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Cesar Vargas Anamuro*†, Nadège Varsier*, Jean Schwoerer* and Xavier Lagrange†
*Orange Labs, Meylan, France
Email: {cesaraugusto.vargasanamuro, nadege.varsier, jean.schwoerer}@orange.com
†IMT Atlantique/IRISA, Rennes, France
Email: xavier.lagrange@imt-atlantique.fr

***Abstract*—Device-to-Device (D2D) communication for Massive Machine-Type Communication (mMTC) applications is a promising approach to reduce the energy consumption of the battery-limited Machine-Type Devices (MTDs) located in poor coverage areas. In this paper, we analyze the energy consumption of the MTDs when Automatic Repeat reQuest (ARQ) and Hybrid ARQ with Chase Combining (CC-HARQ) mechanisms are used to improve the reliability of D2D communication. By using the tools of stochastic geometry, we derive analytical expressions for the system success probability, the average number of transmissions, and the average MTD energy consumption. Numerical results show that CC-HARQ mechanism outperforms ARQ mechanism in terms of energy consumption, especially when the distance between an MTD and its relay increases (at low relay density) or when the density of MTDs sharing the same sub-channel increases.**

***Index Terms*—Energy consumption, Device-to-Device, mMTC, HARQ with Chase Combining, Stochastic Geometry**

I. Introduction

Reducing the energy consumption of Machine-Type Devices (MTDs) is one of the main challenges of Massive Machine-Type Communication (mMTC) applications since MTDs typically operate using a battery, which is not recharged or replaced for several years. In addition, MTDs are low-complexity devices and have relaxed requirements in terms of data rate.

Device-to-Device (D2D) communication is considered as one of the technical enablers for future 5G networks. D2D refers to the direct communication between two devices, without going through the base station. Recently, D2D technology has been studied as an alternative for mMTC applications. In that case, the User Equipments (UEs) act as relays establishing D2D links with nearby MTDs [1] [2] [3]. This configuration allows reducing the energy consumption of the MTDs since the MTD-UE path-loss is less than the MTD-BS path-loss.

In D2D communications, there are two modes for resource allocation [4]. In mode 1 or Scheduled mode, the base station schedules and assigns resources. All MTDs inside the cell then use dedicated resources to transmit as in traditional cellular communications, avoiding intra-cell interference but not inter-cell interference. In mode 2 or Autonomous mode, MTDs autonomously select resources from pools that are preconfigured or given by the base station if they are in coverage. In this mode, depending on the traffic expectations, the mobile operators dimension the resource pools. In autonomous mode, two or more devices could select the same resource causing interference between them. In this paper we focus our analysis on the Autonomous mode, and we leave the Scheduled mode for future work.

Retransmission schemes increase the transmission reliability exploiting the temporal diversity of the channel. The most common schemes are Automatic repeat request (ARQ) and hybrid ARQ (HARQ) that combines ARQ and forward error correction (FEC) mechanisms.

In our analysis, we are considering only the transmission of messages from the MTDs to the network since mMTC traffic is usually uplink-dominated. An MTD uses a UE as a relay to send its messages to the base station. Both devices are connected through a D2D link. ARQ is the simplest retransmission scheme, in which the same packet is retransmitted if requested by the receiver. In HARQ with Chase combining (CC-HARQ) [5], the same operations are done as for ARQ at the transmitter side. Nevertheless, the operations are slightly more complex at the receiver side. In this paper, the MTDs are the transmitters while the relays (UEs) are the receivers. Therefore, ARQ and CC-HARQ would be suitable for mMTC applications since they allow to improve the transmission reliability without increasing the complexity of the MTDs.

Most of the existing studies related to retransmission mechanisms for mMTC do not consider interference [6] [7] [8]. In [8], the authors consider HARQ with Chase Combining for wireless sensor networks due to the simplicity of this protocol. In [9] the authors propose one solution allowing reducing the energy consumption of the MTDs. They consider a model of energy consumption taking into account the cumulative interference, but the analysis was only carried out for the ARQ mechanism.

In this paper, we compare the performance of ARQ and CC-HARQ mechanisms in terms of energy consumption, considering the D2D autonomous resource allocation scheme. We take into account the impact of Rayleigh fading, log-normal shadowing, and interference caused by other MTDs. Analytical expressions for the success probability, the average number of transmissions, and the MTD energy consumption are derived using a stochastic geometry approach.

The remainder of this paper is organized as follows. Section II presents the system model. The system success probability and the number of transmissions are derived in section III. In Section IV, we analyze the energy consumption and we compare with some numerical results in Section V. Finally conclusions are given in Section VI.

II. System Model

A. Network Model

We consider a cellular network where the locations of UEs form a homogeneous Poisson point processes (PPP) Φ_U with density λ_U in $\mathbb{R}^2$. An active MTD transmits its reports using a UE as a relay via a D2D link. D2D links and cellular links are orthogonal. Hence, there is no interference between these systems. We assume that the locations of MTDs form an independent homogeneous PPP Φ_M with density λ_M in $\mathbb{R}^2$. An MTD shares resources with other ones that use the same sub-channel. Hence, a UE acting as a relay suffers interference from other MTD-UE links as shown in Fig. 1.

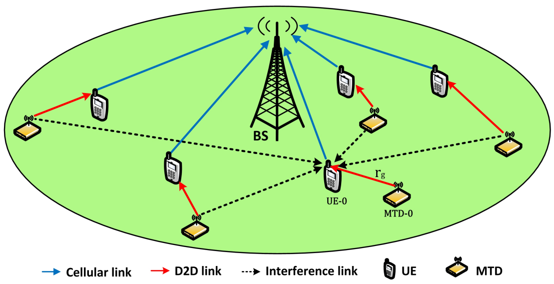

Fig. 1. Network model.

B. Communication Model

During the discovery phase, an MTD searches and selects a UE which will be used as a relay until the transmission is successful. In this study, we only analyze the MTD energy consumption in the data transmission phase, i.e. after the MTD has selected a relay. All the MTDs transmit at fixed power P_{tx} and at fixed rate R_m as in [1].

Without loss of generality, we consider a reference receiver (UE-0) located at the origin of coordinates $(0, 0)$ and its transmitter peer (MTD-0) located at a distance r_g from UE-0. We model the communication channel considering path loss attenuation $r_g^{-\alpha}$, Rayleigh fading H, and log-normal shadowing effect $\exp(\chi)$. Then, the reception power P_{rx} at UE-0 can be derived as

$$P_{rx} = P_{tx} H (r_g/r_0)^{-\alpha} \exp(\chi), \tag{1}$$

where P_{tx} is the MTD transmission power, H is an exponentially distributed random variable (RV) with unit mean, r_0 is a constant propagation parameter, α is the path loss exponent, and χ is zero-mean Gaussian RV with variance σ^2. Log-normal shadowing is also characterized in terms of its dB-spread $\sigma_{dB} = 10\sigma/\ln(10)$.

Let K be the number of available sub-channels for D2D links, which is dimensioned by the operator depending on the density of devices sharing resources. We assume that an MTD in D2D mode randomly selects a sub-channel with the same probability $1/K$ (Autonomous mode). Then, the MTDs that have selected the same sub-channel as MTD-0 form a thinning PPP $\Phi_m = \{x_i\}$ from Φ_M, with density $\lambda_m = \lambda_M/K$. The cumulative interference at UE-0 can be expressed as

$$I = \sum_{x_i \in \Phi_m} P_{tx} H_{x_i} (r_{g,x_i}/r_0)^{-\alpha} \exp(\chi_{x_i}), \tag{2}$$

where all H_{x_i} are i.i.d. exponential RVs with unit mean, all χ_{x_i} are i.i.d. Gaussian RVs with zero mean and variance σ^2, and r_{g,x_i} represents the distance from the origin of coordinates to x_i.

Let θ be the signal-to-interference and noise ratio (SINR) at UE-0. Combining and simplifying (1) and (2), we obtain

$$\theta = \frac{P_{rx}}{N_0 + I} \approx \frac{P_{rx}}{I} = \frac{H r_g^{-\alpha} \exp(\chi)}{\sum_{x_i \in \Phi_m} H_{x_i} r_{g,x_i}^{-\alpha} \exp(\chi_{x_i})}, \tag{3}$$

where N_0 represents the noise power, usually negligible compared to cumulative interference.

In order to simplify our analysis, we use the displacement theorem [10, lemma 1]. Then, we can re-write (3) as

$$\theta = \frac{H r^{-\alpha}}{\sum_{x'_i \in \Phi'_m} H_{x'_i} r_{x'_i}^{-\alpha}}, \tag{4}$$

where $\Phi'_m = \{x'_i\}$ is a homogeneous PPP with density $\lambda_m \mathbb{E}[e^{-2\chi/\alpha}] = \lambda_m e^{2\sigma^2/\alpha^2}$ and $r = e^{-\chi/\alpha} r_g$ is the modified distance between MTD-0 and UE-0. In order to ensure analytical tractability, in the rest of this paper, our analysis is based on the modified distance r.

The transmission success probability of a single transmission is given by

$$P_s = \mathbb{P}(\theta \geq \theta_{th}) = \mathbb{P}\left(\frac{H r^{-\alpha}}{\sum_{x'_i \in \Phi'_m} H_{x'_i} r_{x'_i}^{-\alpha}} \geq \theta_{th} \right), \tag{5}$$

where θ_{th} is the SINR threshold.

Since $H \sim \exp(1)$, and Φ'_m forms a PPP with density $\lambda_m e^{2\sigma^2/\alpha^2}$, we can use the tools of stochastic geometry. Then, (5) can be derived as in [11]:

$$P_s(r) = \exp(-\pi \lambda_m e^{2\sigma^2/\alpha^2} r^2 \theta_{th}^{2/\alpha} \Gamma(1 + 2/\alpha)\Gamma(1 - 2/\alpha)), \tag{6}$$

where $\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$ denotes the gamma function.

The cumulative distribution function (CDF) of the SINR is

$$F_\theta(\theta) = 1 - \exp(-\pi \lambda_m e^{2\sigma^2/\alpha^2} r^2 \theta^{2/\alpha} \Gamma(1+2/\alpha)\Gamma(1-2/\alpha)). \tag{7}$$

Then, the probability density function (PDF) of the SINR can be derived as

$$f_\theta(\theta) = \frac{dF_\theta(\theta)}{d\theta} = \frac{\beta}{\Omega} \left(\frac{\theta}{\Omega} \right)^{\beta - 1} e^{-(\theta/\Omega)^\beta}, \tag{8}$$

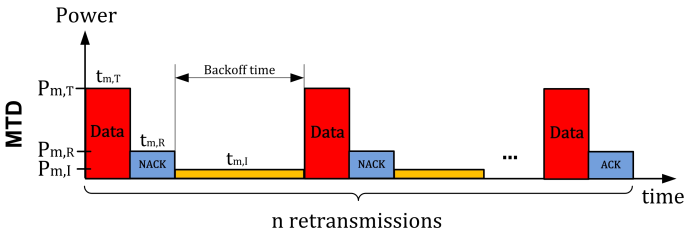

Fig. 2. Retransmission scheme.

where $\Omega = (\pi\lambda_m e^{2\sigma^2/\alpha^2} r^2\Gamma(1+2/\alpha)\Gamma(1-2/\alpha))^{-\alpha/2}$, and $\beta = 2/\alpha$. Note that (8) follows a Weibull distribution of shape parameter β and scale parameter Ω.

III. System Success Probability and Average Number of Transmissions

In this section, we calculate the system success probability and the average number of transmissions for ARQ and CC-HARQ schemes. In both schemes, MTD-0 resends a packet until it is successfully received or until a maximum number of transmissions N is reached. UE-0 answers with an acknowledgment (ACK) if the packet is received correctly or a negative acknowledgment (NACK) if the packet is received with errors as shown in Fig. 2.

A. Performance of ARQ scheme

In ARQ, when a packet is received with errors the receiver discards it and asks for a retransmission of the same packet.

a) System success probability: The probability of failure in each transmission is independent of the other transmissions [9]. We can derive an expression of the system success probability after N transmissions for ARQ scheme:

$$P_{s,arq}(r) = 1 - (1-P_s)^N, \tag{9}$$

where P_s is the success probability in a single transmission, which is defined in (6).

b) Average number of transmissions: Considering the ARQ scheme, the number of transmissions T_{arq} needed to correctly receive a packet varies randomly according to the channel conditions. The average number of transmissions can be obtained as in [9]:

$$\overline{T}_{arq}(r) = \frac{1-(1-P_s)^N}{P_s}. \tag{10}$$

From (9), we can also deduce the z-th percentile number of transmissions for ARQ:

$$T_{z-th,arq}(r) = \lceil \ln(1-z\%)/\ln(1-P_s) \rceil, \tag{11}$$

where $\lceil\cdot\rceil$ is the ceiling operator.

B. Performance of HARQ with Chase Combining scheme

In CC-HARQ, a packet received with errors is not discarded anymore. The receiver stores this packet in a buffer, and then combines it with the next transmitted packet. The transmitted packet is an identical copy of the original packet.

Thanks to the maximal ratio combining (MRC) technique, the energy is accumulated in each transmission. Hence, the global SINR after n transmissions can be written as:

$$\Theta_n = \sum_{i=1}^{n} \theta_i, \tag{12}$$

where θ_i is the SINR at the receiver in round i.

a) System success probability: Unlike the ARQ scheme, in CC-HARQ the success probability in each new transmission depends on the previous transmissions. Let φ_n be the probability that first n transmissions fail in a CC-HARQ scheme:

$$\varphi_n = \mathbb{P}(\Theta_n < \theta_{th}) = \mathbb{P}(\sum_{i=1}^{n}\theta_i < \theta_{th}). \tag{13}$$

We have shown in (8) that θ_i follows a Weibull distribution. Then φ_n is the CDF of the sum of n i.i.d. Weibull RVs of shape β and scale Ω parameters. An approximation for the CDF of the sum of n i.i.d. Weibull RVs is presented in [12]. Using this approximation we have

$$\varphi_n = 1 - \exp(-U_n)\sum_{i=0}^{n-1}\frac{(U_n)^i}{i!}, \tag{14}$$

where
$U_n = \pi\lambda_m e^{2\sigma^2/\alpha^2} r^2 \Gamma(1+\frac{2}{\alpha})\Gamma(1-\frac{2}{\alpha})\left(\frac{\Gamma(n+2/\alpha)}{n!\Gamma(1+2/\alpha)}\theta_{th}\right)^{2/\alpha}$.

We can re-write (14) as

$$\varphi_n = 1 - \frac{\Gamma(n, U_n)}{(n-1)!}, \tag{15}$$

where $\Gamma(a,x) = \int_x^\infty t^{a-1}e^{-t}dt$ is the upper incomplete gamma function.

Then, the system success probability after N transmissions for CC-HARQ can be expressed as

$$P_{s,harq}(r) = 1 - \varphi_N = \frac{\Gamma(N, U_N)}{(N-1)!}. \tag{16}$$

b) Average number of transmissions: The average number of transmissions of CC-HARQ can be derived as in [13]:

$$\overline{T}_{harq}(r) = 1 + \sum_{n=1}^{N-1}\varphi_n. \tag{17}$$

Combining (15) and (17), we obtain

$$\overline{T}_{harq}(r) = N - \sum_{n=1}^{N-1}\frac{\Gamma(n, U_n)}{(n-1)!}, \tag{18}$$

where N is the maximum number of transmissions, and U_n is defined in (14).

The z-th percentile number of transmissions for CC-HARQ $T_{z-th,harq}$ can be derived from (16). We have

$$T_{z-th,harq}(r) = n^*, \tag{19}$$

where n^* is the smallest integer value which satisfy the inequality $\frac{\Gamma(n^*, U_{n^*})}{(n^*-1)!} \geq z\%$. We can use numerical computation to find n^*.

IV. Energy consumption modeling

The MTD energy consumption in a single transmission can be derived as

$$E_{m,1} = P_{m,T} t_{m,T} + P_{m,R} t_{m,R} + P_{m,I} t_{m,I}, \quad (20)$$

where $P_{m,T}$, $P_{m,R}$, and $P_{m,I}$ are the MTD power consumption in Tx state, Rx state, and Idle state respectively; $t_{m,T}$, $t_{m,R}$, and $t_{m,I}$ are the duration of Tx state, Rx state, and Idle state respectively (see Fig. 2).

We assume that an MTD transmits at a fixed power (no power control) and at a fixed data rate (no link adaptation) due to its low complexity and low cost. Then, we have $t_{m,T} = L/R_m$, where L is the packet size and R_m is the MTD bit rate.

The back-off time $t_{m,I}$ is a random time that allows the independence of transmissions in case two or more devices transmit at the same time. In this work, we consider $t_{m,I} = \eta t_{m,T}$, where η is a random integer following an exponential distribution with a mean $\overline{\eta} = 5$. It should be noted that the back-off time does not increase significantly the energy consumption since the MTD during this time is in Idle state. On the other hand, the delay could increase significantly as a function of $\overline{\eta}$. However, mMTC applications are delay-tolerant.

We assume that $t_{m,R} = t_{m,T}$, thereby the ACKs will have enough redundancy in order to ensure that they will be received correctly by the MTD.

Then, the average MTD energy consumption in a single transmission can be expressed as

$$\overline{E}_{m,1} = (P_{m,T} + P_{m,R} + \overline{\eta} P_{m,I}) \frac{L}{R_m}. \quad (21)$$

The average of the global energy consumed by the MTD $\overline{E}_{m,G}$ can be derived as

$$\overline{E}_{m,G}(r) = \overline{E}_{m,1} \overline{T}, \quad (22)$$

where $\overline{T}$ denotes the average number of transmissions defined in (10) and (18) for ARQ and CC-HARQ respectively.

V. Numerical Results

In this section, the analytical and simulation results are presented to validate the accuracy of our analytical models. The simulation parameters are specified in Table I. We consider the same modulation and coding schemes (MCS) as in [14], as well as the same SINR thresholds (see Table II). All the simulations are performed using MATLAB.

TABLE I
Simulation Parameters

Parameter	Assumption
MTD power consumption in Tx state($P_{m,T}$)	545 mW
MTD power consumption in Rx state ($P_{m,R}$)	90 mW
MTD power consumption in Idle state ($P_{m,I}$)	3 mW
MTD Bandwidth (W_m)	1.4 MHz
Packet Size (L)	1080 bits
Path loss exponent (α)	4
Density of MTD (λ_M)	16×10^{-6}
Standard deviation (σ_{dB})	8 dB

TABLE II
Transmission Modes Parameters [14]

Mode	Modulation	Coding rate	Rate (bits/sym.)	SINR Threshold (dB)
MCS 1	BPSK	1/2	0.5	-1.5
MCS 2	QPSK	1/2	1.0	1
MCS 3	QPSK	3/4	1.5	4

The system success probability as a function of the modified distance MTD-UE is shown in Fig. 3. In this figure, NARQ represents a single transmission. We can see that the analytical and the simulation results fit well. We can also notice that as N increases CC-HARQ scheme becomes more advantageous than ARQ scheme.

We compare the performance of ARQ and CC-HARQ in terms of the number of transmissions as well as the average energy consumption. In this regard, we assume N large enough (e.g. $N = 128$) such that the success probability is similar in both retransmission schemes up to a certain MTD-UE distance (see Fig. 3). As shown in Fig. 3, for $N = 128$ and MCS-3, the maximum distance MTD-UE where the success probability is greater than 95% in both retransmission schemes is approximately 140 meters. Therefore, in the rest of this paper, we compare the performance of both ARQ and CC-HARQ for distances MTD-UE less than 140 meters.

The average and the 95th percentile number of transmissions for ARQ and CC-HARQ schemes are presented in Fig. 4. We can see that the analytical and the simulation results fit well. In addition, this figure shows the advantage of CC-HARQ over ARQ in terms of the number of transmissions. This advantage increases when the distance MTD-UE increases. For example, at a distance MTD-UE of 100 meters, 95% of the MTDs transmit successfully in less than 9 and 6 transmissions using ARQ and CC-HARQ respectively.

Fig. 5 shows the average MTD energy consumption for different modulation and coding schemes. Note that the energy consumption could be reduced if the MTD would be able to dynamically adapt its modulation and coding scheme.

One of the main characteristics of the mMTC applications is the high connection density (devices/km^2) while one of the advantages of D2D relaying is the reuse of resources. As we mentioned above, λ_m represents the density of MTDs sharing the same sub-channel. So far, we have considered that all the MTDs share a single sub-channel ($K = 1$). However, due to the interference the number of transmissions and the MTD energy consumption increase exponentially, especially for distances MTD-UE greater than 100 meters. A solution would be to increase the number of sub-channels, which reduce the density of devices sharing a sub-channel. Fig. 6 shows the average MTD energy consumption considering 1, 2, 4 and 8 sub-channels. From this figure, we observe that CC-HARQ outperforms ARQ in terms of energy consumption especially at a high density of devices sharing a sub-channel.

As shown in Fig. 6, the difference between CC-HARQ and ARQ in terms of energy consumption is more evident

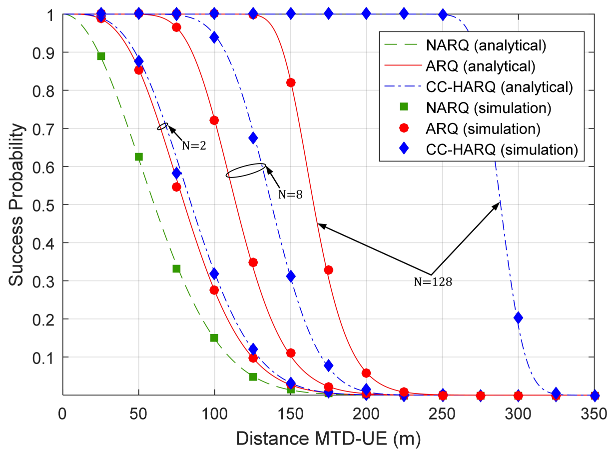

Fig. 3. System success probability of ARQ and CC-HARQ as a function of the modified distance MTD-UE, considering MCS-3, maximum number of transmissions $N = \{2, 8, 128\}$, and one sub-channel ($K = 1$).

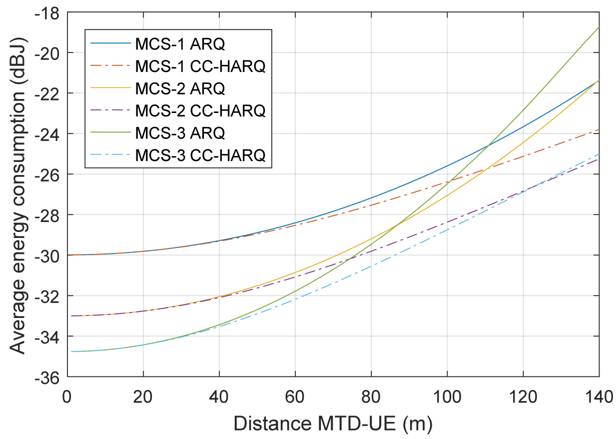

Fig. 5. Average MTD energy consumption of ARQ and CC-HARQ as a function of the modified distance MTD-UE, considering maximum number of transmissions $N = 128$, and one sub-channel ($K = 1$).

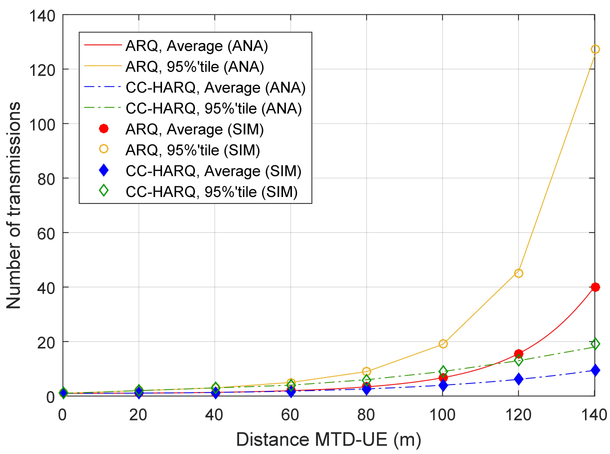

Fig. 4. Number of transmissions of ARQ and CC-HARQ as a function of the modified distance MTD-UE, considering MCS-3, maximum number of transmissions $N = 128$, and one sub-channel ($K = 1$).

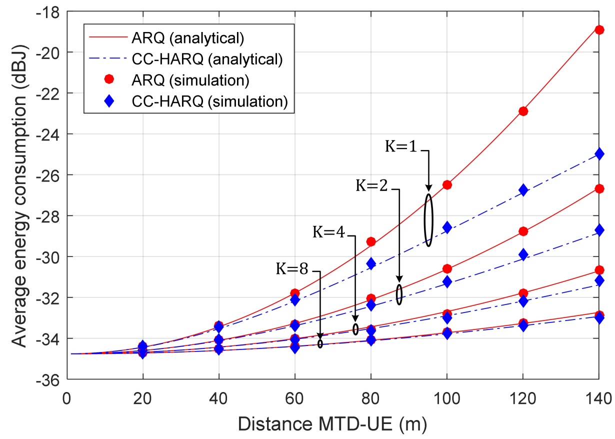

Fig. 6. Average energy consumption of ARQ and CC-HARQ as a function of the modified distance MTD-UE, considering MCS-3, maximum number of transmissions N=128, and number of sub-channels $K = \{1, 2, 4, 8\}$.

as the modified distance MTD-UE r increase. This distance is a random variable since the locations of the MTDs and UEs form two independent PPPs. Assuming that during the discovery phase an MTD selects the nearest UE as its relay. Hence, the CDF of r can be derived as in [15] $\mathbb{P}(r \leq R) = 1 - \exp(-\lambda_U \pi R^2)$. It is worthwhile noting that the distance MTD-UE depends only on the density of UEs λ_U. For example, for $\lambda_U = \{16 \times 10^{-6}, 32 \times 10^{-6}, 64 \times 10^{-6}\}$ in 90% of cases the MTD-UE distances are less than 214, 151, 107 meters respectively. The MTD density and the UE density are two important parameters when comparing the ARQ and CC-HARQ schemes.

VI. Conclusion and Future Works

In this paper, we compared the performance of ARQ and CC-HARQ mechanisms in terms of the average energy consumption for D2D communications. Using stochastic geometry, we derived analytical expressions for the system success probability, the average number of transmissions, and the average MTD energy consumption of ARQ and CC-HARQ. Our analysis takes into account Rayleigh fading, shadowing and the interference among D2D links when they share the same sub-channel. The accuracy of these analytical expressions is confirmed by simulations.

For future work, we will investigate the energy consumption of the MTDs using D2D relaying mechanisms where the resources allocation is performed in scheduled mode. Moreover, the model of the energy consumption will be extended considering the discovery phase.

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