A Hybrid Network Model Embracing NB-IoT and D2D Communications: Stochastic Geometry Analysis

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Abstract. A narrow-band system introduced in Release 13 of 3GPP has recently gain momentum to support a range of IoT use-cases. Narrowband-Internet of Things (NB-IoT) comes with low-cost devices characterized by extremely low power consumption, offering a battery life of more than 10 years, and broad radio coverage to target tens of kilometers, but on the cost of low data rate and higher end-to-end latency. NB-IoT can be deployed in three different modes of operation; standalone, in-band, and within the guard-band of existing LTE carrier. In this paper, a hybrid network model embracing both NB-IoT and D2D technologies has been introduced. we first present an analytical framework to derive analytical rate expressions for D2D in NB-IoT networks. Then, the performance gains of network model are investigated through numerical evaluations that demonstrate the superiority of proposed model over the traditional NB-IoT network.

Keywords: NB-IoT networks · Cellular networks · Spectrum sharing · Stochastic geometry

1 Introduction

The 3rd Generation Partnership Project has latterly introduced a number of key features to support a variety of IoT use-cases in its latest release 13 [1]. The main purpose of these features is to improve the existing for mobile Communications [2] and LTE (Long-Term Evolution) [3], respectively, in order to better serve for

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rapid deployment as well as for the best use case of the Internet of Things. A third track, NB-IoT [4] as well shares these objectives as well. NB-IoT is a new narrowband IoT system built on the top of existing LTE framework: it possible to reuse the same hardware while sharing the LTE spectrum [5,6]. It can be deployed into three different modes of operation: stand-alone, in-band , and within the guard-band of an existing LTE carrier. In stand-alone deployments, NB-IoT can occupy one GSM channel while for in-band and guard-band deployments, it will use one or more physical resource blocks (PRBs) of LTE (180 kHz). The low-cost devices, high coverage, long device battery life and massive capacity with relaxed latency are some of the major design considerations of NB-IoT [6,7] (see Fig. 1).

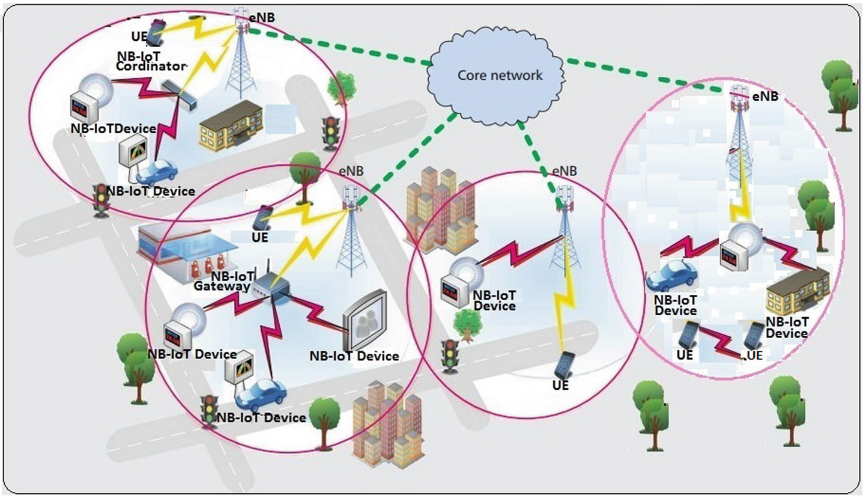

Fig. 1. Hybrid network model embracing NB-IoT and D2D communications coexisting with cellular networks.

For NB-IoT networks deployment , one or more PRBs are reserved, for example In-band mode of operations. The following four access modes can generally be identified in NB-IoT network:

Direct Access to an Evolved NodeB: An NB-IoT device can joint an eNB in hybrid networks without an intermediate device that is ordinary communication. Although this is the easiest direct access method, it can lead eNB congestion due to the large number of NB-IoT devices on the hybrid network.

Gateway Access: NB-IoT devices can benefit from cellular connectivity via NB-IoT gateways. An NB-IoT gateway is a dedicated device with features different from those of conventional NB-IoT objects. NB-IoT gateways transmit data between eNBs and a group of NB-IoT objects but do not generate their own data traffic. This NB-IoT gateway can be used by connecting a set of NB-IoT objects. This NB-IoT gateway can be used to connect a set of NB-IoT objects.

NB-IoT Device Coordinator Access: In some cases, adjacent NB-IoT devices can be grouped together to reduce redundant signaling and avoid congestion. A group-derived NB-IoT device can act as a coordinator to communicate with eNB, acting as a temporary NB-IoT gateway for its group. This access mode minimizes the power consumption of NB-IoT devices and extends the life of devices with battery constraints.

UE Access: NB-IoT devices can obtain connectivity via a cellular UE. Secondly, interoperability between NB-IoT users and cell phone users must be taken into account. This last configuration is particularly interesting to analyse in light of D2D communication technologies, which enable direct communication between devices.

D2D introduces a new communication method for commercial services that are close, including social network applications, public security, local data transfer [8,9]. In addition, D2D may have benefits such as improved energy consumption, increased cellular coverage, and spectral efficiency [10,11].

The main objectives of this article are to provides a hybrid network model embracing NB-IoT and D2D Communications and to develop a analytical framework for the analysis with a performance evaluation. The main tool that is used in this paper study is stochastic geometry, namely the Poisson Point Processes (PPP).

In this paper, the following threefold objectives are achieved. First we introduce a hybrid network model embracing NB-IoT and D2D technologies, in which a random distribution of Euclidean positions of mobile objects is modeled by the Poisson Point Process (PPP) [13,14]. Second, we present an analytical framework and third, we derive analytical rate expressions for D2D communications in NB-IoT networks.

The paper is organized as follows: In Sect. 2, we provide more details on the joint adoption of D2D and NB-IoT technologies. We introduce a hybrid network model embracing NB-IoT and D2D technologies in Sect. 3, in which the random and unpredictable distributions, mainly in Euclidean spaces of mobile users are modeled by PPP. While an analytical framework to derive analytical rate or throughput expressions for D2D in NB-IoT networks is presented in Sect. 4. In the last spring, concluding remarks are mentioned in the Sect. 5.

2 Background and Related Work

2.1 D2D Communication

D2D communication in traditional cellular networks is defined as direct communication between two mobile users with a proximity distance without passing through the eNB. In [15], Doppler *et al.* demonstrated that D2D communications supported, by a cellular infrastructure, can contribute to four types of profits. The communication between nearby devices can allow a very high bit rate, low delays and high energy consumption. Secondly, the jump gain refers to the use of a single link in D2D mode rather than the use of an uplink and downlink resource when exchanging between an device and eNB in cellular mode. Third, the re-use gain implies that radio resources can be used simultaneously by cellular links and D2D links, thus reinforcing the re-use factor even the re-use system. Finally, the matching gain refers to the degree of selection freedom of the UEs communicating with the eNB and UE pairs using a direct link of the same time and the same frequency resources [16,17].

Based on the spectrum usage of D2D users, D2D communications are classified into two groups: in-band D2D communications and out-band D2D communications. In in-band D2D communications, D2D terminals use licensed spectrum. The in-band communications can further be divided into underlay and overlay. Underlay D2D communications occur where cellular and D2D nodes share the same spectrum. On the contrary, overlay D2D communications eliminate intra-cell interference between cellular service and D2D communications by dividing the licensed spectrum into two part through orthogonal channel assignment. Out-band D2D communications use unlicensed spectrum which eliminates the interference between D2D and cellular communication [17,18].

Currently, several research projects have focused on D2D communication, using stochastic geometry. In [19], Xin *et al.* develop a model to analyze the performance of hierarchical data transmissions in the D2D underlying network based on spatio-temporal mathematical tools, the work conducted in [20] proposed a poisson point process model to design an interference-free network. Subhankar *et al.* [21] develop a stochastic geometry namely Poisson point process-based network modelling and performance analysis in heterogeneous wireless network and Basem *et al.* [22] consider an analytical approach to evaluate the outage behavior of the (D2D) communication, which is underlaid with hybrid networks, as an enabling technology for IoT.

2.2 NB-IoT In-Band Cellular Networks

Deployment of NB-IoT can be done in three different modes of operation: guard-band, stand-alone and in-band. In this article, we focus on the mode of operation in the band in existing cellular networks. For NB-IoT in-band operation, one or more PRB LTEs are reserved for NB-IoT. A NB-IoT carrier intended to facilitate the initial synchronization of the UE is called an anchor carrier. For example, in a 10 MHz LTE carrier, the NB-IoT anchor carriers are 4, 9, 14, 30, 35, 40, 45 [23,24].

Figure 2 shows the different options of NB-IoT deployment. The PRB of the bandwidth above the DC subcarrier (PRB# 25) is centered at 97.5 kHz. The DC LTE subcarrier is placed on the 100 kHz frame, the center of the PRB# 25 is located at 2.5 kHz from the nearest 100 kHz grid. The same is for PRB# PRB# 30, PRB# 35, PRB# 40 and PRB# 45 which are also centered at 2.5 kHz from the nearest 100 kHz grid [24,25]. A PRB that does not have a value greater than 7.5 kHz of the 100 kHz frame can be considered and used as the NB-IoT anchor carrier. In addition, an NB-IoT anchor carrier should not be one of the six LTE carrier middle PRBs [24,25]. In fact, these six middle PRBs are occupied by the LTE synchronization and diffusion channels, which makes their use difficult by the NB-IoT.

The eNB power is used between the LTE and the NB-IoT with a better possibility to use the increase of the spectral power density. This sharing allows for more efficient use of the spectrum for better performance and continuous capacity growth, as more devices can be added to the system faster and easier.

Currently, several research projects have focused on the deployment of NB-IoT. In [26], Nitin textit et al. uses existing LTE infrastructure by studying the deployment of NB-IoT, the work in [27] develops a monitoring system to monitor the drop rate and volume of a patient's real-time infusion losses. They also discuss future challenges for building a smart hospital using IoTs.

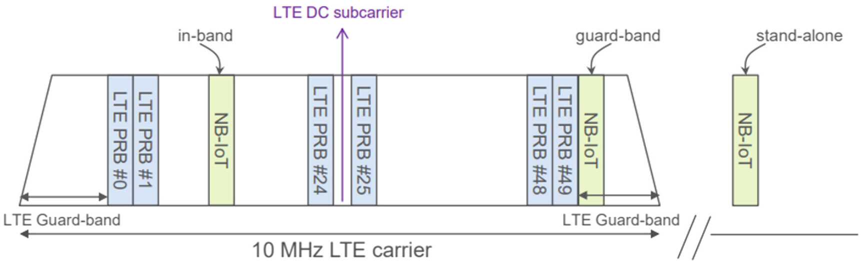

Fig. 2. Examples of NB-IoT deployments [28].

3 System Model

3.1 Network Model

We consider hybrid networks consisting of both NB-IoT, cellular, cellular D2D, and NB-IoT D2D links. Based on [15,18,28], we consider a circular cell of radius R with an evolved NodeB (eNBs) equipped with an omni-directional antenna located at the center of each cell that consists N_n orthogonal NB-IoT users, N_{dn} orthogonal NB-IoT D2D links , N_c orthogonal cellular users and N_{dc} orthogonal cellular D2D links uniformly distributed in the cell. The Fig. 3 show the system model and approximate interference analysis. Specifically, a fraction β of the spectrum is allocated to the cellular D2D objects data transmission and the remaining $1 - \beta$ is allocated to the cellular objects data transmission, where $0 \leq \beta \leq 1$. In the same way, a fraction γ of the spectrum is allocated to the NB-IoT D2D objects data transmission and remains $1-\gamma$ is allocated to NB-IoT objects data transmission, where $0 \leq \gamma \leq 1$. Founded on [29–31], denoting by

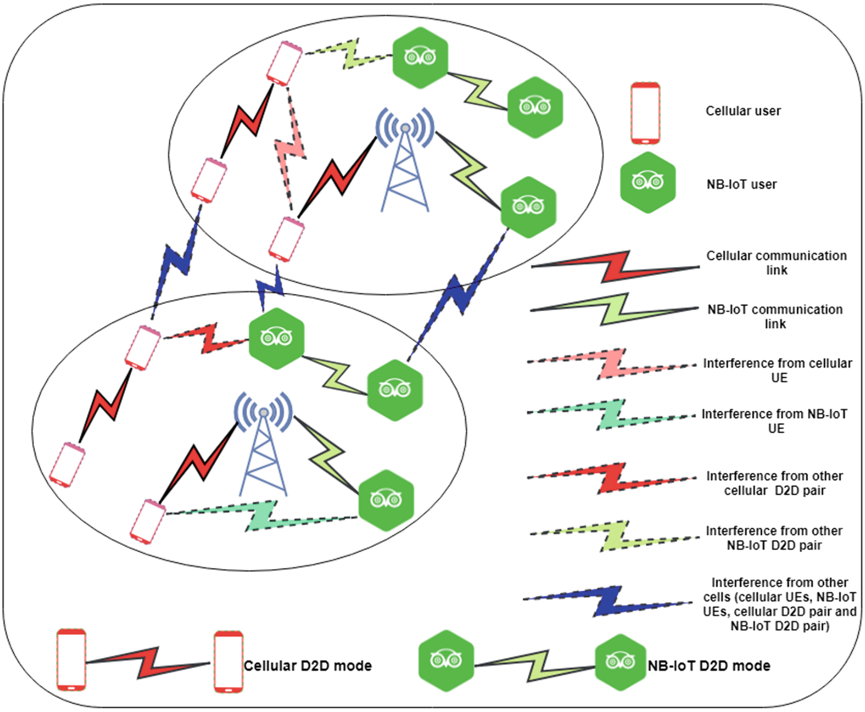

Fig. 3. Network model embracing NB-IoT technologies and D2D communications

$1/\lambda_b$ in the hybrid networks the area of a hexagonal cell, λ_b can be regarded as the average number of (eNB) per unit area. The spatial PPP corresponds to a uniform distribution of NB-IoT users and cellular users in the hybrid network, which is the baseline assumption for many mobile system studies [29]. Denote by $\varPhi \in \mathbb{R}^2$ the unmarked PPP $\{X_i\}$ with intensity λ_1 . The transmit user equipment (NB-IoT UEs and Cellular UEs) are randomly distributed and modeled by an independently market Poisson Point Process PPP denoted as $\{\tilde{\varPhi}_1, \tilde{\varPhi}_2\}$ with $\tilde{\varPhi}_1 = \{(X_i, \delta_i, L_i, P_i)\}$ and $\tilde{\varPhi}_2 = \{(Y_j, \delta_j, L_j, P_j)\}$. where X_i denote the spatial locations of NB-IoT UEs. Each UE has its associated defined parameters that collectively form a marked PPP $\tilde{\varPhi}$. L_i is the distance between the *ith* NB-IoT UE and P_i is the transmit power of the *ith* NB-IoT UE. The parameter δ_i indicates the inherent type of the *ith* transmit NB-IoT UE which may be a potential NB-IoT D2D UE with probability $q_1 = \mathbb{P}(\delta_i = 1)$ or a NB-IoT UE with probability $1 - q_1$, where $q_1 \in [0, 1]$. For national simplicity, we denote by L_n the link length between a typical NB-IoT UE and the associated eNB. Similarly, L_{dn} represents the link lengh between a typical NB-IoT D2D UE and NB-IoT D2D receiver UE.

The parameters Y_j, L_j, P_j, δ_j in cellular networks respect the same assumptions as those of NB-IoT networks. The notations and simulation parameters used are summarized in Tables 1 and 2.

Table 1. Set of notations used throughout the proposed model

Parameter	Description
δ_i	Inherent type of the *ith* NB-IoT UEs
δ_j	Inherent type of the *ith* cellular UEs
β	Spectrum factor
α	Path-loss exponent
X_i	Spatial locations of the *ith* NB-IoT UEs
Y_i	Spatial locations of the *ith* cellular UEs
P_i	Transmitting power of the i-th UEs
P_n	Transmitting power of NB-IoT UEs operating in NB-IoT mode
P_{dc}	Transmitting power of potential NB-IoT D2D in D2D mode
P_{dn}	Transmitting power of potential cellular D2D in D2D mode
$\bar{P}_{dc}$	Transmitting power of potential NB-IoT D2D in cellular mode
$\bar{P}_{dn}$	Transmitting power of potential cellular D2D in NB-IoT mode

4 Framework for Hybrid Network System Performance Evaluation Based on Stochastic Geometric

In this section, analytical results are presented laying the foundation stone for the paper under study of underlay D2D in-band deployed in legacy cellular networks.

Mobile transmitters including mobiles NB-IoT devices and Potential NB-IoT D2D devices in NB-IoT operation mode form a PPP Φ_n with intensity λ_n :

$$\lambda_n = (1 - q_1)\lambda_1 + q_1\lambda_1\mathbb{P}(D_1 \geq \mu_1) \tag{1}$$

Potential NB-IoT D2D devices in D2D operation mode form a Φ_{dn}, Poisson Point Processes with intensity λ_{dn}

$$\lambda_{dn} = q_1\lambda_1\mathbb{P}(D_1 < \mu_1) \tag{2}$$

From (2) and (3) we obtain:

$$\lambda_n + \lambda_{dn} = \lambda_1 \tag{3}$$

We assume $\lambda_1 \geq \lambda_b$, which is reasonable as the uplink transmitter density is usually larger than the (eNB) density. At the same time, for cellular devices and cellular D2D devices in cellular mode form a poisson point processes Φ_c with intensity λ_c :

$$\lambda_c = (1 - q_2)\lambda_2 + q_2\lambda_2\mathbb{P}(D_2 \geq \mu_2) \tag{4}$$

Potential cellular D2D devices in D2D mode form Poisson Point Processes Φ_{dc} with intensity λ_{dc}

$$\lambda_{dc} = q_2\lambda_2\mathbb{P}(D_2 < \mu_2) \tag{5}$$

Table 2. Simulation/numerical parameters

System assumptions	Value
Density of macro cells	$(\pi 500^2)^{-1}\text{m}^{-2}$
Density of UEs	$10 * (\pi 500^2)^{-1}\text{m}^{-2}$
Potential NB-IoT D2D UEs q_1	0.2
mode selection threshold μ_1	200 m
$\daleth$, Aloha access probability	1
n, spectrum partition factor	0.2
β, spectrum access factor	1
sub-channels number	1
Value of l-th moment	1
$SINR_m$	10 dB
B	1 MHZ
Path Loss exponent α (Urban Area)	2,7–3,5

From (5) and (6), we obtain:

$$\lambda_c + \lambda_{dc} = \lambda_2 \tag{6}$$

In this paper, we use the channel inversion for power control, *i.e.,* $P_i{=}L_i^{\alpha}$, where $\alpha > 2$ denotes the path loss exponent. Similarly, we use P_n, P_{dn}, P_c, and P_{dc} to denote the transmit powers variables of NB-IoT users, potential NB-IoT D2D users, cellular users and potential cellular users, respectively.

4.1 Spectral Efficiency

Either a typical pair receiver and transmitter scrambled by a type of heterogeneous interference. We focus on frequency narrowband channels. Under these assumptions above, $SNIR$ for the two modes:

$$SINR = \frac{P_i L_i^{-\alpha} G_i}{I + \sigma^2} \tag{7}$$

where P_i is a transmitting power, $L_i^{-\alpha_i}$ is a link length for NB-IoT and G_i is a channel fading, and interference power I. In our model networks we have a multiple interference, interference due to mobile NB-IoT UEs I_n in NB-IoT mode, interference due to other NB-IoT D2D UEs in NB-IoT D2D mode I_{dn}, interference due to cellular UEs I_c and interference due to cellular D2D UEs I_{dc}.

In this paper we focus our study from D2D in NB-IoT deployed in legacy cellular networks. We consider channel inversion, i.e $P_i L_i^{-\alpha_i} = 1$, so we obtain $P_i L_i^{-\alpha_i} G_0 = G_0$. Based on result given by [29–31], the following model can be derived:

$$I = I_n + I_{dn} + I_c + I_{dc} \tag{8}$$

Lemma 1: The received $SNIR_{dn}$ and $SNIR_n$ for NB-IoT D2D mode and NB-IoT mode our model are given by

$$SINR_{dn} = \frac{G_0}{I_{dn}^{D2D^{mode}} + \sigma^2} \tag{9}$$

where

$$\begin{gathered}
I_{dn}^{D2D^{mode}} = \sum_{X_i \in \Phi_{n,i}} P_{n,i} G_i ||X_i||^{-\alpha} + \\
\sum_{X_i \in \Phi_{dn,i} \setminus \{o\}} P_{n,i} G_i ||X_i||^{-\alpha} + \sum_{X_j \in \Phi_{c,j}} P_{c,j} G_j ||X_j||^{-\alpha} \\
+ \sum_{X_j \in \Phi_{dc,j}} P_{c,j} G_j ||X_j||^{-\alpha}
\end{gathered}$$

and

$$SINR_n = \frac{G_0}{I_n^{NB-IoT^{mode}} + \sigma^2} \tag{10}$$

where

$$\begin{gathered}
I_n^{NB-IOT^{mode}} = \sum_{X_i \in \Phi_n \setminus \{o\}} P_{n,i} G_i ||X_i||^{-\alpha} + \\
\sum_{X_i \in \Phi_{dn}} P_{n,i} G_i ||X_i||^{-\alpha} + \sum_{X_j \in \Phi_c} P_{c,} G_j ||X_j||^{-\alpha} \\
+ \sum_{X_j \in \Phi_{dc}} P_{c,j} G_j ||X_j||^{-\alpha}
\end{gathered}$$

Corollary 1: Suppose $SNIR = \frac{P_i L_i^{-\alpha_i} G_0}{I+\sigma^2}$, where $P_i L_i^{-\alpha_i} = 1$, $G_0 \sim exp(1)$ denote Rayleigh fading, I denote interference powers and σ^2 denote the noise power.I, G_i are independent and we have:

$$\mathbb{E}[log(1 + SINR)] = \int_0^\infty \frac{e^{-\sigma^2 x}}{1+x} \mathscr{L}_I(x) dx \tag{11}$$

where, $\mathscr{L}_I(s) = \mathbb{E}[e^{-sI}]$ denotes the Laplace transform of I .

Next we define the effective throughput R, which combines modulation and codding schemes in the physical layer and multiple access protocols in the medium access control layer. It could be expressed :

$$R = \mathbb{E}[\tau.log(1 + SNIR)] \tag{12}$$

where tau indicates the time or frequency on the one hand or the time and frequency resources on the other hand accessed in hybrid networks by the typical link.

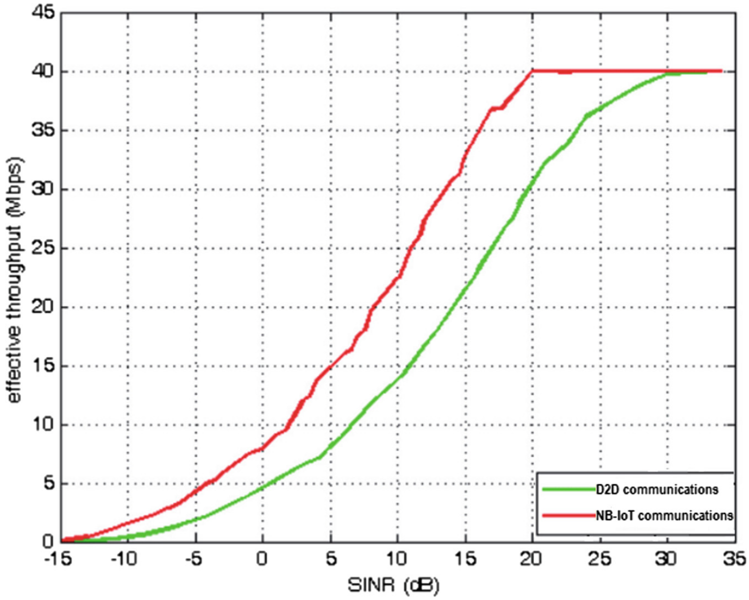

Fig. 4. Effective throughput for NB-IoT and D2D communications in system model

Figure 4 shows the effective throughput of NB-IoT and D2D NB-IoT in a hybrid network model embracing NB-IoT and D2D Communications. The effective throughput of NB-IoT device is much greater than the throughput of D2D NB-IoT device. This effective throughput of D2D NB-IoT in this hybrid network contributes to improve the data transmission, although it is impacted by multiple interference.

5 Conclusion

In this paper, a D2D network overlaid on an uplink cellular network was considered where the locations of the mobile UEs (e.g., NB-IoT and Cellular UEs) as well as the eNBs were modeled as PPP. A novel stochastic geometric approach was exploited for evaluating the D2D network performance in hybrid network presenting an analytical framework and derived analytical rate expressions for D2D scenarios in NB-IoT networks. The numerical results demonstrate the performance gains of D2D communications in comparison with conventional NB-IoT networks.

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