Boosting Energy Efficiency of NB-IoT Cellular Networks Through Cooperative Relaying

Davide Di Lecce[1], Alessandro Grassi[1,2], Giuseppe Piro[1,2] and Gennaro Boggia[1,2]
[1]Dept. of Electrical and Information Engineering, Politecnico di Bari, Bari, Italy
[2] CNIT, Consorzio Nazionale Interuniversitario per le Telecomunicazioni
{name.surname}@poliba.it

***Abstract*—NarrowBand Internet of Things (NB-IoT) is a novel radio interface proposed by the Third Generation Partnership Project for addressing the challenging requirements of Machine-Type Communications through a mobile network architecture. Although it natively promises an impressive battery lifetime to constrained devices, advanced methodologies that further reduce energy consumptions are still required. To this aim, this work investigates an extended NB-IoT architecture, embracing the cooperative relaying paradigm. It formulates an optimal relay selection algorithm that minimizes the overall amount of energy consumed in a NB-IoT cell. In addition, it proposes a greedy algorithm able to reach the same goal with a lower computational complexity. System level simulations clearly demonstrate that the adoption of the proposed cooperative relaying paradigm brings to an energy saving up to 30%. Moreover, the greedy approach registers energy consumptions which are only 10% higher than the optimal strategy.**

***Index Terms*—NB-IoT, cooperative relaying, optimization problem, energy consumption**

I. INTRODUCTION

Machine Type Communication (MTC) is becoming dominant in the current Internet landscape [1] [2]. Differently from conventional communications, MTC devices typically operate autonomously, i.e., without the human intervention, sporadically produce small amounts of data while frequently generating bursts of heavy traffic load when deployed in thousands within a geographical area served by a given base station [3] [4]. To properly address MTC requirements, the Third Generation Partnership Project (3GPP) standardized with the Release 13 a novel radio communication technology, namely NarrowBand IoT (NB-IoT) [5]. This solution exploits a narrowband channel, simplifies the hardware design, and grants an extended coverage to devices experiencing poor reception conditions [6]. Even if the battery lifetime promised by NB-IoT is impressive, it could significantly vary depending on the position of the node moving from the cell center to the edge. Devices far away from the base station can successfully transmit packets by using robust Modulation and Coding Scheme (MCS) and several retransmissions. But, this negatively impacts to their energy consumptions.

In literature, it has been already demonstrated how cooperative relaying techniques, based on device-to-device communications, are able to optimize the performance of wireless networks [7]. Such an approach was investigated in the NB-IoT context for optimizing end-to-end delay [8], improving communication security [9], and extending the network coverage through connected vehicles [10]. Nevertheless, at the time of this writing and to the best of the authors' knowledge, no contributions already envisaged the possibility to exploit cooperative relaying for energy-saving purposes.

Starting from the main technological facets of NB-IoT, the work presented herein formulates a novel approach that optimally configures relay-aided communications in a typical MTC scenario, minimizing the overall amount of energy consumed by devices attached to a serving base station. In addition, a greedy algorithm is properly conceived for reaching a satisfactory management of relay nodes, without requiring high computational efforts like the aforementioned optimal strategy. The performance of both optimal and greedy approaches has been evaluated with system level simulations, modeling realistic NB-IoT scenarios with different traffic load scenarios. Obtained results clearly show that relay-aided communications in the NB-IoT air interface produce an energy saving up to 30% with respect to conventional communication techniques. Also, the greedy approach achieves an overall energy consumption that is, on average, only 10% higher than the optimal strategy.

The rest of the paper is organized as it follows: Sec. II presents the state of the art on both NB-IoT and relaying, Sec. III describes the proposed techniques, Sec. IV discusses the simulation's results. Then, Sec. V concludes the paper by sketching future research directions.

II. STATE OF THE ART ON NB-IOT AND RELAYING

NB-IoT works considering a system bandwidth of 180 kHz for both downlink and uplink [5]. When a higher capacity is needed, additional channels can be exploited as secondary carriers. Its main features (e.g., physical layer based on Orthogonal Frequency Division Multiplexing, numerologies, channel modulation, coding schemes and higher layer protocols) are inherited from the Long Term Evolution (LTE) technology.

In downlink, NB-IoT adopts a subcarrier spacing equal to $\Delta f = 15$ kHz, resulting in 12 subcarriers (simply referred to as *tones*) per carrier. Similarly to LTE, a single transmission leverages all the 12 subcarriers lasting 1 ms [11]. In uplink, instead, a different approach is introduced: the subcarrier spacing can be set to $\Delta f = 15$ kHz or $\Delta f = 3.75$ kHz and a user equipment can either use *Single-Tone* or *Multi-Tone* transmission techniques. That is, the number of tones exploited by each transmission (n_T), the slot duration and the number of users that may be scheduled at the same time within a 180 kHz bandwidth can be selected among the settings reported in Tab. I. As a consequence, the conventional resource block concept cannot be applied to the uplink. Instead, NB-IoT defines a Resource Unit (RU) as the smallest element that maps a transport block [12].

With respect to output transmission power, three classes of devices are specified in [13]: class 3 with a maximum output power of 23 dBm ± 2 dB of tolerance, class 5 with 20 dBm ± 2 dB, and class 6 with 14 dBm ± 2.5 dB (see Release 14). While the first one is directly inherited from LTE, the other two classes further reduce the connectivity impact on the battery lifetime.

TABLE I: Uplink Resource Units in NB-IoT.

Transmission mode	**# of tones n_T**	**Δf [kHz]**	**Slot duration [ms]**	**# of schedulable devices in 180 kHz**
Single-Tone	1	3.75	32	48
	1	15	8	12
Multi-Tone	3	15	4	4
	6	15	2	2
	12	15	1	1

A. Relaying

According to the cooperative networking paradigm, mobile terminals can help each other by relaying information towards the base station. This is done by establishing device-to-device links, without increasing infrastructure costs for the network operator [14]. Few contributions started to explore its adoption in the NB-IoT context. In [9], for example, the authors investigate the potential benefits of direct communication among devices for enabling cooperative content upload through short-range multihop relaying. In [10], the positive effects of vehicle-based relays on network performance, expressed in terms of connection reliability, transmission latency, and communication energy efficiency, are outlined. Dynamic programming-based algorithms for optimizing the delivery ratio and the end-to-end delay in typical NB-IoT deployments are proposed in [8].

The possibility to apply the device-to-device relaying concept for energy-saving purposes in NB-IoT scenarios has not been addressed in the current literature yet. Therefore, differently from the contributions previously summarized, the this work envisages that intermediate nodes can act as relays and can cooperate for delivering data from source devices to the base station, while consuming less energy.

III. OPTIMAL AND GREEDY RELAY SELECTION

In a communication system in which both direct device to base station and device to device communication types are allowed, the main challenge is to perform the relay node selection in the most efficient way.

The reference scenario considered in this contribution is depicted in Fig. 1. A single cell NB-IoT network is taken into account, where N different MTC devices are uniformly distributed in the coverage area of the base station and maintain a fixed position during an observation period T. Without loss of generality, these devices are classified into two categories: *active* (they have data to transmit during T) and *idle* (they have nor data to transmit nor data to receive during T). In a MTC scenario there is a massive number of devices typically sending data, rather than receiving it. Thus, the analysis is restricted to the uplink transmissions only. It is assumed that idle devices can act as relay nodes, thus enabling a two-hop communication path between devices at the cell edge and the base station. For the sake of simplicity, each relay node can assist only one remote terminal.

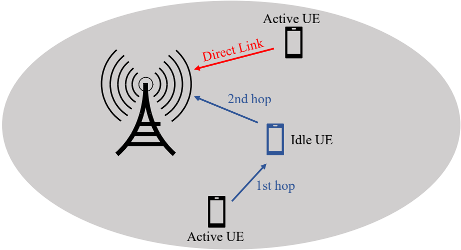


Figure 1: Reference scenario.

According to the 3GPP specifications [5], different MCSs can be used at the physical layer and the resulting Transport Block Size (TBS) is obtained as a function of the MCS index and the number of RUs assigned to the uplink transmission (see Tab. II). The MCS index is generally selected by taking into account the channel quality experienced by the MTC device. Due to the absence of standardized procedures for the MCS selection, based for instance on the knowledge of BLock Error Rate (BLER) curves, the coverage area of the reference scenario is divided into equally wide concentric zones. Thus, MCS indexes are distributed across the cell, becoming inversely related to the distance between the device and the base station.

For a direct communication link, only one MCS index is selected. Let $I_{i,0}$ be the MCS index assigned to the i-th device for transmitting data to the base station. When the distance between the i-th device and the base station increases, a more robust MCS index with higher redundancy is selected. Conversely, two MCS indexes have to be considered when a relay-aided communication is established. The device at the cell edge (i.e., an active device) and the relay node (i.e., an idle device) are denoted with i and j respectively. Thus, $I_{i,j}$ is the MCS index selected for the transmission link between node i and relay j; whereas $I_{j,0}$ is the MCS index used by relay j to transmit packets to the base station. It is worth noting that $I_{i,j}$ is identified by centering the concentric zones on the node j, rather than the base station.

TABLE II: TBS Table (additional MCS indexes for Multi-Tone are reported in gray).

MCS index	RUs							
	1	2	3	4	5	6	8	10
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	680
5	72	144	224	328	424	504	680	872
6	88	176	256	392	504	600	808	1000
7	104	224	328	472	584	712	1000	1224
8	120	256	392	536	680	808	1096	1384
9	136	296	456	616	776	936	1256	1544
10	144	328	504	680	872	1000	1384	1736
11	176	376	584	776	1000	1192	1608	2024
12	208	440	680	1000	1128	1352	1800	2280
13	224	488	744	1032	1256	1544	2024	2536

A. *Optimal relay selection*

Let P and t_s be the transmission power and the slot duration, respectively. In addition, let N_i and N_a be the number of idle and active devices, respectively.

As first step, it is supposed that the device i has data to transmit to the base station. By jointly considering the coverage zone where the device is located, the related MCS index $I_{i,0}$, the amount of data to transmit and the TBS values reported in Tab. II, it is possible to compute the amount of RUs to be used at the physical layer, that is $R_{i,0}$. Indeed, the amount of energy required to transmit data from device i to the base station, $E_{i,0}$, can be expressed as: $E_{i,0} = P \cdot R_{i,0} \cdot t_s$.

When a relay-aided communication is considered, it is necessary to calculate the amount of energy consumed for the transmission between device i and relay j, $E_{i,j}$, as well as the amount of energy spent on the link between relay j and base station, $E_{j,0}$. In line with the approach described before, it is possible to write: $E_{i,j} = P \cdot R_{i,j} \cdot t_s$ and $E_{j,0} = P \cdot R_{j,0} \cdot t_s$. In this case, $R_{i,j}$ represents the number of RUs required to transmit data from node i and relay j; whereas $R_{j,0}$ is the number of RUs required to transmit data from relay j to the base station. By generalizing, the amount of energy consumed within a NB-IoT network for delivering data packets generated by device i, that is $\bar{E}_i$, can be expressed as:

$$\bar{E}_i = \alpha_i E_{i,0} + \sum_{j=1}^{N_i} \beta_{i,j} \left(E_{i,j} + E_{j,0} \right), \tag{1}$$

where α_i and $\beta_{i,j}$ are binary coefficients. In particular, $\alpha_i = 1$ when the i-th device transmits its data directly to the base station. Conversely, $\beta_{i,j} = 1$ when the i-th device employs the j-th device as a relay node.

Therefore, the total amount of energy spent within the considered scenario with N_a active devices and N_i idle devices, E_{TOT}, is:

$$E_{TOT} = \sum_{i=1}^{N_a} \bar{E}_i = \sum_{i=1}^{N_a} \left(\alpha_i E_{i,0} + \sum_{j=1}^{N_i} \beta_{i,j} (E_{i,j} + E_{j,0}) \right)$$

The optimal relay selection approach should aim at minimizing E_{TOT}. Therefore, the resulting optimization problem can be formulated as:

$$\min_{\alpha_i, \beta_{i,j}} \quad \sum_{i=1}^{N_a} \left(\alpha_i E_{i,0} + \sum_{j=1}^{N_i} \beta_{i,j} \left(E_{i,j} + E_{j,0} \right) \right) \tag{2}$$

$$\text{subject to} \quad \begin{cases} \alpha_i \in \{0,1\} & \forall i, \\ \beta_{i,j} \in \{0,1\} & \forall i, \forall j, \\ \alpha_i + \sum_{j=0}^{N_i} \beta_{i,j} = 1 & \forall i. \end{cases}$$

The constraint $\alpha_i + \sum_{j=0}^{N_i} \beta_{i,j} = 1$ implies that: (i) when a relay-aided communication is established, the direct link between node i and base station is not allowed at all; (ii) only one idle device can be selected as relay.

B. *Greedy approach*

It is important to note that the optimization problem described in Eq. (2) is non-trivial: a high computational effort is required to find a solution. For this reason, a greedy and low complexity algorithm is conceived herein. First, it assumes that device positions are known a priori. Then, it starts from the intuitive consideration that devices at the cell edge may obtain significant energy saving when relay nodes are used.

According to the procedure depicted in Fig. 2, the algorithm sorts active devices by decreasing distance to the base station and for each of them it calculates the amount of energy needed to send data through a direct link. Starting from the farthest device, the algorithm tries to select a suitable relay node among the idle devices. To this end, it only considers idle devices whose distance with respect to the considered active device is smaller than the distance between the active device and the base station. Hence, the amount of energy consumed by the two-hop transmission link is calculated. Finally, the relay node is selected by choosing the idle device that grants the largest energy saving. If the amount of energy consumed by any two-hop transmission link is higher than the one estimated for the direct communication, no relay is selected for the considered active device. The procedure is repeated for each active user, until no further idle devices are available for relaying purposes. The complexity is evaluated as follows: the algorithm considers all the active users, and for each one it verifies the possibility to select one of the idle users as a relay node. Thus, given the double loop executed by the overall approach, it is possible to conclude that the complexity of the algorithm is equal to $O(N_i N_a)$

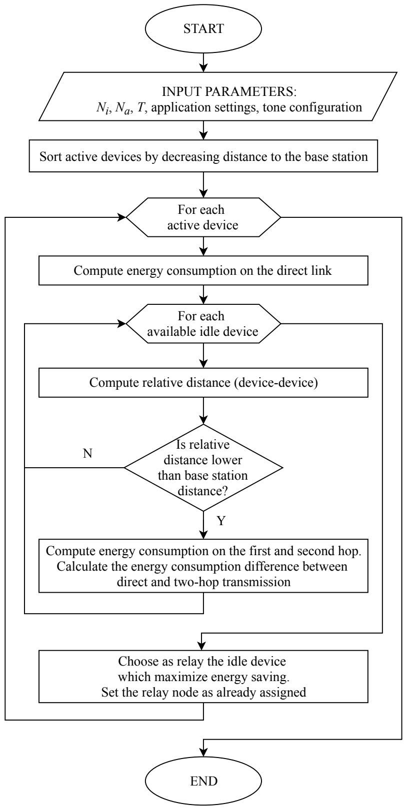
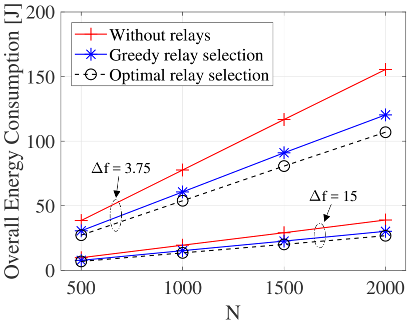


Figure 2: Flowchart describing the greedy algorithm.

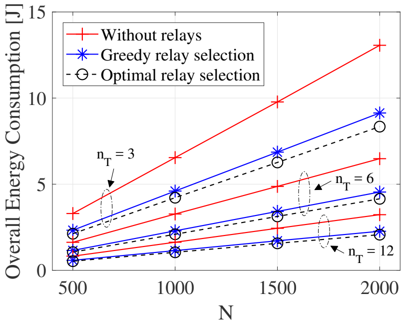
IV. NUMERICAL RESULTS

The performance of the proposed methodology has been evaluated through system level simulations. A NB-IoT scenario with one base station and a variable number of users (up to 2000) uniformly distributed within a cell is modeled in Matlab. All the devices belong to the power class 3 and no power control is applied. In order to satisfy a minimum receiving sensitivity when the total transmission power is set to $P = 23$ dBm, the macro-cell propagation model for urban areas [15] is considered, the penetration loss is set to 10 dB and the cell radius is set to 4 km. Only a subset of devices (i.e., 1/3 and 1/2) is configured as active. These terminals generate a 20 byte long packet every 600 s [16] to model typical NB-IoT services, like outdoor and indoor sensors providing motion detection, alarm systems, or monitor systems measuring gas, water and heating parameters. All configurations for both Single-Tone and Multi-Tone are investigated and each simulation considers an observation period of 300 s. To reduce the impact of statistical fluctuations, reported results have been averaged across 40 different runs.

The overall energy consumptions are reported in Figs. 3a-4b. As expected, the amount of energy spent within the NB-IoT network always increases with the number of active devices. In fact, the higher the number of nodes with data to transmit, the higher the number of physical transmissions to be handled across the NB-IoT radio interface. Moreover, all tests demonstrate that the usage of relay nodes in any case produces an energy saving spanning from 12% (in the Single-Tone configuration with $\Delta f = 15$ kHz and $1/2$ of active devices) up to 30% (in the Multi-Tone configuration with $n_T = 12$ and $1/3$ of active devices).



(a) Single-Tone configuration.

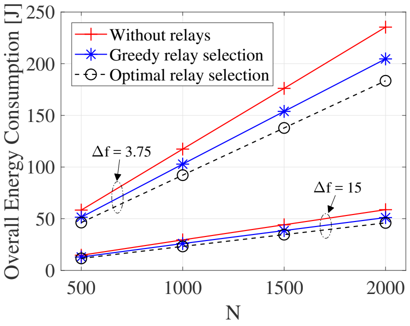


(b) Multi-Tone configuration.

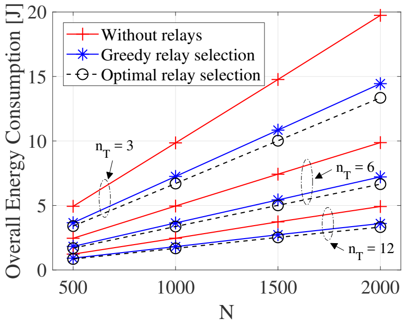
Figure 3: Energy consumption with 1/3 of active devices.

With reference to the Single-Tone configuration (Fig. 3a and Fig. 4a), it is possible to observe that better performance are registered when a higher value of the subcarrier space is set. In fact, when $\Delta f = 15$ kHz, the shorter time slot duration allows the transmission of a given burst of data in a lower amount of time. With any Multi-Tone configuration (Fig. 3a and Fig. 4b), it is possible to reach a reduction of the energy consumption equal to one order of magnitude. According to Tab. I, Multi-Tone configurations generally use a lower time slot duration with respect to the Single-Tone case. This ensures the transmission of a given burst of data in an even lower amount of time. Of course, better performance is registered when the number of tones used by a single transmission increases. In that case, in fact, devices are able to send their data by using a smaller time interval.

Finally, obtained results also highlight that the conceived greedy approach offers sub-optimal solutions. Tab. III shows that the overall energy consumption registered by the greedy approach is 10% higher than the optimal strategy on average. Definitively, such a simple algorithm is still able to provide satisfactory results, which are not too far from those achievable by using an optimal, but extremely complex, solution.



(a) Single-Tone configuration.



(b) Multi-Tone configuration.

Figure 4: Energy consumption with 1/2 of active devices.

TABLE III: Performance degradation of the greedy vs. optimal algorithm, expressed in percentage [%].

Configuration			**N**			
			500	**1000**	**1500**	**2000**
1/3 of active devices	Single-Tone	Δf = 3.75	11.7	11.9	11.9	12
		Δf = 15	11.4	12	12	12.1
	Multi-Tone	$n_T = 3$	9.2	8.8	9.1	9.1
		$n_T = 6$	8.9	9	8.9	9
		$n_T = 12$	9.3	9	9	9.1
1/2 of active devices	Single-Tone	Δf = 3.75	10.6	11	11	10,9
		Δf = 15	11	11.1	10.8	10.6
	Multi-Tone	$n_T = 3$	7.4	7.9	7.9	7.9
		$n_T = 6$	7.6	7.9	8.1	8.1
		$n_T = 12$	7.2	7.8	7.8	8

V. CONCLUSION

This work investigated the adoption of cooperative relaying techniques in NB-IoT. It formulated an optimal relay selection that minimizes the amount of energy consumed in the overall network and conceived a greedy algorithm that reaches sub-optimal (but very satisfying) performance with a lower computational complexity. System level simulations clearly highlighted the improvements achieved exploiting the proposed methodology in different NB-IoT network configurations, with different traffic loads and physical settings. Future research activities aim at extending the performance evaluation to other metrics of interest (like throughput and delays), while considering more realistic communication models, power control mechanisms, packet scheduling and retransmission functionalities.

ACKNOWLEDGEMENTS

This work was framed in the context of the project SymbIoTe, which receives funding from the European Union's Horizon 2020 research and innovation programme under grant agreement 688156. It has also been partially funded by the FFABR fund (by the Italian MIUR).

REFERENCES

[1] Cisco, "The Zettabyte Era: Trends and Analysis," White Paper, Jun. 2017.

[2] H. Malik, H. Pervaiz, M. M. Alam, Y. Le Moullec, A. Kuusik, and M. A. Imran, "Radio resource management scheme in nb-iot systems," *IEEE Access*, vol. 6, pp. 15 051–15 064, 2018.

[3] T. Taleb and A. Kunz, "Machine type communications in 3GPP networks: potential, challenges, and solutions," *IEEE Communications Magazine*, vol. 50, no. 3, 2012.

[4] M. S. Mahmoud and A. A. Mohamad, "A study of efficient power consumption wireless communication techniques/modules for internet of things (iot) applications," 2016.

[5] 3GPP, "E-UTRA; Physical layer procedures (Release 15)," TS 36.213, Dec. 2017.

[6] G. Naddafzadeh-Shirazi, L. Lampe, G. Vos, and S. Bennett, "Coverage enhancement techniques for machine-to-machine communications over LTE," *IEEE Communications Magazine*, vol. 53, no. 7, 2015.

[7] S. Wen, X. Zhu, Y. Lin, Z. Lin, X. Zhang, and D. Yang, "Achievable transmission capacity of relay-assisted device-to-device (D2D) communication underlay cellular networks," in *Proc. of IEEE Vehicular Technology Conference (VTC Fall)*, 2013.

[8] Y. Li, K. Chi, H. Chen, Z. Wang, and Y. h. Zhu, "Narrowband Internet of Things Systems with Opportunistic D2D Communication," *IEEE Internet of Things Journal*, 2017.

[9] L. Militano, A. Orsino, G. Araniti, M. Nitti, L. Atzori, and A. Iera, "Trusted D2D-based data uploading in in-band narrowband-IoT with social awareness," in *Proc. of IEEE Annual Int. Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2016.

[10] V. Petrov, A. Samuylov, V. Begishev, D. Moltchanov, S. Andreev, K. Samouylov, and Y. Koucheryavy, "Vehicle-Based Relay Assistance for Opportunistic Crowdsensing over Narrowband IoT (NB-IoT)," *IEEE Internet of Things Journal*, 2017.

[11] M. Sauter, *From GSM to LTE-Advanced Pro and 5G: An Introduction to Mobile Networks and Mobile Broadband*. Wiley, 2017.

[12] 3GPP, "E-UTRA and E-UTRAN; Overall description; Stage 2 (Release 15)," TS 36.300, Dec. 2017.

[13] 3GPP, "E-UTRA; User Equipment (UE) radio transmission and reception (Release 15)," TS 36.101, Dec. 2017.

[14] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions," *IEEE Communications Magazine*, vol. 52, no. 5, 2014.

[15] 3GPP, "BS radio transmission and reception (Release 15)," TS 36.104, Dec. 2017.

[16] R. Ratasuk, J. Tan, and A. Ghosh, "Coverage and Capacity Analysis for Machine Type Communications in LTE," in *Proc. of IEEE Vehicular Technology Conference (VTC Spring)*, 2012.