

Delay-Sensitive Resource Allocation for Relay-Aided M2M Communication over LTE-Advanced Networks

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Abstract—Machine-to-machine (M2M) communications consist of a large number of smart devices that communicate automatically without human intervention. The Third-Generation Partnership Project (3GPP) Long-Term Evolution (LTE) and LTE-Advanced (LTE-A), due to some features such as IP connectivity and scalability, are ready-to-use infrastructures for the M2M communications implementation. In the next generation of cellular networks with M2M devices, radio resource allocation is a major issue. In order to solve the issue, this paper addresses the efficient resource block (RB) allocation problem for different relay-aided cellular and M2M user equipments (UEs) to maximize the end-to-end data rate under different constraints of Single Carrier Frequency Division Multiple Access (SC-FDMA). The proposed solution also satisfies the maximum power budget, the minimum data rate and statistical QoS delay requirements for prioritizing different traffics under total power constraint. Numerical results demonstrate the effectiveness of the proposed scheme.

Index Terms—SC-FDMA, Resource allocation, M2M communication, Delay quality-of-service.

I. INTRODUCTION

The Third-Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard for uplink multiple access scheme uses Single Carrier Frequency Division Multiple Access (SC-FDMA) [1]. Compared to Orthogonal Frequency Division Multiple Access (OFDMA), SC-FDMA has many benefits such as low Peak-to-Average Power Ratio (PAPR) which improves the efficiency of the transmission power for mobile terminals [2].

Machine-to-machine (M2M) communications provides a way to make connectivity among different machines or devices, independent of human intervention. M2M communications has many different applications such as e-health, smart cities, infrastructure management and monitoring. In the meantime, due to the growing machine type communication (MTC) devices besides currently used human type communication (HTC), it is important to guarantee the quality-of-service (QoS) requirements for various types of delay sensitive

services [3], [4]. Thus, there is a need to intelligent solutions for efficient resource management among all the coexisting MTC and HTC demanded services with respect to their QoS requirements so that none of human-based services are sacrificed.

A. Related Work

The resource scheduling problem over LTE and LTE-A is discussed in many papers in recent years. A rich survey about scheduling techniques in LTE and LTE-A has been presented in [5] and [6]. The authors of [5] presented a tutorial and a survey about scheduling problems in LTE and LTE-A networks. They also presented an evaluation methodology to compromise the scheduling algorithms. However, in [6], the authors looked to the LTE uplink scheduling problem from an M2M perspective. By considering the M2M communications aspects such as power efficiency, QoS requirements, multi-hop transmission and network scalability, they presented a classification for uplink scheduling techniques over the LTE and LTE-A. The authors in [7] presented a LTE uplink scheduling algorithm that distinguishes between M2M and H2H services and applied different scheduling methods for each one. In addition, for M2M services, a two-phase scheduling mechanism based on maximum-utility scheduling and round robin scheduling was presented. Moreover, an algorithm named Iterative Maximum Expansion (IME) is used for scheduling H2H services. In [8] the impact of massive M2M traffics on the performance of different H2H services like VoIP, CBR and video over the LTE uplink channels was investigated, when both dynamic and semi-persistent scheduling is used. The authors in [9] and [10] presented a predictive uplink resource allocation scheme for event based M2M application over LTE. The problem of energy conservation in uplink resource and power allocation over LTE-A networks is investigated in [11]. They proposed heuristic methods to reduce the energy consumption of machines while guaranteeing their QoS requirements at the same time. A class based dynamic priority (CBDP) algorithm

TABLE I: System model and notations

Notation	Physical interpretation
$K : k \cong \{1, \dots, K\}$	Set of traditional cellular UEs (CUEs)
$M : m \cong \{1, \dots, M\}$	Set of M2M UEs
$L : l \cong \{1, \dots, L\}$	Set of available RBs
u_ς	A UE served by relay ς
$h_{u_\varsigma,1}^l, h_{u_\varsigma,2}^l$	Link gain in first & second hops over RB l , respectively
$p_{u_\varsigma,1}^l, p_{u_\varsigma,2}^l$	Transmit power in first & second hops over RB l , respectively
$\theta_{u_\varsigma}^T$	Delay bound for u_ς^{th} UE, $u_\varsigma \in \{K \cap M\}$
$x_{u_\varsigma}^l \in \{0, 1\}$	RB allocation indicator for u_ς over RB l

for LTE uplink scheduling with co-existence M2M and H2H traffics is proposed in [12]. The algorithm considers the delay tolerance and minimum guaranteed bit rate required by communications to achieve the goal of supporting M2M communications with the least impact on H2H flows. In addition, a variable chunk size based method is proposed in [12] to allocate resource blocks (RBs) to a user. The papers of [13] and [14] introduced a packet scheduling mechanism for LTE networks with M2M communications. The proposed approach uses the system's current information to classify and prioritize data traffics to reduce the impact of M2M communications on H2H beside considering the QoS and fairness by adjusting the congestion level. A resource allocation scheme is proposed in [15] that considers the constraints of SC-FDMA for assigning LTE radio resources to device-to-device (D2D) communication more efficiently. The proposed scheme in [15] determines the transmission power of D2D user equipments (DUEs) in order to guarantee certain performance of cellular user equipments (CUEs). Then, this schemes, couples a CUE and a D2D as a resource sharing pair (RSP) and allocate the subchannels based on well-known proportional fairness (PF) scheduling algorithm. A green uplink radio resource allocation schemes for LTE networks is proposed in [16] to efficiently allocate the RBs and transmission power of UEs. The proposed scheme in [16] uses the Opportunistic and Efficient RB Allocation (OEA) algorithm to maximize the aggregate throughput by considering the SC-FDMA constraints. An enhanced version of algorithms, namely, QoS-based OEA is presented to deal with QoS differentiation. To provide the fly wireless communications in the specific geographical area, the paper [17] deployed an unmanned aerial vehicle (UAV) as a flying base station, that considers a co-existence environment with UAV, for downlink data transmission and an underliad D2D communication network. An interval type-2 fuzzy logic approach for resource allocation in LTE is introduced in [18], that enhance the energy consumption and QoS by considering and handling system uncertainties such as noise.

Unlike most of the existing work in LTE-A cellular networks, in this work, we study the advantages of relay for allocating radio resources. Recently, due to the growing number of battery limited H2H and M2M devices, which always have not battery replacement option and bandwidth restriction resource, the proper optimization of resources becomes a critical issue. In this paper, we address the problem of resource allocation

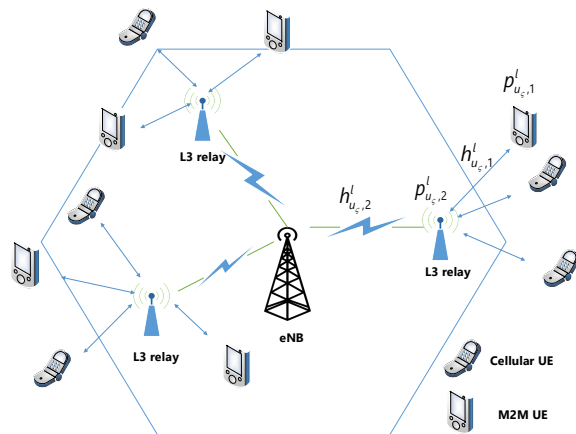


Fig. 1: A multiple relays single cell with multiple M2M/H2H co-existence users scenario.

in an LTE-A network with M2M devices.

B. Contributions and Outline

The main contributions of this paper can be summarized as follows:

- We formulate and obtain globally optimal solution for the problem of RB and power allocation at the relay nodes to analyze the performance of relay-assisted M2M communication. In order to reach the best solution, we formulate the problem considering the delay QoS constraint of different M2M/H2H traffics as a priority parameter.
- The radio resource, i.e., RB and transmit power, allocation algorithm is performed with polynomial time complexity analysis at each relay.

The rest of this paper is organized as follows. The system model and assumptions is presented in Section II. In Section III, we formulate the RB and power allocation problem. We propose a distributed algorithm to allocate resources and discuss it's complexity in Section IV. In Section V, we evaluate the performance of results and finally we conclude the paper in Section VI.

II. SYSTEM MODEL

A. Network Model

Fig. 1 shows a single cell with multi-user M2M/H2H co-existence and multiple relay nodes scenario. In addition, some

important notations and assumptions are defined in Table I. We consider that in order to communicate directly, the cellular user equipment (CUE)-eNB links are undesirable and instead they should employ relays. M2M user equipments (UEs) also need relays due to poor link condition and/or long distance between M2M devices and eNB. Note that we assume that the coherence time of the channel is greater than the Transmission Time Interval (TTI), and $\sigma^2 = N_0 B_{RB}$, where B_{RB} is the bandwidth of a RB and N_0 denotes the thermal noise power per unit of bandwidth in Additive white Gaussian noise (AWGN) channel.

In order to reduce the computation load at the eNB, we use LTE-A Layer 3 (L3) relay¹ which has capabilities to schedule and allocate system resources among the UEs in the relay node.

B. Achievable Data Rate

The achievable data rate for each UE (both cellular and M2M users) over RB l in the first and second hop links are represented as:

$$R_{u_\zeta,1}^l = B_{RB} \log_2(1 + p_{u_\zeta,1}^l h_{u_\zeta,1}^l / \sigma^2), u_\zeta \in U = \{K, M\}, \quad (1)$$

$$R_{u_\zeta,2}^l = B_{RB} \log_2(1 + p_{u_\zeta,2}^l h_{u_\zeta,2}^l / \sigma^2), u_\zeta \in U = \{K, M\}, \quad (2)$$

respectively. Thus, the overall two hops end-to-end achievable data rate for the u_ζ^{th} UE can be calculated as:

$$R_{u_\zeta}^l = \frac{1}{2} \min\{R_{u_\zeta,1}^l, R_{u_\zeta,2}^l\}. \quad (3)$$

C. Traffic Prioritizing Weight

In this work, in order to delay-sensitive protecting, we define a weight w_{u_ζ} which signifies the user priority in order to ensure the exponent quality of service (QoS) requirement for the u_ζ^{th} UE. Stringent and loose exponent QoS requirements are shown by large and small values of θ , respectively. For example, the system can tolerate long delays when $\theta \rightarrow 0$, whereas $\theta \rightarrow \infty$ implies the system cannot tolerate any delay. Finally, the probability of exceeding delay from a maximum bound $\theta_{u_\zeta}^T$ is related to θ according to [20]:

$$w_{u_\zeta} = e^{-\theta_{u_\zeta}^T} \quad (4)$$

where $\theta_{u_\zeta}^T$ is in unit of a symbol duration and denotes the delay bound of each UE. The symbol duration T_s is equal to $T_s = 1/B$, where B is the system bandwidth.

III. PROBLEM FORMULATION

A. Formulation of the Nominal Resource Allocation Problem

Let the set of UEs assisted by relay ζ is Ω_ζ such that $\Omega_\zeta \subset U$ and $\cap \Omega_\zeta = \emptyset$. Consider that the maximum allowable transmit power for UE (relay) is $P_{u_\zeta}^{\max}(P_\zeta^{\max})$. Hence, the resource allocation problem for each relay ζ can be stated as follows:

¹A self-backhaul configuring L3 relay node can operate as an eNB but it has a smaller cell size and uses a lower power to transmission [19].

$$\begin{aligned} \text{(P1) Maximize} \quad & \sum_{u_\zeta=1}^{\Omega_\zeta} w_{u_\zeta} \sum_{l=1}^L x_{u_\zeta}^l R_{u_\zeta}^l \\ \text{s.t.} \quad & \sum_{u_\zeta=1}^{\Omega_\zeta} x_{u_\zeta}^l \leq 1, \forall l, \quad (5a) \\ & \sum_{l=1}^L x_{u_\zeta}^l P_{u_\zeta,1}^l \leq P_{u_\zeta}^{\max}, \forall u_\zeta, \quad (5b) \\ & \sum_{u_\zeta=1}^{\Omega_\zeta} \sum_{l=1}^L x_{u_\zeta}^l P_{u_\zeta,2}^l \leq P_\zeta^{\max}, \quad (5c) \\ & R_{u_\zeta} \geq R_{\min, u_\zeta}, \forall u_\zeta, \quad (5d) \\ & p_{u_\zeta,1}^l \geq 0, p_{u_\zeta,2}^l \geq 0, \forall l. \quad (5e) \end{aligned}$$

The constraint in (5a) gives each RB to only one UE. The constraints in (5b) and (5c) ensure that the transmit power in the first and second hop, respectively, to be bounded by the maximum power thresholds. With the constraint in (5d), the minimum QoS requirement (R_{\min}) is ensured for the CUEs and M2M UEs. Consequently, by using the constraint in (5e), the non-negativity condition for the transmit power is considered.

From (3), the maximum data rate for UE u_ζ over RB l is achieved when $p_{u_\zeta,1}^l h_{u_\zeta,1}^l = p_{u_\zeta,2}^l h_{u_\zeta,2}^l$. Hence, with replacing $p_{u_\zeta}^l h_{u_\zeta}^l = p_{u_\zeta,1}^l h_{u_\zeta,1}^l$, the data rate for UE u_ζ over RB l can be expressed as: $r_{u_\zeta}^l = \frac{1}{2} \log_2(1 + \frac{p_{u_\zeta}^l h_{u_\zeta}^l}{\sigma^2})$. On the other hand, to further simplify the problem, we assumed that $P_{u_\zeta}^{\max} = P_\zeta^{\max}$.

B. Relaxation and Reformulation

The optimization problem P1 is computationally intractable due to the fact that it is a mixed-integer non-linear program. In order to tackle such problems, relaxing the constraints is a common approach. Our problem can be relaxed by using the time-sharing factor [21] $x_{u_\zeta}^l \in (0, 1]$ that causes a RB to be used by only one UE. Moreover, a new variable $\mu_{u_\zeta}^l = x_{u_\zeta}^l p_{u_\zeta}^l$ is introduced which signifies the actual transmit power of UE u_ζ on RB l [22]. Then, the relaxed upper bound optimization problem can be presented as follows:

$$\begin{aligned} \text{(P2) Maximize} \quad & \sum_{u_\zeta=1}^{\Omega_\zeta} w_{u_\zeta} \sum_{l=1}^L \frac{1}{2} x_{u_\zeta}^l B_{RB} \log_2(1 + \frac{\mu_{u_\zeta}^l h_{u_\zeta}^l}{x_{u_\zeta}^l \sigma^2}) \\ \text{s.t.} \quad & \sum_{u_\zeta=1}^{\Omega_\zeta} x_{u_\zeta}^l \leq 1, \forall l, \quad (6a) \\ & \sum_{l=1}^L \mu_{u_\zeta}^l \leq P_{u_\zeta}^{\max}, \forall u_\zeta, \quad (6b) \\ & \sum_{l=1}^L \frac{1}{2} x_{u_\zeta}^l B_{RB} \log_2(1 + \frac{\mu_{u_\zeta}^l h_{u_\zeta}^l}{x_{u_\zeta}^l \sigma^2}) \geq R_{\min, u_\zeta}, \forall u_\zeta, \quad (6c) \\ & \mu_{u_\zeta}^l \geq 0, \forall l. \quad (6d) \end{aligned}$$

The time-sharing condition is satisfied by our optimization problem, and hence, the solution is asymptotically optimal [23]. Since the objective function is convex, the optimization problem P2 is convex, and thus, there exists a unique optimal solution.

Algorithm 1 Optimal resource allocation algorithm

Step1: Initialization

- K : Number of CUEs devices.
- M : Number of M2M devices.
- D_r : M2M UEs-relay distance.
- θ_u^T : Delay bound for UEs.

- 1: Estimate the link gains for each relay from previous time slot.
- 2: Give some positive value to Lagrange multipliers for initialization.
- 3: Calculate w_{u_ζ} for u_ζ using (4).

Step 2: Calculate the optimal solution

- 4: Set $t := 0$, $\mu_{u_\zeta}^l := \frac{P_{u_\zeta}^{\max}}{L} \forall u_\zeta, l$.
- 5: **while** $t = T_{\max}$ or $|R_\zeta(t) - R_\zeta(t-1)| < \epsilon$ (convergence criterion) **do**
- 6: Set $t := t + 1$.
- 7: Calculate $p_{\mu_\zeta}^{l*}$ for u_ζ, l using (7) and update the lagrangian multipliers (see Appendix B).
- 8: Calculate the aggregated achievable network rate as $R_\zeta(t) := \sum_{u_\zeta} R_{u_\zeta}(t)$.
- 9: **end while**

Step 3: Assign resources

- 10: Assign RB and transmit power to associated UEs and calculate the average achievable data rate.
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Statement 1: (a) The power allocation for UE u_ζ on RB l is given by:

$$p_{u_\zeta}^{l*} = \frac{\mu_{u_\zeta}^{l*}}{x_{u_\zeta}^{l*}} = [\delta_{u_\zeta}^l - \frac{\sigma^2}{h_{u_\zeta}^l}]^+, \quad (7)$$

where $\delta_{u_\zeta}^l = \frac{\frac{1}{2} B_{RB} \frac{(w_{u_\zeta} + \phi_{u_\zeta})}{\lambda_{u_\zeta}}}{\lambda_{u_\zeta}}$ and $q^+ = \max\{q, 0\}$.

(b) The RB allocation is given as follows:

$$x_{u_\zeta}^{l*} = \begin{cases} 1, & \rho_l \leq \xi_{u_\zeta}^l \\ 0, & \rho_l > \xi_{u_\zeta}^l \end{cases} \quad (8)$$

and

$$\xi_{u_\zeta}^l = \frac{1}{2} (w_{u_\zeta} + \phi_{u_\zeta}) B_{RB} [\log_2(1 + \frac{\mu_{u_\zeta}^l h_{u_\zeta}^l}{x_{u_\zeta}^l \sigma^2}) - v_{u_\zeta}^l], \quad (9)$$

where $v_{u_\zeta}^l = \frac{\mu_{u_\zeta}^l \gamma_{u_\zeta}^l}{(x_{u_\zeta}^l \sigma^2 + \mu_{u_\zeta}^l \gamma_{u_\zeta}^l) \ln 2}$ and $\gamma_{u_\zeta}^l = \frac{h_{u_\zeta}^l}{\sigma^2}$.

Proof. See Appendix A. \square

Proposition 1. A globally optimal solution of the problem P1 can be obtained by $(x_{u_\zeta}^{l*}, p_{u_\zeta}^{l*})$.

Proof. The solution $(x_{u_\zeta}^{l*}, p_{u_\zeta}^{l*})$, due to the fact that P2 is a relaxed version of P1, can give an upper bound to P1. On the other hand, a lower bound of P1 can be obtained by P2. It is because the fact that expressions in (7) and (8) satisfy all P1's constraints due to $x_{u_\zeta}^{l*}$ assures the binary constraints in P1. \square

IV. PROPOSED OPTIMAL ALGORITHM

A. Joint RB and Power Allocation Algorithm

The eNB allocates resources to the associated UEs in its coverage area. Algorithm 1 provides the joint RB and power allocation in summary.

Unlike Layer 1 (L1) and Layer 2 (L2) relays in [19], the L3 relays such as an eNB can apply their own scheduling. These relays are able to gather scheduling required information such as the energy consumption at the other relays, link gain information, etc.

B. Complexity of the Proposed Algorithm

Proposition 2. The proposed algorithm uses a gradient-based manner with a small step size to update the variables in (B.1) - (B.3). Number of successive iterations is achieved when the difference of two respectively sum-rates is less than an arbitrary $\epsilon > 0$. Thus, it can be said that the computation complexity at each iteration is a polynomial in $|\Omega_\zeta|$ and L .

Proof. See Appendix C. \square

V. PERFORMANCE EVALUATION

A. Simulation Parameters and Assumptions

In this section, we evaluate the performance of the proposed resource allocation scheme. Our simulation model and assumptions used for obtaining the numerical results are based on [24]. The channels between each UE and relay and between relay and eNB follow the following path-loss equation, respectively:

$$PL_{L_{su_\zeta}, s}(d)_{[dB]} = 103.8 + 20.9 \log(d) + L_{su_\zeta} + 10 \log(\varrho), \quad (10)$$

$$PL_{\zeta, eNB}(d)_{[dB]} = 100.7 + 23.7 \log(d) + L_{s\zeta} + 10 \log(\varrho), \quad (11)$$

where d is the links distance in kilometer, L_{su_ζ} and $L_{s\zeta}$ are log-normal random fading channel and are represented by an exponential variables for modeling shadow fading, respectively; ϱ is the power gain of Rayleigh distributed random variable.

The results are obtained by averaging over 100 realizations of the simulation scenarios i.e., UE locations and link gains. The distance between M2M UE and relay node is denoted by D_r which is a simulation parameter in this simulation. The M2M UEs are uniformly distributed in the perimeter of a circle with radius D_r . For each UE, the delay QoS exponent $\theta_{u_\zeta}^T$ constraint is a random value in the interval $[10^{-6}, 10^0]$.

B. Results

Fig. 2 shows the convergence behavior of the proposed algorithm when $a = 0.001$ and $a = 0.01$. For convergence, the step size should be selected carefully. We consider the same step size for all the Lagrange multipliers, i.e., for any Lagrange multiplier β , step size at iteration t is calculated as $k_\beta^{(t)} = \frac{a}{\sqrt{t}}$, where a is a small constant. It is clear from this figure that when a is sufficiently small, the algorithm converges very quickly i.e., in less than 20 iterations, to the optimal solution.

In Fig. 3, we compare the performance of Algorithm 1 under different M2M UE-relay distances when the number of M2M devices increases. The average achievable data rate R_{ave} for

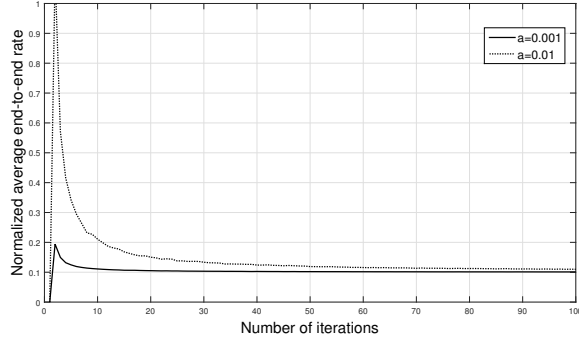


Fig. 2: Convergence behaviour of the proposed algorithm: number of cellular and M2M devices are 15 and 25 ($|K| = 15, |M| = 25$), respectively. The average end-to-end rate is calculated by $\frac{R_c}{|U_c|}$, the distance of UE from relay, $D_r = 60$ meter.

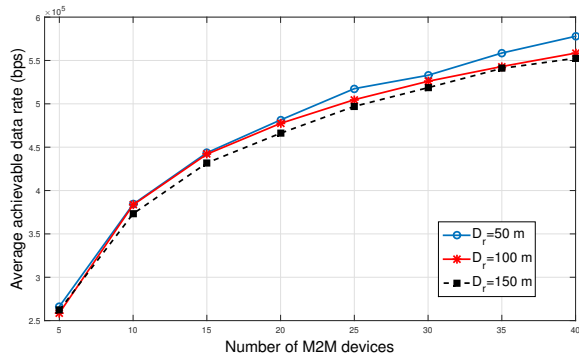


Fig. 3: Performance of the proposed algorithm under different M2M UE-relay distances when the number of cellular UEs is 10 ($|K| = 10$).

M2M links is calculated as $R_{ave} = \frac{\sum_{u \in M} R_u^{ach}}{|M|}$, where R_u^{ach} is the achievable data rate for link u and $|\cdot|$ denotes the set cardinality.

Fig. 4 shows the behavior of the proposed resource allocation approach in terms of the achievable aggregated data rate under different number of M2M UEs and different relay-M2M UE distance. As can be seen from this figure, the proposed relaying scheme handles even large relay-M2M UE distances, e.g., $D_r \geq 75m$ with considerable achievable rate. To evaluate the performance of our method under moderately and densely situation of network, we vary the number of M2M UEs. It can be seen from Fig. 3 that the achievable rate increases with increasing the number of M2M devices and decreasing the M2M UE-relay distances.

Fig.5 compares the proposed scheme with reference scheme [24] which is ignored traffic priorities effect on simulation results. The graph associated with the proposed algorithm is obtained by averaging of the achievable rate under various delay QoS exponent values. As can be seen from this figure, with increasing the number of M2M UEs, our proposed approach in addition to guarantees the exponent QoS requirements, can performs close to reference scheme with the same complexity.

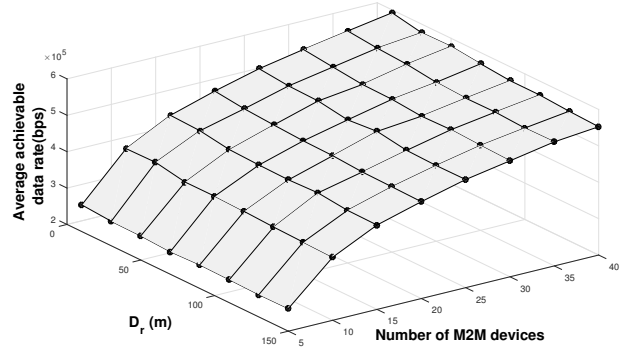


Fig. 4: Achievable aggregated data rate under different number of M2M UEs and different relay-M2M UE distance when the number of cellular UEs is 10 ($|K| = 10$).

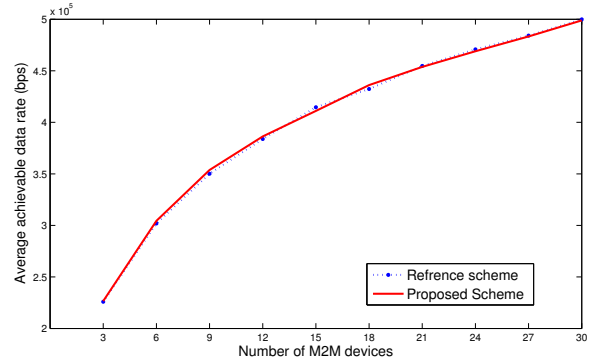


Fig. 5: Comparison of the proposed scheme with reference scheme. The proposed scheme results by averaging on the various delay QoS exponent values in the interval $[10^{-6}, 10^0]$.

VI. CONCLUSION

In this paper, we have investigated the optimal delay-sensitive resource allocation in LTE networks for relay-aided M2M communication. To allocate radio resources efficiently, we have formulated the resource allocation problem under minimum data rate and statistical delay QoS constraints and we investigated the convexity of the problem. Numerical results have shown that the proposed design is mostly considered as the suitable solution for delay limited applications with constraints on energy consumption of the system.

APPENDIX A

POWER AND RB ALLOCATION FOR THE NOMINAL PROBLEM

We use Karush-Kuhn-Tucker (KKT) Theorem in order to observe the optimality of power allocation for a UE. The Lagrangian function is defined in (A.1), where ρ, λ, ϕ , respectively are the vectors of multipliers associated with assigned resources i.e. RB and transmit power, and individual QoS requirements for UEs. Differentiating (A.1) with respect to $\mu_{u_c}^l$ and $x_{u_c}^l$, respectively gives the expressions (7) and (8) for power and RB allocation.

$$\begin{aligned}
L(X, \mu, \rho, \lambda, \phi) = & - \sum_{u_\zeta=1}^{\Omega_\zeta} w_{u_\zeta} \sum_{l=1}^L \frac{1}{2} x_{u_\zeta}^l B_{RB} \log_2 \left(1 + \frac{\mu_{u_\zeta}^l h_{u_\zeta}^l}{x_{u_\zeta}^l \sigma^2} \right) \\
& + \sum_{l=1}^L \rho_l \left(\sum_{u_\zeta=1}^{\Omega_\zeta} x_{u_\zeta}^l - 1 \right) + \sum_{u_\zeta=1}^{\Omega_\zeta} \lambda_{u_\zeta} \left(\sum_{l=1}^L \mu_{u_\zeta}^l - P_{u_\zeta}^{\max} \right) \\
& + \sum_{u_\zeta=1}^{\Omega_\zeta} \phi_{u_\zeta} \left(R_{\min, u_\zeta} - \sum_{l=1}^L \frac{1}{2} x_{u_\zeta}^l B_{RB} \log_2 \left(1 + \frac{\mu_{u_\zeta}^l h_{u_\zeta}^l}{x_{u_\zeta}^l \sigma^2} \right) \right) \quad (\text{A.1})
\end{aligned}$$

APPENDIX B

UPDATE OF VARIABLES AND LAGRANGE MULTIPLIERS

After that the $\rho_{u_\zeta}^{l*}$ and $x_{u_\zeta}^l$ are obtained, by using expressions (B.1) - (B.3), the variables at the $(t+1)$ -th iteration are updated, where k_β^t is the small step size at iteration t for variable β .

APPENDIX C

COMPLEXITY ANALYSIS

Consider $|\Omega_\zeta|L$ computations are needed to find the gains and if T_{\max} iterations to be enough in order to convergence of the algorithm, then it can be said that the overall complexity of the applied scheme is $O(|\Omega_\zeta|L + T|\Omega_\zeta|L)$.

Consider $\beta(0)$ is in the interval $[0, \beta_{\max}]$ for any Lagrange multiplier β . Then it can be said that β_{\max} is upper bound of the distance between $\beta(0)$ and β^* . Also, the upper bound of the distance between the current best objective and the optimum objective at iteration t can be driven by $\frac{\beta_{\max}^2 + \beta(t)^2 \sum_{i=1}^t k_\beta^{(i)^2}}{2 \sum_{i=1}^t k_\beta^{(i)}}$. If the variables updating step size are considered with $k_\beta^{(i)} = \frac{a}{\sqrt{i}}$, where a is an arbitrary small constant, then for convergence the bound less than ε , $O(\frac{1}{\varepsilon^2})$ iterations are required [25]. Hence, the overall complexity of the proposed algorithm is $O(|\Omega_\zeta|L + \frac{|\Omega_\zeta|L}{\varepsilon^2})$.

$$\rho_l(t+1) = [\rho_l(t) + k_{\rho_l}^t \left(\sum_{u_\zeta=1}^{\Omega_\zeta} x_{u_\zeta}^l - 1 \right)]^+, \quad (\text{B.1})$$

$$\lambda_{u_\zeta}(t+1) = [\lambda_{u_\zeta}(t) + k_{\lambda_{u_\zeta}}^t \left(\sum_{l=1}^L \mu_{u_\zeta}^l - P_{u_\zeta}^{\max} \right)]^+, \quad (\text{B.2})$$

$$\phi_{u_\zeta}(t+1) = [\phi_{u_\zeta}(t) + k_{\phi_{u_\zeta}}^t \left(R_{\min, u_\zeta} - \sum_{l=1}^L \frac{1}{2} x_{u_\zeta}^l B_{RB} \log_2 \left(1 + \frac{\mu_{u_\zeta}^l h_{u_\zeta}^l}{x_{u_\zeta}^l \sigma^2} \right) \right)]^+. \quad (\text{B.3})$$

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