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Reliable Machine-to-Machine Multicast Services with Multi-Radio Cooperative Retransmissions

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Abstract The 3GPP is working towards the definition of service requirements and technical solutions to provide support for energy-efficient Machine Type Communications (MTC) in the forthcoming generations of cellular networks. One of the envisioned solutions consists in applying group management policies to clusters of devices in order to reduce control signaling and improve upon energy efficiency, e.g., multicast over-the-air (OTA) firmware updates. In this paper, a Multi-Radio Cooperative Retransmission Scheme is proposed to efficiently carry out multicast transmissions in MTC networks, reducing both control signaling and improving energy-efficiency. The proposal can be executed in networks composed by devices equipped with multiple radio interfaces which enable them to connect to both a cellular access network, *e.g.,* LTE, and a short-range MTC area network, *e.g.,* Low-Power Wi-Fi or ZigBee, as foreseen by the MTC architecture defined by ETSI. The main idea is to carry out retransmissions over the M2M area network upon error in the main cellular link. This yields a reduction in both the traffic load over the cellular link and the energy consumption of the devices. Computer-based simulations with ns-3 have been conducted to analyze the performance of the proposed scheme in terms of energy consumption and assess its superior performance compared to non-cooperative retransmission schemes, thus validating its suitability for energy-constrained MTC applications.

Keywords Machine-to-Machine · Machine Type Communications · Multi-Radio Cooperation · Cooperative ARQ · Energy Efficiency.

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1 Introduction

Machine Type Communications (MTC) or Machine-to-Machine (M2M) communication refers to the exchange of data between automated devices without (or minimal) human intervention. This kind of communication between devices can facilitate a wide range of smart applications, e.g., smart building and automation, telemetry, e-health, smart cities, or smart grids, among many others. The main goal of M2M networks is thus to provide End-To-End (E2E) connectivity between the sensor devices collecting data, e.g., environmental measurements or detection of events, on one end, and an M2M server running the applications on the other end. From the market and business points of view, predictions suggest a huge potential growth in the mobile M2M share during the forthcoming years [1]. From the technological point of view, there are many challenges ahead to get to efficient and standardized M2M networks. These cover from the management of huge number of devices to the extremely low-energy consumption required to ensure the long lifetime of networks.

International organizations and fora, such as the 3GPP [2], study the impact that M2M traffic will cause to the current and future networks. Existing networks were mainly designed to handle the requirements imposed by Human-to-Human (H2H) communications – Human-based traffic is characterized by low transmission delay tolerance, high throughput requirements, and asymmetric traffic dominated by uplink transmissions [3]. Instead, M2M traffic is very heterogeneous in terms of delay tolerance, priority, and periodicity requirements. In addition, the majority of M2M applications will just need to transmit very short data messages, in contrast to the long data streams associated to the majority of H2H applications, e.g., video streaming or multimedia transmissions[1]. Therefore, communication networks shall be redesigned to meet the requirements of M2M applications without jeopardizing the quality of service offered to H2H communications [4].

Among other challenges, the enhancement of the energy-efficiency of today's networks is fundamental to ensure the success of M2M applications. Today, cellular communication standards are becoming more powerful and flexible, but also more complex, thus requiring increasing energy consumption on the terminal side [5]. Unfortunately, low-cost autonomous M2M devices require extremely low-power operation to ensure that, once deployed, they can operate for several years. For this reason, the research community is making significant efforts to redesign cellular networks in order to make them considerably more efficient and suitable for M2M. One particular way of contributing to the improvement of the energy-efficiency of cellular networks consists in providing them with reliable methods to multicast critical information with minimum amount of resources. This is the main motivation for the work presented in this paper.

A reliable multicast service implies a guaranteed reception by all ends. To achieve this, the sender entity, i.e., the transmitter, must confirm that the transmitted data has been correctly received at the intended destination. Some mechanisms, like Forward Error Correction (FEC), can help in error recovery at end devices by encoding redundant information within the data messages. Nevertheless, errors may be unrecoverable in harsh channel conditions. In terms of energy efficiency, FEC may lead to resource wastage as the amount of redundancy added is typically set to help the receiver in the worst expected channel conditions. Another technique to provide error control is Automatic Repeat reQuest (ARQ). This consists in using explicit acknowledgements (ACK) or negative ACKs (NACKs) to indicate the correct or incorrect reception of a data message, respectively. If the sender receives a NACK (or does not receive an expected ACK) it will retransmit the data along the same transmission channel. Hence, it provides a reliable service over an unreliable channel.

The result of combining FEC and ARQ is known as Hybrid Automatic Repeat request (HARQ) [6]. In this case, data is encoded with a FEC code and parity bits are sent, either together with the data message or upon request when a receiver detects an error. These mechanisms are commonly used nowadays. For example, Long Term Evolution (LTE) implements HARQ at the MAC layer and ARQ at the Radio Link Control (RLC) layer [7]. However, in terms of energy, these techniques are not efficient when bursty channel conditions are long-lasting and no spatial or frequency diversity can be provided to overcome adverse channel conditions. This means that, due to the time correlation of the wireless channel, if a packet has been received with errors, subsequent retransmissions along the same channel are also likely to be received with errors, with high probability [8]. In addition, schemes based on ARQ have intrinsic scalability issues for multicast transmissions [9]. The first one is **implosion**, which happens when all receivers send ACKs or NACKs simultaneously, causing an overload and potential collisions at the sender. When only a few receivers lost a packet, **exposure** may arise when the sender retransmits those requested retransmissions to the entire multicast group, pushing those devices that did not request a retransmission to receive unsolicited packets. These limitations have motivated the design of alternative solutions such as the Scalable Reliable Multicast (SRM) protocol [10]. In SRM, NACKs are sent to all the multicast session members in case of reception errors, and any member that received a correct copy of the information is able to retransmit it. In order to moderate implosion, NACK transmissions follow an exponential back-off in order to prevent multiple retransmission requests for the same information. Seamlessly, the retransmissions use an exponential back-off to avoid duplication. However, the protocol is prone to exposure, since all members will receive all packet retransmissions.

Cooperative schemes, as generically depicted in Figure 1, have proven to outperform non-cooperative approaches in terms of energy consumption per device in several practical scenarios [11, 12, 13, 14]. As an example, an efficient and scalable solution based on a cooperative retransmission scheme was proposed in [12]. In this solution, direct Device-to-Device (D2D) communication is established between nearby devices to form cooperative clusters, referred to as wireless grids. D2D refers to transmissions performed directly between end

[1] An extensive comparison between these traffics is given in Table I in [3].

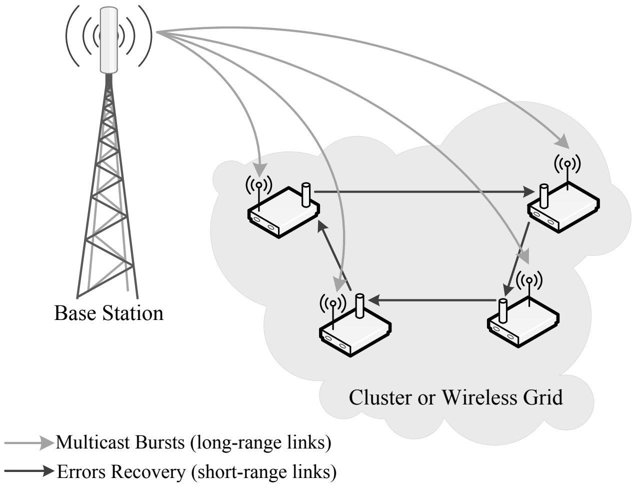

Fig. 1 Multi-Radio Cooperation Scenario.

devices located in proximity to each other within the context of a cellular network [15],[16]. D2D communications enable the use of one-hop links which simplifies routing mechanisms and improves the spectrum efficiency [17]. The short distances also have an immediate decrease in the transmission power and additionally, D2D links could also be established in order to relay data between a base station and a third device outside the network coverage. All this benefits could also be attained in multi-radio cooperative communications.

In [12], It is assumed that all devices are simultaneously connected to a cellular access point (or base station) through a long-range link and can establish a short-range distributed area network. Therefore, both centralized (long-range) and distributed (short-range) topologies can cooperate to enhance the performance of the system [13]. Transmission errors over the long-range link can be recovered by local retransmissions performed by the surrounding devices over the short-range link. In the strategy proposed in [12], a Time Division Duplex (TDD) system was considered, where the base station dynamically reserves cooperation slots in the uplink subframe to carry local retransmissions. The scheme is proven to outperform other alternatives [12]. However, it does not consider the cooperation strategy over an additional radio technology.

The integration between cellular and other radios has been presented in [18] for the particular case of UMTS and mobile ad-hoc networks, aiming at increasing the effective delivery of multicast services over cellular networks; multihop communications are used to enhance the network scalability. Moreover, the Multi-Radio Cooperative Automatic Retransmission Request (MC-ARQ) scheme proposed in [19]. This is a realistic approach as today's terminals are often equipped with at least two radio technologies: *i)* a cellular network interface, and *ii)* one or more short-range local network interfaces, *e.g.,* Bluetooth, ZigBee and Wi-Fi. The integration of the networks provide several benefits [20]; the use of the local network interfaces to perform short-range cooperative retransmissions can yield the following benefits:

1. Provision of inherit system, spatial, and frequency diversity gain.
2. Reduction of signaling and traffic load on the cellular network, one of the key concerns of the massive M2M traffic aggregation.
3. Reduction of the energy consumption devoted to transmission and reception, as the local network interfaces require lower power to perform these tasks.

Motivated by these facts, the main contribution of this paper is the design of a new Multi-Radio Reliable Multicast Cooperative protocol, previously introduced in [21]. The design is based on the Cooperative Retransmission Protocol (CRP) of [12], and modified to allow its application in networks where devices are equipped with both a cellular long-range interface and a short-range network interface, by exploiting the principles described in [19]. The proposed solution efficiently handles reliable multicast services, reducing the average number of retransmission over the cellular network and avoiding multiple retransmissions of the same message when required by more than one device. The proposed scheme improves the energy efficiency of the communications, a critical condition for M2M networks. The performance of the proposed technique has been evaluated over a cellular LTE network, composed by devices also equipped with Wi-Fi interfaces, by means of computer-based simulations with ns-3 [22]. Results show the superior performance of the proposed mechanism when compared to non-cooperative traditional multicast schemes. Ns-3 is an open-source discrete-event network simulator developed for research and educational purposes.

The remainder of this paper is organized as follows; The system model is presented in Section 2. Then, in Section 3, the proposed multicast multi-radio cooperative scheme is presented on detail. In Section 4, the scenario for the simulation experiments and the energy consumption models are described. The main performance results are also discussed in this section showing the performance of the proposed mechanism in comparison to non-cooperative multicast schemes. Finally, Section 5 concludes the paper and outlines open and future research challenges.

2 System Model

We consider a cellular base station that transmits bursts of m multicast packets in the downlink. This batch will be referred to as a *multicast round*. The destination of these packets is a group of n devices equipped with multi-radio interfaces. More precisely, we consider the case when each device has two radio interfaces: *i)* a cellular and *ii)* a short-range interface. These interfaces operate in different frequency bands. Devices use their short-range interfaces to establish a cluster to perform cooperation when some packets are received with errors over the cellular interface, as schematically represented in Figure 1. When the cellular base station transmits a multicast round, it expects only one confirmation message from one of the devices of the cluster, e.g. the cluster-head. This message will be an ACK if all packets have been received without errors, or a NACK to request the retransmission of some packets.

In the occurrence of transmission errors in the cellular link, i.e., at least one device has received a data packet with unrecoverable errors, a cooperative scheme is proposed to provide reliability. We assume independent and identically distributed (i.i.d.) channel realizations from the base station to each of the devices. Therefore, the probability that k devices $\{k \in \mathbb{Z} | k \geq 2\}$ lose the same data packet of a multicast round is usually very low [12]. For this reason, a subgroup of k devices from the cluster can be selected to perform the retransmissions over the short-range link, thus increasing the probability of recovering all the errors in the cluster. The subgroup of k retransmitting devices is referred to as *primary devices*. The remaining devices in the cluster are referred to as *auxiliary devices*. As primary devices are going to perform retransmissions, they are expected to consume more energy than auxiliary devices. The device responsible for initiating the cooperation process in the cluster is referred to as the *first primary device*.

The proposed Multi-Radio Reliable Cooperative Multicast protocol is described in the next section.

3 Multi-Radio Reliable Multicast protocol

As in [12], it is assumed that each device in the network maintains a *neighbor table* with information related to the devices present in the local neighborhood. Therefore, devices must overhear all ongoing transmissions in order to maintain the table updated. This table can be sorted by different weighted combinations of metrics that should be included in the control fields of the radio packets. This metrics can be the following:

- Remaining battery level: taking into account this value may prevent devices with low battery levels to act as primary devices, thus extending the lifetime of the overall network. Devices in the network with no energy constrains – those directly connected to energy supplies – could be dedicated to serve as primary devices.
- Cellular link quality: in order to ensure that devices selected as primary devices are those with lower packet error probability in the cellular link.
- Retransmission counter: this metric may prevent overloading the radio resources of a device, aiming to provide fair use of the devices willing to cooperate within the cluster.

The device in the first position of the neighbor table will take the role of the first primary device in the case that a cooperative phase needs to be initiated after the transmission of a multicast round to recover packets received with errors. In such case, the selected device will broadcast a control packet over the short-range interface to announce the beginning of a cooperation phase within the cluster or wireless grid. This packet is referred to as the *Cooperation Announcement*. When a cooperation phase starts, all devices initiate the exchange of a token packet. This token will record which packets were received with errors and which were correctly received.

The $(k-1)$ devices after the first position of the neighbor table will act as primary devices. The remaining $(n-k)$ devices will act as auxiliary devices for a given cooperative phase. The implementation details of the neighbor table are out of the scope of this paper. The number of devices acting as primary devices on each batch (k) is not restricted; based on the sorting metric for the neighbor table, the first primary device is able to estimate the number of primary devices that will be required for the cooperation phase to be successful, i.e., recover all packets in error if possible.

As in [12], once a multicast round has been initiated from the base station, the considered cooperation strategy is split into two consecutive steps. First, the retransmission requests are collected within the cluster, gathering information among the devices to know which packets need to be retransmitted. Then, local retransmissions are executed. The steps to enable the multi-radio implementation are detailed in next subsections. In addition, a mechanism to improve the energy efficiency of the overall cooperative scheme will be also proposed in subsection 3.3.

3.1 First Step: gathering cluster information

Upon the reception of a burst of m packets from the base station, every device generates a binary vector,

4 bits	4 bits	1 bit	(3 x m) bits	64 Bytes
Type	PTL	CRB	LPM	Optional

Fig. 2 Structure of the Token Packet.

referred to as the Lost Packet Vector (LPV), containing m bits. Each bit represents each of the packets of the multicast round and is marked with "1" in the case of erroneous reception and with "0" in case of correct reception.

The first primary device creates the token packet, attaches its LPV to it, and sends it to the next device in the neighbor table. Subsequently, each device will attach its LPV to the token packet and transmit the resulting packet to the next device. The information from all the LPV gathering the information of all the devices in the cluster can thus be collected in the form of a binary matrix referred to as the Lost Packet Matrix (LPM). This matrix contains the information of all the packets lost by the devices in the cluster. The structure of the token packet is shown in Figure 2, where each field represents the following:

- Type: indicates the type of packet (token packet).
- PTL (Primaries To Live): counter that indicates the number of primary devices. The first primary device sets this field to k and the following primary devices in the round decreases this counter by one. When the counter is zero, the device will behave as an auxiliary device.
- CRB (Complete Reception Bit): this field is for auxiliary devices to check is primary devices will be able to recover all the errors in the cluster. The last primary device checks if it is possible to recover all the errors within the cluster only with retransmission from primary devices. If so, it sets this flag to "1" and the Optional field (see below) to "0". Otherwise, it sets the flag to "0".
- LPM (Lost Packet Matrix): this field contains the corresponding binary matrix gathering the information about losses in the cluster.
- Optional: auxiliary devices will check the CRB field; if it is "0", it means that primary will not be able to recover all the errors in the cluster. If any auxiliary device can help to recover the remaining errors, it will include his identifier in this field. Once the primary devices perform their retransmission task, they will pass the retransmission responsibility of the remaining packets to the auxiliary devices that added his identifier in this field.

The LPM is generated from the LPV vectors of each device and includes an additional vector, referred to as the Lost Packet Information (LPI). This additional vector resumes all the losses in the cluster and will be useful during the second step. A $LPM_{((n+1),m)}$ matrix was first proposed in [12]. In this matrix, each device adds a new row of m positions with information related to the erroneous receptions. The last row corresponds to the LPI. With this approach, the higher the number of members in the cluster the larger the size of the LPM, as well as the length of the token packet.

To avoid this extra overhead, a compression mechanism is applied to reduce the dimensions of the LPM from $n+1$ to $k+1$ rows [12]. Each primary device adds a particular row, but auxiliary devices mark their losses in a random row, chosen from those added by primary devices. This approach can cause a non-optimal execution of the retransmission procedure, where retransmission requests from primary devices have priority over those from auxiliary devices. For this reason we introduce a second compression mechanism to reduce the LPM dimensions to only 3 rows; The first row carries the information of all primary device's losses, the second row carries the auxiliary device's losses, and the third row corresponds to the LPI. Figure 3 shows the new compressed LPM.

The first procedure ends when the first primary device receives the token packet with the complete LPM, *i.e.,* after the token has been passed over all the devices of the cluster, including primary and auxiliary devices. A complete flowchart for the first procedure is shown in Figure 4.

3.2 Second Step: retransmissions over short-range links

Upon completion of the first step of the cooperative mechanism, the first primary device compares its LPV to the LPI in order to find out the packets it can retransmit. The number of retransmission that each primary device can perform may be bounded to a maximum in order to provide some fairness among primary devices and avoid draining the energy of the ones that have received most of the packets without errors. Every device scans the primary row(s) to identify the packets

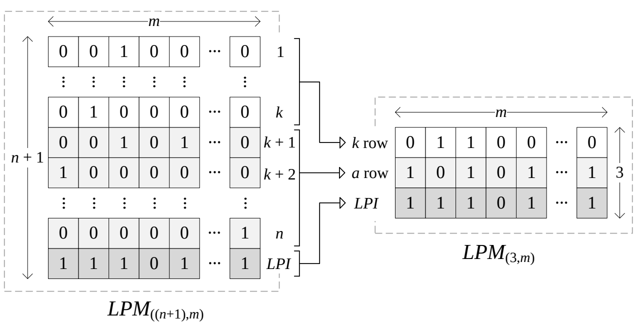

Fig. 3 Compression of the Lost Packet Matrix.

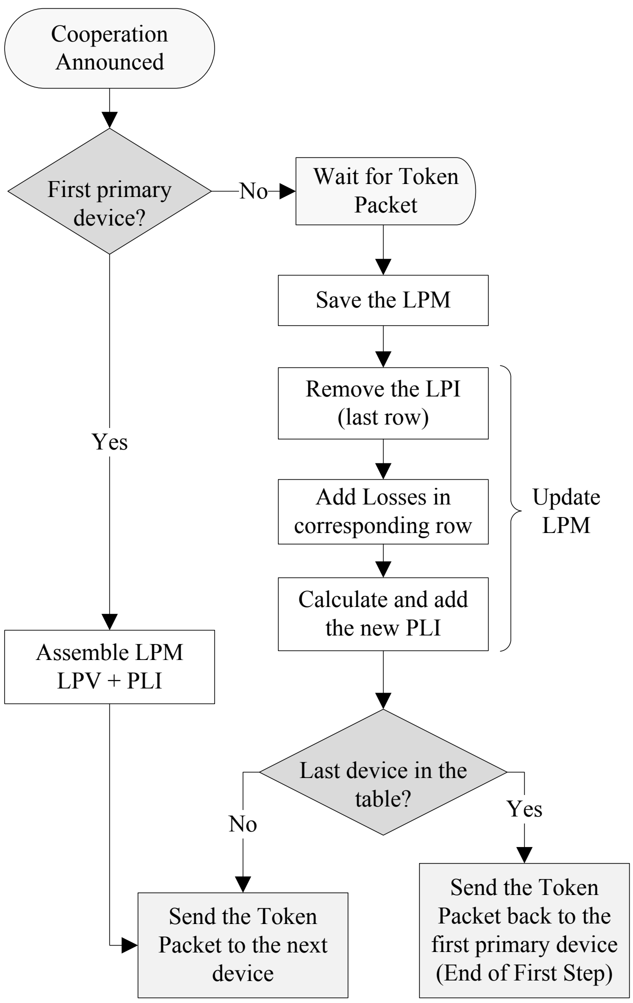

Fig. 4 First Step Flowchart: gathering cluster information.

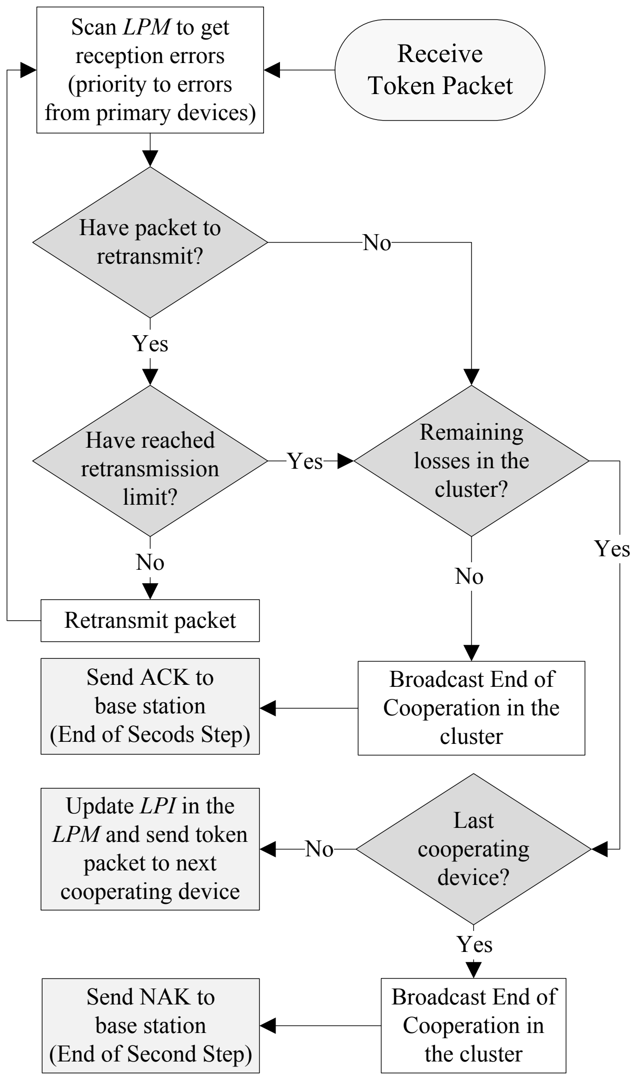

Fig. 5 Second Step Flowchart: retransmissions over short-range links.

that have been received with errors by other primary devices, and starts the retransmission of these packets first. Then, the primary device scans the auxiliary row to search for additional losses from auxiliary devices and retransmit the appropriate packets up to the maximum allowed. After completing the scheduled retransmissions, the device with the token updates the LPI in the LPM and passes the token to the next primary device. This procedure is repeated by all the primary devices.

If there are remaining losses in the cluster when the last primary device has performed the retransmission procedure, it will check the CRB and the *Optional* fields. If the value of CRB is "0", it means that there are unrecoverable errors in the cluster and the last primary device will request the missing packets directly to the base station, which will need to be retransmitted over the cellular interface. Otherwise, if the value of CRB is "1", the *Optional* field will indicate which auxiliary device can complete the local retransmission. The last primary device will send the token packet to this particular auxiliary device, and the latter will perform the remaining retransmissions.

If a given device is able to clear the LPI, it will send the ACK to the base station over the cellular interface and the procedure is finished. Indeed, there is no need to keep sending the token packet until reaching the last primary device as specified in [12]. The last cooperating device will send an *End of Cooperation* packet to all the cluster members over the short-range interface and afterwards an ACK to the base station. Finally, the base station will retransmits, if necessary, those packets that could not be recovered. A comprehensive flowchart for the second procedure is shown in Figure 5.

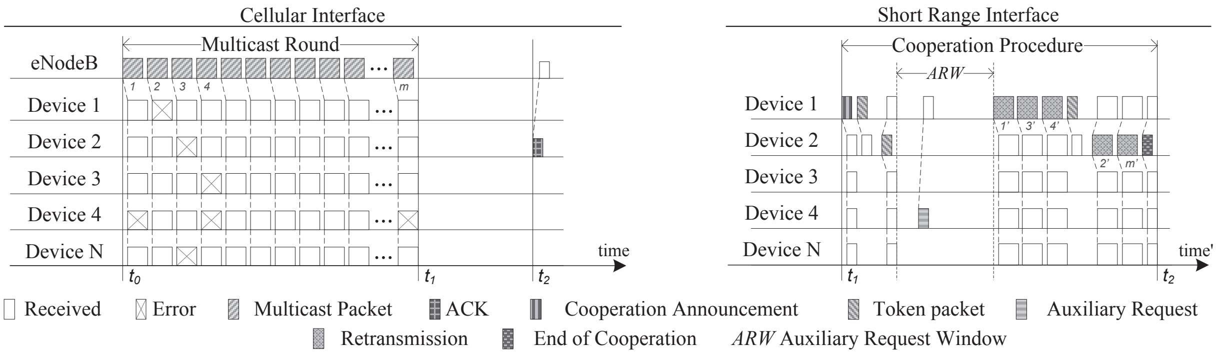

Fig. 6 Enhanced Procedure with Auxiliary Request Window.

3.3 Enhanced Procedure

It is not necessary to pass the token packet over all the auxiliary devices, it only has to be exchanged among primary devices. This fact reduces the number of transmissions of control information over the short-range interface during the first step of the cooperation phase. Once the token round is completed, the last primary device broadcasts the LPM to the cluster and a period of time is reserved for auxiliary devices when they can announce packet losses not stated yet by primary devices. This period of time is referred to as *Auxiliary Request Window* (ARW). This improvement reduces significantly the cooperation delay and the number of transmissions carried within the cluster, thus increasing scalability and improving energy efficiency.

The packets exchange corresponding to this enhanced procedure is depicted in Figure 6. In this example, there are N devices in the cluster and 2 primary devices (k). The transmissions that occur over the cellular interface are shown on the left side of the figure; the base station (an LTE eNodeB in this scenario) triggers multicast transmissions from t_0 to t_1 and it expects to receive the cooperation resolution from the cluster after t_2. All packets marked with “Error” will need to be retransmitted to at least one member of the cluster. The cooperation procedure occurs from t_1 to t_2 over the short-range interface, which corresponds to the time elapsed between the end of the multicast round and the ACK transmission on the cellular interface.

On the right side of the figure, the cooperation procedure over the short-range interface is shown. It starts with the transmission of the *Cooperation Announcement* packet to from the first primary device to all the cluster member. This is followed by the token packet transmission from the first primary device to the second (and last) primary device. This device broadcasts the token packet containing the LPM which contain retransmission request for packets 2 and 3. The transmission of the LPM indicated the beginning of the ARW so auxiliary devices can request retransmissions to the cluster. In this example, Device 4 will request additional retransmission for packets 1, 4 and m (last packet), which complete the matrix of lost packets in the cluster and therefore, no other auxiliary request is needed. When the ARW finishes, the second cooperation step starts. Primary devices perform retransmissions, the first primary device will retransmit packet 1, 3 and 4 while the second primary device will retransmit packets 2 and m, finishing the local recovery of all lost packets. Finally, the last cooperative device broadcasts the *End of Cooperation* packet in the cluster and will transmit the combined ACK over the cellular interface.

4 Performance Evaluation

In this section we evaluate the performance of the proposed cooperative scheme in terms of energy efficiency. The total amount of energy required to transmit each useful bit is calculated. This shows that exploiting the synergy between the cellular and the short-range interfaces to perform cooperation can be beneficial from the energy consumption point of view. To do so, computer-based simulations have been carried out using the popular ns-3 simulator [22].

4.1 Scenario

For the cellular interface, we have considered a LTE network, where a single eNodeB acts as the multicast server. The LTE model used for the simulation of this interface is the public release of the LENA project [23]. However, at the time of writing, this LENA model has no energy-model implemented. For this reason, a new energy model for the LTE network has been developed. The energy parameters for the LTE interface are based on [24], considering a transmission power 1.8W for the User Equipment (UE). In this paper we only focus on the energy efficiency of the devices.

Regarding the short-range communication, we have considered an IEEE 802.11g interface in ad hoc mode. The energy consumption model is based on the Broadcom BCM4326 chipset, with a reception power of 295mW and transmission power of 625mW. Additional values for the cooperative strategy parameters used in the simulation are shown in Table 1. Notably, devices are deployed in a grid topology, with a device separation of 1m and all devices are considered to in fixed positions.

We have considered different simulation parameters regarding the total number of devices n, the number of devices acting as primaries k and the size of the multicast round m. All the devices belong to a single cluster over the complete multicast transmission. The packet error rate (PER) over the LTE interface is considered to be 2%. A uniform error distribution is assumed. Therefore, the maximum number of retransmissions from primary devices can be bounded to a maximum. This value can be computed by rounding up the ratio between the total number of losses in the cluster (l) and the number of primary devices. A primary device will retransmit packets until the number of retransmissions reaches the maximum allowed $\lceil l/k \rceil$. Finally, the size of the ARW is fixed at 12ms.

In the next subsection, two schemes are compared, the Multi-radio Cooperative Retransmission Protocol (M-CRP) and the Enhanced Multicast Cooperative Retransmission Protocol (EM-CRP) proposed in this paper. Each scheme has been evaluated for 2 and 4 primary devices to compare the performance with different numbers of available relaying devices. Moreover, these strategies are compared to a multicast service over the LTE network, assuming the same parameters above but without performing cooperation on the short-range link to recover the retransmission errors within the cluster.

Table 1 Simulation Parameters

	Values	Unit
n	2 - 256	devices
k	2, 3, 4, 5, 6	devices
m	10, 20, 40, 60	packet
PER	2	%
ARW	12	ms
Packet Size [a]	1024	Bytes
Device Separation	1	m
Short-Range Energy Parameters: [b]		
tx, rx, i [c]	625, 295, 40	mW
Long-Range Energy Parameters: [b]		
tx, rx, i [d]	1800, 900, 40	mW

[a] for multicast packets.
[b] tx=transmission, rx=reception, i=idle.
[c] based on Broadcom BCM4326 chipset.
[d] as presented in [24].

4.2 Results

Figure 7 shows a comparison between the non-cooperative retransmission and the multi-radio cooperative strategies in terms of energy efficiency (average energy consumption per useful bit) on each device within the cluster. It can be appreciated how both cooperative strategies reduce significantly the energy consumption used to transmit the same amount of information. Also, for higher number of devices in the cluster, the cooperative strategies exhibit better scalability than the scenario where there is no cooperation.

A more detailed comparison between the multi-radio cooperative strategies is shown in Figure 8, where the energy efficiency of both schemes is depicted for 2 and 4 primary devices in the cluster (with 60 multicast packets and 2% PER). In both multi-radio cooperative strategies, for a higher number of cooperating devices, the average energy consumption increases. This is because the retransmission task is shared among more devices, increasing the average consumption per device. This behavior will only hold for low PER, otherwise the number of losses in the cluster might be too high to be recovered by only 2 cooperating devices and retransmissions will be required from the base station. This will increase considerably the energy consumption per device.

It can be appreciated how the ARW becomes an effective improvement in the EM-CRP as the number of device in the cluster increases. The average energy consumption per device decreases when the number of devices in the cluster is high because for a low PER as 2%, most devices can suppress the requirement to

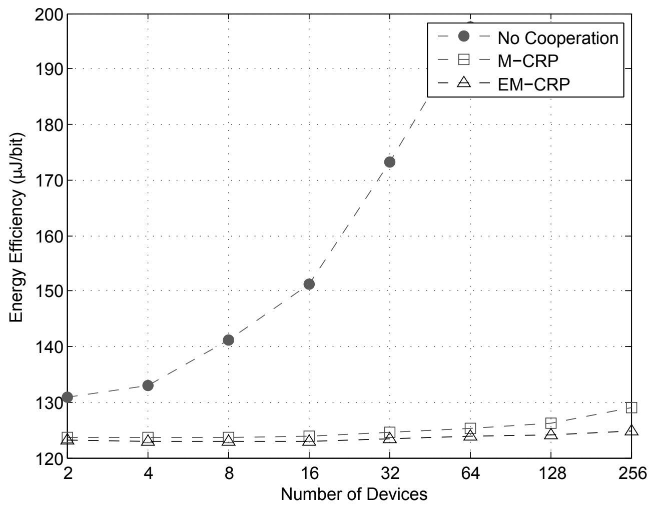

Fig. 7 Performance comparison between the multi-radio cooperation schemes and a non-cooperative strategy over the cellular network. 60 multicast packets, 2% PER.

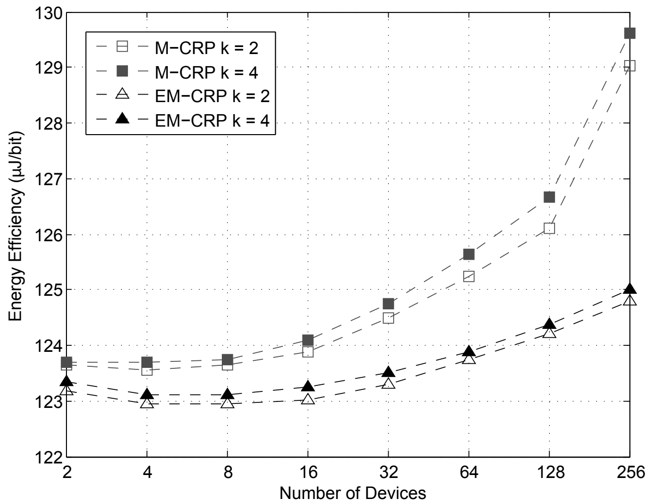

Fig. 8 Performance comparison between the original M-CRP and the proposed EM-CRP in a Multi-Radio scenario; for 2 and 4 primary devices.

send messages in both the cellular interface and the short-range interface; it is more likely that losses from auxiliary devices are already part of the losses from primary devices and, therefore, many of the auxiliary devices can avoid sending a retransmission request.

Figure 9 shows the performance of the EM-CRP when using 2 primary devices for different lengths of the multicast rounds (transmitting the same total amount of information). It can be seen how the average energy consumption per device decreases as m increases. This demonstrates that reducing the information exchange over the cellular network has an important impact over the energy consumption on each device. The only consideration that should be taken into account is that,

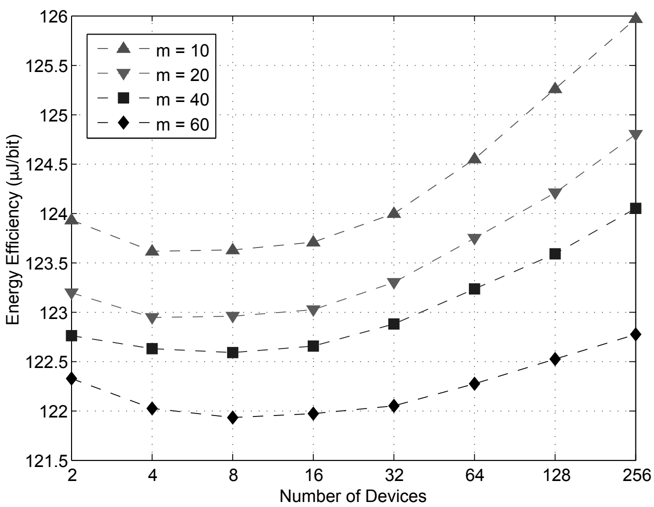

Fig. 9 EM-CRP performance with different multicast round lengths (m). 60 multicast packets, 2% PER. After each round, the cooperation procedure is performed in the cluster.

if the multicast round size increases and the number of primary devices is fixed, the number of retransmissions performed by each primary device also increases. In other words, the increasing retransmission task will be shared among the same number of devices.

This alternative may be useful in cases where there are devices in the cluster that do not depend on limited energy sources and can be used continuously as relays, since results show how the energy efficiency can be improved when the number of multicast rounds is reduced by a factor of 6, *i.e.,* when increasing the length of the multicast rounds from $m = 10$ to $m = 60$, less rounds are performed and our results show an energy efficiency improvement of 3%, which should further improve for larger rounds or even for clusters former by larger number of devices, more than 256.

5 Conclusion

A reliable multicast scheme with cooperative retransmissions has been proposed in this paper. The mechanism aims at reducing the energy consumption of devices to overcome errors during reliable multicast services in M2M networks. The mechanism is motivated by the fact that typically M2M devices are deployed in the close vicinity of each other and can establish short-range local area connectivity. The proposed mechanism exploits the fact that some M2M devices will be equipped with both cellular interfaces and additional short-range radio interfaces, and thus it is possible to facilitate cooperation between the two interfaces to improve upon energy-efficiency. The solution proposed in this paper has been compared to non-cooperative strategies in order to show the superior performance. Computer based simulations with ns-3 have been conducted to confirm and quantify the gains attained by exploiting multi-radio cooperation. The proposed solution is simple to implement and constitutes an effective mechanism to reduce traffic overload over cellular networks and reduce the energy consumption of the M2M devices.

Future work should be aimed at studying different relay selection mechanisms within the cluster. Current selection is only based on address tables but additional features such as radio link quality and energy levels should be considered when making the selection of the primary devices in the cluster. Moreover, it would be desirable to extend the current scope to include a study of the balance between cooperative and centralized retransmissions on scenarios with high packet error rates and detailed analysis of the trade-offs between increasing the size of multicast-rounds and the number of primary devices required to efficient manage local retransmissions within the cluster.

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References

1. J. Hase, M2M Market - Guide to Selling M2M Products. in *M2M Magazine* (2012). URL `http://www.machinetomachinemagazine.com/2012/10/02`
2. 3rd Generation Partnership Project (3GPP), Study on Facilitating Machine to Machine Communication in 3GPP Systems. Tech Rep 22.868, version 8.0.0, 3GPP (2007)
3. A. Laya, L. Alonso, J. Alonso-Zarate, Is the random access channel of lte and lte-a suitable for m2m communications? a survey of alternatives. Communications Surveys Tutorials, IEEE **16**(1), 4 (2014). DOI 10.1109/SURV.2013.111313.00244
4. Y. Zhang, R. Yu, M. Nekovee, Y. Liu, S. Xie, S. Gjessing, Cognitive machine-to-machine communications: visions and potentials for the smart grid. Network, IEEE **26**(3), 6 (2012). DOI 10.1109/MNET.2012.6201210
5. J. Dohl, G. Fettweis, Energy Aware Evaluation of LTE Hybrid-ARQ and Modulation/Coding Schemes. in *Communications (ICC), 2011 IEEE International Conference on* (2011), pp. 1 –5. DOI 10.1109/icc.2011.5962570
6. K. Kotuliakov, D. imlatkov, J. Polec, Analysis of arq schemes. Telecommunication Systems pp. 1–6 (2013). URL `http://dx.doi.org/10.1007/s11235-011-9659-1`. 10.1007/s11235-011-9659-1
7. M. Meyer, H. Wiemann, M. Sagfors, J. Torsner, J.F. Cheng, ARQ Concept for the UMTS Long-Term Evolution. in *Vehicular Technology Conference, 2006. VTC-2006 Fall. IEEE 64th* (2006), pp. 1 –5. DOI 10.1109/VTCF.2006.442
8. T. Predojev, J. Alonso-Zarate, M. Dohler, Energy efficiency of cooperative ARQ strategies in low power networks. in *Computer Communications Workshops (INFOCOM WKSHPS), 2012 IEEE Conference on* (2012), pp. 139 –144. DOI 10.1109/INFCOMW.2012.6193475
9. C. Papadopoulos, G. Parulkar, G. Varghese, An error control scheme for large-scale multicast applications. in *Proceedings of the seventeenth annual ACM symposium on Principles of distributed computing* (ACM, New York, NY, USA, 1998), PODC ’98, pp. 310–. DOI 10.1145/277697.277759
10. Floyd, S., Jacobson, V., Liu, C., McCanne, S., and Zhang, L., A Reliable Multicast Framework for Light-weight Sessions and Application Level Framing. in *IEEE/ACM Transactions on Networking*, vol. 5 (1997), vol. 5, pp. 784–803
11. F.H. Fitzek, M.D. Katz (eds.), *Cooperation in Wireless Networks: Principles and Applications: Real Egoistic Behavior is to Cooperate!* (Springer, 2006)
12. Q. Zhang, F. Fitzek, V. Iversen, Design and Performance Evaluation of Cooperative Retransmission Scheme for Reliable Multicast Services in Cellular Controlled P2P Networks. in *Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on* (2007), pp. 1–5. DOI 10.1109/PIMRC.2007.4394773
13. F.H. Fitzek, M.D. Katz (eds.), *Cognitive Wireless Networks: Concepts, Methodologies and Visions Inspiring the Age of Enlightenment of Wireless Communications* (Springer, 2007)
14. M. Garcia, S. Sendra, J. Lloret, A. Canovas, Saving energy and improving communications using cooperative group-based wireless sensor networks. Telecommunication Systems pp. 1–14 (2013). URL `http://dx.doi.org/10.1007/s11235-011-9568-3`. 10.1007/s11235-011-9568-3
15. K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, K. Hugl, Device-to-device communication as an underlay to lte-advanced networks. Communications Magazine, IEEE **47**(12), 42 (2009). DOI 10.1109/MCOM.2009.5350367
16. D. Feng, L. Lu, Y. Yuan-Wu, G. Li, G. Feng, S. Li, Device-to-device communications underlaying cellular networks. Communications, IEEE Transactions on **61**(8), 3541 (2013). DOI 10.1109/TCOMM.2013.071013.120787
17. A. Laya, K. Wang, A. Widaa, J. Alonso-Zarate, J. Markendahl, L. Alonso, Device-to-device communications and small cells: enabling spectrum reuse for dense networks. Wireless Communications, IEEE **21**(4), 98 (2014). DOI 10.1109/MWC.2014.6882301
18. S. Spinella, G. Araniti, A. Iera, A. Molinaro, Integration of ad-hoc networks with infrastructured systems for multicast services provisioning. in *Ultra Modern Telecommunications Workshops, 2009. ICUMT ’09. International Conference on* (2009), pp. 1–6. DOI 10.1109/ICUMT.2009.5345596
19. J. Alonso-Zarate, E. Kartsakli, M. Katz, L. Alonso, C. Verikoukis, Multi-Radio Cooperative ARQ in wireless cellular networks: a MAC layer perspective. Telecommunication Systems pp. 1–11 (2010). 10.1007/s11235-011-9449-9
20. J. Zhou, R. Venkatesha Prasad, Y. Lu, I. Niemegeers, Simulation-based analysis of a multi-hop integrated umts and wlan network. Telecommunication Systems pp. 1–14 (2013). URL `http://dx.doi.org/10.1007/s11235-011-9666-2`. 10.1007/s11235-011-9666-2
21. A. Laya, K. Wang, L. Alonso, J. Alonso-Zarate, Multi-radio cooperative retransmission scheme for reliable machine-to-machine multicast services. in *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on* (2012), pp. 1–6. DOI 10.1109/PIMRC.2012.6362682
22. The ns-3 network simulator. URL `http://www.nsnam.org/`
23. N. Baldo, M. Miozzo, M. Requena-Esteso, J. Nin-Guerrero, An open source product-oriented LTE network simulator based on ns-3. in *Proceedings of the 14th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems* (ACM, New York, NY, USA, 2011), MSWiM ’11, pp. 293–298. DOI 10.1145/2068897.2068948
24. M. Lauridsen, A. Jensen, P. Mogensen, Reducing LTE Uplink Transmission Energy by Allocating Resources. in *Vehicular Technology Conference (VTC Fall), 2011 IEEE* (2011), pp. 1 –5. DOI 10.1109/VETECF.2011.6092935