schemes. In [14] the authors present methodologies and models for assessing the performance and reliability of short packet transmission protocols for ultra reliable communications. They utilize both physical layer and MAC layer parameters for approximating the probabilities of successful packet transmission and reception that can apply for V2V and V2I communications. Additionally, the work [15] provided analytical models for assessing the performance of communication among vehicles using the CV2X mode 4, by approximating the averaged Packet Deliver Ratio (PDR). Furthermore, the authors in [16] presented a framework for calculating reliability metrics in industrial networks that require ultra-reliable as well as low-latency communications, and a RAN slicing methodology for efficiently managing resources for demanding applications.

Another work related to analytical studies for wireless industrial networks is presented in [17] where the authors investigate the network throughput maximization in networks allowing resource sharing among D2D and cellular links, therefore appropriate analytical expressions are presented to study the effect of interference among them and to define appropriate power and admission control strategies. Additionally, in [18] the authors focus on the Mode 4 resource scheduling for C-V2X that employs sensing-based and semi-persistent scheduling (SB-SPS) and proposed an adaptive transmitted power control scheme for improving the QoS and reducing interference based on real-time sensing.

4. Integrated Resource Allocation framework

A C-V2X system model (depicted in Figure12) is considered consisting of a number of vehicular nodes within an LTE coverage area. The nodes are considered to communicate either with the LTE base station or with their proximal nodes (either in unicast or groupcast modes) or even in clusters. Similar scenarios can be envisaged by considering ProSe D2D nodes.

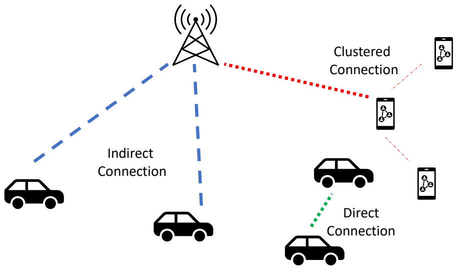

Fig. 12 D2D Connectivity Scenarios

In all scenarios order to ensure the network operation, the fundamental conditions that have to be met are the following:

$$SINR_{i,j} \geq \gamma \qquad (1)$$

where γ is the minimum acceptable threshold of Signal to Interference plus Noise Ratio (SINR) which is necessary for node *j* to receive the signal transmitted by node *i*. Considering that N nodes reuse the same resource block (RB), the SINR can be expressed as:

$$SINR_{i,j} = \frac{\frac{P_i}{L_{i,j}}}{\sum_{\substack{k=1 \\ k \neq i}}^{N} \frac{P_j}{L_{k,j}} + N_0 W} \tag{2}$$

Where P_i is the transmit power of the i-th vehicular node, $L_{i,j}$ is the wireless link loss between the i-th and j-th vehicular nodes, k corresponds to the k-th interfering vehicular node $(1 \leq k \leq N, k \neq i, j)$ that uses the same RB as node i and its signal is received by node j, N_0 is the power spectral density of noise, W is the bandwidth of the RB.
In case the transmitted power per node is fixed $(P_i = P_0, 1 \leq i \leq N)$, then the abovementioned condition (1) can be expressed as:

$$P_0 \geq \frac{N_0 W}{\frac{1}{\gamma L_{i,j}} - \sum_{\substack{k=1 \\ k \neq i}}^{N} \frac{1}{L_{k,j}}} \tag{3}$$

Considering only the l closest interfering nodes around the receiver j in the abovementioned calculations, we can approximate the minimum path loss between the signal receiver j and the l co-channel D2D interferers k_0 as

$$min\left(L_{k_0,j}\right) \approx \gamma l \cdot L_{i,j} \tag{4}$$

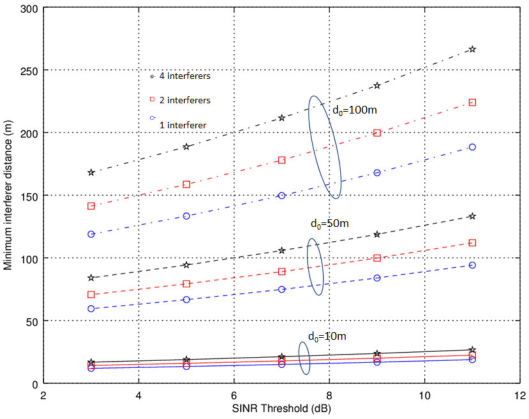

Fig. 13 Minimum distance among nodes sharing the same Resource Block

Considering a distance-dependent path loss model with exponent α,

$$L_{k_0,j} = \left(d_{k_0,j}\right)^{\alpha} \text{ and } L_{i,j} = \left(d_{i,j}\right)^{\alpha} \tag{5}$$

where $d_{k_0,j}$ the distances between the signal receiver and the interferers, and $d_{i,j}$ the distance between the signal receiver and the intended transmitter nodes respectively, we have the following minimum interferer distance approximation:

$$min\left(d_{k_0,j}\right) \approx \sqrt[\alpha]{l\gamma} \cdot d_{i,j} \tag{6}$$

Figure 13 illustrates the variation of the minimum interferer distance for various values of the SINR threshold γ.

In the case of having power control for each node, the required transmitted power level vector can be calculated by considering the linear system described by expression (2) and by using the methodology presented in [19] that requires knowledge of all path losses in the direct and interfering cochannel links. In order to achieve the reduction of the model's complexity, a distributed approach may be employed, where the mathematical model of expression (2) can be rewritten as:

$$SINR_{i,j} = \frac{\frac{P_i}{L_{i,j}}}{IM_i + N_0 W} \tag{7}$$

Where the term IM_i represents a fixed interference margin that is considered in order to allow for maintaining the required SINR at the presence of possible interferers.
Additionally, according to [15] the probability of sensing a signal at a distance d can be approximated by the following expression:

$$p_s(d) = \frac{1}{2}\left[1 + erf\left(\frac{P_0 - 40log(d) - S}{\sigma\sqrt{2}}\right)\right] \tag{8}$$

Where, P_0 is the transmit power,
S represents the minimum necessary received power level for sensing a transmission
σ is the standard deviation of the lognormally distributed shadowing component of the propagation losses.
Figure 14 depicts the variation of the sensing probability for various distances and transmitted power values.
Additionally, according to [14], the reliability R of a D2D link can be approximated with the expression

$$R = (1 - PER_1) \cdot (1 - PER_2) \tag{9}$$

where PER_1, PER_2 are the Packet Error Rates for both links between the proximal nodes and can be approximated - assuming an AWGN channel- by the formula [14]

$$PER_i = \frac{1}{2}\left\{1 - erf\left[\frac{n\log(1+\rho) - k + {}^{\log(n)}/_{2}}{\log(e)\sqrt{2n\rho\frac{2+\rho}{(1+\rho)^2}}}\right]\right\} \tag{10}$$

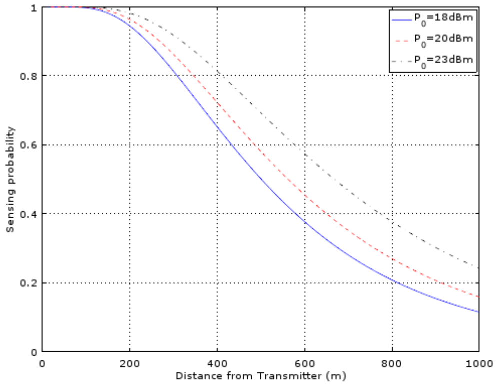

Fig. 9 Sensing Probability versus distance from transmitter

where n is the packet length, k corresponds to the data bits per packet and ρ represents the received SNR, that is linked to the achieved throughput by the Shannon's capacity formula

$$T = log(1+\rho) \tag{11}$$

Finally, for assessing the power consumption, a model for reception P_{RX} and transmission P_{TX} has been presented in [13].

$$P_{RX} = P_{ON} + P_{RXBB}(R_{RX}) + P_{RXRF}(S_{RX}) + \beta_{RX} \cdot \qquad (11)$$

$$P_{TX} = P_{ON} + P_{TXBB}(R_{TX}) + P_{TXRF}(S_{TX}) + \beta_{TX} \qquad (12)$$

where P_{ON} is the power consumption when the device is connected within the cell, β_{RX} is the additional consumption during reception and transmission respectively, P_{RXRF} and P_{TXRF} represent RF block power consumption during reception and transmission respectively and depend on the received and transmitted power levels and bit rates respectively and P_{RXBB} and P_{TXBB} correspond to baseband power consumption during reception and transmission respectively and similarly depend on the received and transmitted power levels and bit rates respectively.

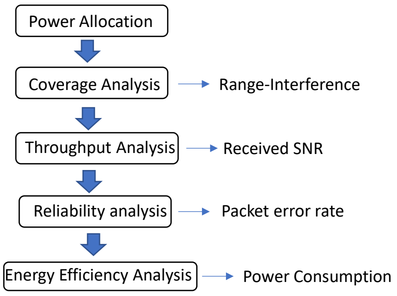

Fig. 15 Integrated resource calculation framework for D2D communications

Based on the abovementioned analysis, we propose an integrated resource calculation framework (depicted on Figure 15) that includes the assessment of the achieved throughput, Packet Error Rate and Power consumption based on parameters such as initial power allocation, distance between D2D nodes, PHY layer parameters such as coding rate, and Noise spectral density, in order to evaluate the choice of specific design parameters and D2D topologies in terms of throughput performance and energy efficiency.

Table 1: Test parameters

Parameter	***Value***
Transmitted Power	8,11,14 dBm
Path Loss Exponent	4
Number of RBs	16
RB bandwidth	180kHz
Noise spectral density	-174 dBm/Hz
Coding Rate	0.5
Packet Size	600 bits

Based on that framework a series of tests have been performed considering the parameters that are included in Table 1.

Figures 16, 17, 18 depict the obtained results in terms of Packet Error Rate, Normalized Throughput and Normalized receiver power consumption.

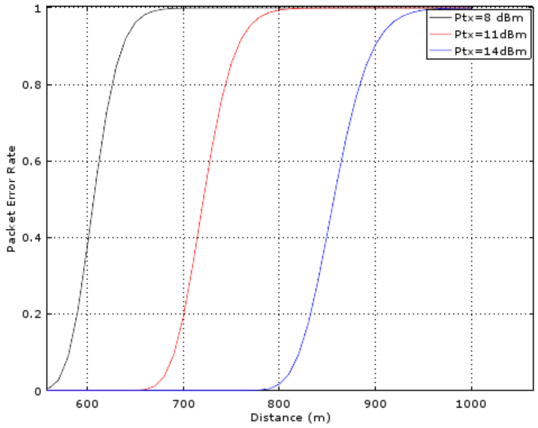

Fig. 16 Packet Error Rate vs D2D distance

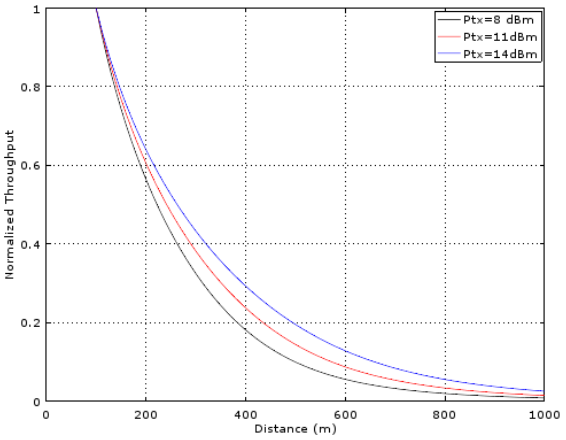

Fig. 17 Normalized Throughput vs D2D distance

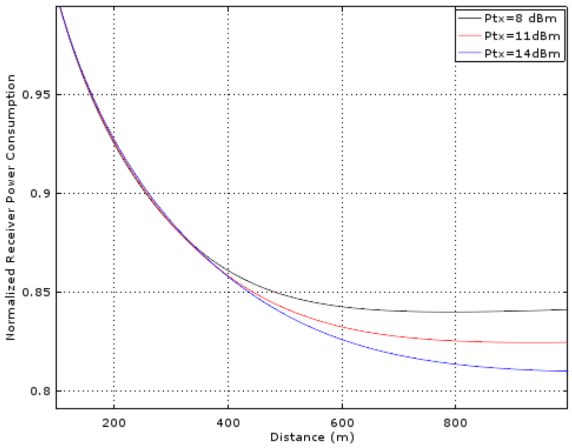

Fig. 18 Normalized Receiver Power Consumption vs D2D distance

5. Simulation Modeling for D2D signaling

This section will present a modeling approach for studying signaling in D2D communications, assuming ProSe Services. This provides a useful step complementing the integrated resource allocation framework that was presented in the previous section.
The steps shown are for ProSe discovery function assuming two UEs at proximity and running the same ProSe-enabled application. but can be extended to any fixed or mobile D2D communication scenario. The UE which wants to be discovered in this model will announce broadcast messages in pre-defined resources, and UEs in proximity which are interested in communicating will read those messages. For the implementation scenarios the following assumptions were made: Three UEs were in proximity, namely UE-A, UE-B, UE-C (same cell, same eNB). The three UEs were registered in X communication application, and UE-A and UE-B were registered as 'friends. The following two procedures are assumed to model UE-A discovering friends in proximity. The eNB in these two scenarios acted as a relay to between the UEs and the ProSe Application server stored data for mapped identifiers. This procedure basically allows the UEs in proximity to discover and communicate with each other after receiving a private expression code from the ProSe server (the proximity services server). This code is made to hide the actual identity of each UE and provide confidentiality. The steps are:

1. UE-A retrieves list of identifiers "friends", let's assume UE-A identifier is: A@example.com

2. For UE-A to be notified that one of its friends is in proximity, the 3GPP layers retrieve a private expression code for UE-A and UE-A's friends.

If a UE is not authorized to use ProSe discovery, then the ProSe server rejects the request

3. The ProSe server maps all provided application-layer identities to private expression codes.

4. The mapped identities are stored in the 3GPP layers for further use.

5. The ProSe-enabled application in the UE-A requests from the 3GPP layers to start discovery.
The steps from 2 to 4 are also done in UE-B.

6. When UE-B receives the ProSe Announcement from UE-A, it determines that the announced expression code is known and maps it to a certain application.

The implementation of these scenarios was done in NS2. The following metrics were considered for the testing part: Distance dependent path loss Path loss as expressed in equation (5), Signal to Interference plus Noise Ratio as expressed in equation (7) and throughput as approximated in equation (11). The objective was to simulate the signaling exchange between the UEs, the eNB and the ProSe App Server in order to assess the total delay, which includes the sum of the times spent at each of the abovementioned node plus the individual packet transport delays and propagation delays.
The basic topology is illustrated in Figure 19, depicting two proximity UEs in the same cell (served by the same eNB) and the eNB connected with ProSe Server and UE-A that wants to discover friends in proximity. The distance between the two UEs is considered to be equal to 10 m and between the UE and the eNB it is equal to 100 m.

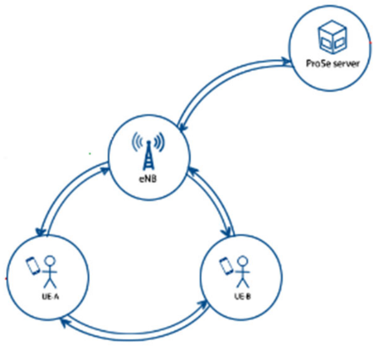

Fig. 19: The Network Topology

Figure 20 shows the flow chart of the procedure and the related signaling exchange.

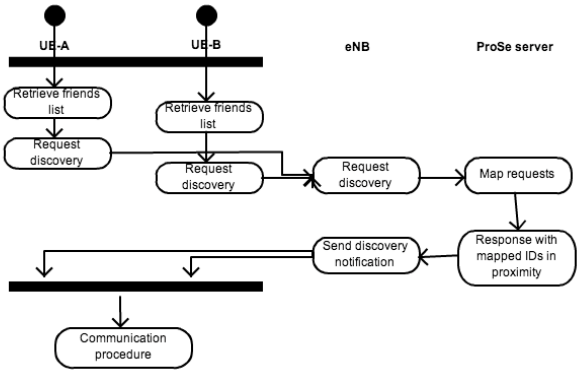

Fig. 20: Simulated Flow chart and signaling exchange

Table 2 shows the simulation results for the measured Total end-end Packet Delay (d_t), Average Signaling Delay (for preparing the communication between UE A and B) and average measured packet rate.

Table 2: Simulation Results

Parameter	***Value***
Total end-end Packet Delay	0.304ms
Average Signaling Delay	16 ms
Average Packet Rate	39.58 packets/sec

The abovementioned model can be extended to cover different D2D communication scenarios using also elements of the analytical model presented in section 4, for assessing key performance metrics that depend on cross layer mechanisms.

6. Conclusions

The paper provided a comprehensive coverage of the evolving standardization in device-device communications within bodies such as 3GPP. It presented key approaches for assessing the performance and energy efficiency of D2D resource allocation mechanisms and also provided an integrated cross-layer framework considering key analytical simulation models for assessing resource allocation parameters and choices in terms of throughput and delay performance as well as energy efficiency.

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