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Enhancing the QoS of Real-Time Video Streaming over LTE MBMS using D2D Communications

Elias Yaacoub and Adnan Abu-Dayya
Qatar Mobility Innovations Center (QMIC)
Qatar Science and Technology Park
Doha, Qatar
{eliasy, adnan}@qmic.com

ABSTRACT

Real-time video streaming over LTE multicast and broadcast multimedia services (MBMS) is investigated. The impact of device-to-device (D2D) communications in enhancing the quality of service (QoS) and reducing energy consumption from the batteries of mobile terminals (MTs) is studied. We propose an approach where devices cooperate on the short range by forming coalitions for the purpose of energy efficiency. In each coalition, an MT is selected to receive the video stream from the base station on the long range LTE MBMS links. Simulation results show that significant energy savings can be achieved with the proposed approach compared to the non-collaborative case, in addition to significantly enhanced QoS.

Categories and Subject Descriptors

J.2 [**Computer Applications**]: Physical Sciences and Engineering; H.4.3 [**Information Systems Applications**]: Communications Applications; F.2.m [**Analysis of Algorithms and Problem Complexity**]: Miscellaneous

General Terms

Theory, Algorithms, Performance

Keywords

Device-to-device communications, LTE, MBMS, energy efficiency, real-time video streaming

1. INTRODUCTION

In state-of-the-art wireless systems, mobile terminals (MTs) are required to support the exchange of large amounts of data in addition to the increase in demand for multimedia services, which leads to high power consumption. However, because of limitations of the battery life of MTs, several attempts are made in the literature in order to find solutions that reduce the consumed energy, decrease the latency, and increase the throughput.

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Q2SWinet'12, October 24–25, 2012, Paphos, Cyprus.
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This led to the investigation of heterogenous network architectures where the MTs would be active on two wireless interfaces: one to communicate with a wireless base station (BS) on the long range (LR) such as WiMAX, LTE, or UMTS, and one to communicate with other MTs on the short range (SR) using technologies such as Bluetooth, WLAN, or ultra-wide band (UWB). An example is presented in [6] for real-time video streaming. Results show promising opportunities to decrease the total energy consumed by increasing the number of collaborative MTs.

It would be interesting for practical purposes if both LR and SR communications can be performed over the same technology. This would also facilitate the cross layer operation of the content distribution operation between the wireless interfaces of the same device. For example, this would be useful when receiving video packets on the LR from the BS, transferring them to the SR interface, then forwarding them to neighboring MTs on the physical layer while maintaining real time display of the video on the application layers of the MTs. Such an option is under investigation in LTE-Advanced (LTE-A), and it is referred to as device-to-device (D2D) communication.

In fact, D2D communication has received some research attention in the literature [8, 7, 11] as part of LTE-A, with standardization efforts still lagging behind. D2D enables linking an MT to another MT directly using the cellular spectrum. This could allow large amounts of data (e.g. multimedia) to be transferred from one MT to another over short distances and using a direct connection. This data exchange occurs over the SR without the need to use the cellular network itself, thus leading to offloading some traffic from the network. The main challenge with D2D communication is to keep the interference to the primary cellular network at tolerable levels [11]. In [8], the D2D communication is investigated as a network underlaying the LTE-A cellular network. Mechanisms for D2D communication session setup and management are proposed. The D2D communication can operate in multiple modes. It can underlay the cellular transmission, or the cellular network can assign dedicated resources to the D2D terminals, or they can reuse the same resources used by the cellular network [7]. Based on the results of the single cell studies, a mode selection procedure for a multi-cell scenario is proposed in [7]. The problem of radio resource allocation to the D2D communications is formulated as a mixed integer nonlinear programming problem in [11]. Due to the difficulty of solving this problem, a greedy heuristic algorithm that reduces the interference to the primary cellular network by utilizing channel gain infor-

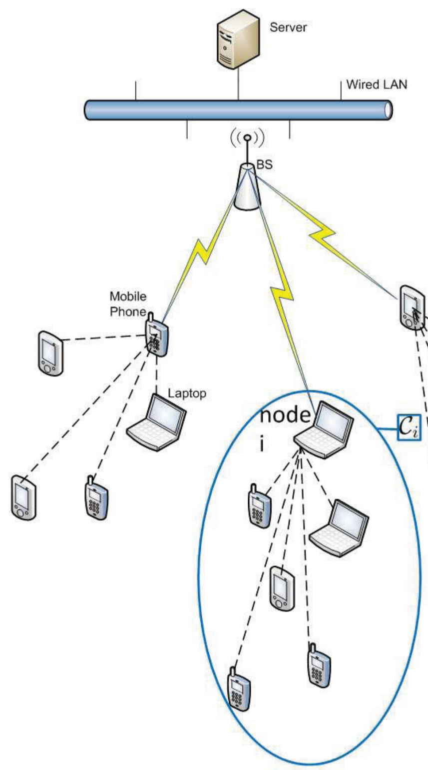

Figure 1: System model.

mation is proposed. Proprietary implementations of D2D have already been tested, e.g., Qualcomm's "FlashlinQ" [15, 12], which enables automatic discovery and communication between MTs without using the cellular infrastructure. Consequently, an SR cooperative wireless network is built between FlashLinQ-enabled MTs, allowing those devices to share content.

The novelty in this work is in jointly investigating the performance of D2D communication with real-time video streaming over LTE multicast and broadcast multimedia services (MBMS) [1, 2, 13]. The focus of the investigation is in the formation of cooperative coalitions between MTs to reduce battery consumption during video streaming while simultaneously enhancing their quality of service (QoS).

The paper is organized as follows. The system model is presented in Section 2. The proposed approach is discussed in Section 3. The simulation results are presented and discussed in Section 4. Finally, conclusions are drawn in Section 5, and indications for future research directions are given.

2. SYSTEM MODEL

Real-time video streaming within a single cell is considered. The streamed video content is to be delivered from the BS to K requesting MTs distributed throughout the cell area of the BS. The MTs are interested in the same content. They communicate with the BS using LTE MBMS, or with neighboring MTs using D2D communications. MTs form cooperating clusters for the purpose of energy minimization during cooperative content distribution. Within each cooperating cluster, the content is delivered on the LR to a single MT, the cluster head (CH), which in turn multicasts the content to the other MTs in that cluster using SR collaboration. Fig. 1 shows the scenario considered.

At a given fading realization, each MT receives the video content from a single source, which could be either the BS or another MT. Receiving parts of the content from different sources is suboptimal in terms of energy minimization. In fact, the energy minimization problem for content distribution in a single cluster of cooperating MTs is formulated and solved in [5]. It was shown that the optimal solution in a single cluster is to send all data to a single MT, the cluster head, and that cluster head should distribute the content to all other MTs cooperating with it.

We assume that MTs form coalitions where the energy consumption in the coalition is lower than the sum of the individual energy consumptions of the coalition members. We use the term "node" to refer to either an MT or the BS. Having K MTs in the system, they are numbered from node n_1 to node n_K, with the BS being referred to as n_0 and given the index 0. We denote by $\mathcal{C}_i$ the coalition of nodes forming a single cooperative cluster with n_i as cluster head communicating on the LR with the BS on behalf of all the cluster members. Consequently, the CHs form a multicast group to which the BS sends the data using MBMS.

2.1 Rate Calculations and Channel Model

In LTE, the available spectrum is divided into resource blocks (RBs), each consisting of 12 adjacent subcarriers. The assignment of an RB takes place every 1 ms, agreed to be the duration of one transmission time interval (TTI), or the duration of two 0.5 ms slots [4]. Given the transmit power $P_{t,kj}^{(x)}$ that n_k is using in order to transmit to n_j over subcarrier x, the channel gain $H_{kj}^{(x)}$ of the channel between n_k and n_j over subcarrier x, and the thermal noise power σ^2, the received signal-to-noise ratio (SNR) $\gamma_{kj}^{(x)}$ on the link between n_k and n_j over subcarrier x can be calculated following $\gamma_{kj}^{(x)} = \frac{P_{t,kj}^{(x)} H_{kj}^{(x)}}{\sigma^2}$. Given the target bit error rate P_e and the SNR, the bit rates on the link between any two nodes n_k and n_j over subcarrier x can be calculated as follows:

$$R_{kj}^{(x)} = W^{(x)} \cdot \log_2(1 + \beta\gamma_{kj}^{(x)}) \qquad (1)$$

In (1), $W^{(x)}$ is the passband bandwidth of the subcarrier, and β is called the SNR gap. It indicates the difference between the SNR needed to achieve a certain data transmission rate for a practical M-QAM system and the theoretical Shannon limit [14]. It is given by: $\beta = \dfrac{-1.5}{\ln(5P_e)}$. The rate achievable over an RB is the sum of the rates on the subcarriers that form that RB.

The channel gain $H_{kj}^{(x)}$ is expressed as:

$$H_{kj,\text{dB}}^{(x)} = (-\kappa - \upsilon \log_{10} d_{kj}) - \xi_{kj} + 10 \log_{10} F_{kj}^{(x)} \qquad (2)$$

In (2), the first factor captures propagation loss, with d_{kj} the distance between nodes k and j, κ the pathloss constant, and υ the path loss exponent. The second factor, ξ_{kj}, captures log-normal shadowing with a standard deviation σ_ξ, whereas the last factor, $F_{kj}^{(x)}$, corresponds to Rayleigh fading (generally considered with a Rayleigh parameter a such that $E[a^2] = 1$). A block fading model is considered, where the fading remains constant over the subcarriers of an RB for a duration T_{dec}. After T_{dec}, the channel decorrelates and a new realization occurs for another T_{dec}, and so on. The fading is considered IID over RBs.

2.2 Video QoS Metric

Video sequences are encoded into groups of pictures (GOPs) according to the H.264 standard. Each GOP consists of one I-frame and a sequence of P-frames and has a duration T_{GOP}. Hence, when a GOP becomes available at the BS, coming from the video streaming server, the BS should distribute the GOP to the MTs within a duration of T_{GOP}. When T_{GOP} has elapsed, the transmission of a new GOP begins. All the frames from the previous GOP that are not received at a given MT are assumed lost. Error concealment is adopted in this case by repeating the last correctly received frame until the next I-frame is received [10]. To measure video QoS, loss distortion, corresponding to the distortion caused by lost frames during transmission over the wireless channels, is considered (loss distortion is to be differentiated from source distortion, which depends on the compression method at the source, and is beyond the scope of this paper). The distortion for replacing a frame f, of dimensions $N_1 \times N_2$ pixels, with an estimated frame $\hat{f}$ can be computed as follows [10]:

$$D = \frac{1}{N_1 N_2} \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} \cdot \left(f(n_1, n_2) - \hat{f}(n_1, n_2) \right)^2 \qquad (3)$$

3. CLUSTER FORMATION APPROACH

In this section, we present the proposed cluster formation method based on cooperative coalitions for the purpose of energy efficiency.

3.1 Energy Calculations

The time needed to transmit a content of size S_T bits on a link between nodes n_k and n_j having an achievable rate R_{kj} bps is given by S_T/R_{kj}. Denoting the power drained from the battery of node n_j to receive the data from node n_k by $P_{\text{Rx},kj}$, then the energy consumed by n_j to receive the data from n_k is given by $S_T \cdot P_{\text{Rx},kj}/R_{kj}$. Similarly, denoting by $P_{\text{Tx},k}$ the power drained by the battery of n_k to transmit the data via multicasting, then the energy consumed by n_k to transmit the content to n_j is given by $S_T \cdot P_{\text{Tx},k}/R_{kj}$. It should be noted that $P_{\text{Tx},k}$ can be expressed as:

$$P_{\text{Tx},k} = P_{\text{Tx}_{\text{ref}},k} + P_{t,k} \qquad (4)$$

where $P_{\text{Tx}_{\text{ref}},k}$ corresponds to the power consumed by the circuitry of node n_k during transmission on the communication interface, and $P_{t,k}$ corresponds to the power transmitted over the air interface by n_k.

Denoting by $E_{\mathcal{C}_k}$ the energy consumed by the MTs that are members of cluster $\mathcal{C}_k$ with node n_k as cluster head, then the energy consumed in $\mathcal{C}_k$ is given by:

$$E_{\mathcal{C}_k} = \frac{S_T \cdot P_{\text{Rx},0k}}{R_{0k}} + \frac{S_T \cdot P_{\text{Tx},k}}{\min\limits_{i \neq k; n_i \in \mathcal{C}_k} R_{ki}} + \sum_{j \neq k; n_j \in \mathcal{C}_k} \frac{S_T \cdot P_{\text{Rx},kj}}{\min\limits_{i \neq k; n_i \in \mathcal{C}_k} R_{ki}} \qquad (5)$$

where the first term corresponds to the energy consumed by node n_k to receive the data from the BS on the LR cellular link, the second term corresponds to the energy consumed by node n_k to transmit the data to the other nodes in its cluster on the SR via D2D communication, and the last term corresponds to the energy consumed by the nodes to receive their data from node n_k on the SR. To avoid multiple transmissions among nodes of the same cluster, MT k transmits using multicasting. Thertefore, the second term does not involve any summation over the MTs, conversely to the third term. In addition, with SR multicasting, $R_{kj} = \min\limits_{i \neq k; n_i \in \mathcal{C}_i} R_{ki}$, since transmission should take place at the minimum achievable rate in the cluster in order to guarantee that all MTs in the cluster receive the desired multimedia information. The LTE resource allocation on the LR to perform multicasting using MBMS is described in Section 3.3.

When all MTs have similar characteristics in terms of powerr consumption, then we have: $P_{\text{Rx},0k} = P_{\text{Rx,LR}} \forall k$ for the power drained from the batteries of the MTs during reception on the LR from the BS, $P_{\text{Rx},kj} = P_{\text{Rx,SR}} \forall k, j$ for the power drained from the batteries of the MTs during reception on the SR from the CHs, and $P_{\text{Tx},k} = P_{\text{Tx,SR}} \forall k$ for the power drained from the batteries of the CHs during multicasting on the SR to the other MTs. In this case, (5) can be simplified as follows:

$$E_{\mathcal{C}_k} = S_T \cdot \left(\frac{P_{\text{Rx,LR}}}{R_{0k}} + \frac{P_{\text{Tx,SR}} + (|\mathcal{C}_k| - 1) P_{\text{Rx,SR}}}{\min\limits_{i \neq k; n_i \in \mathcal{C}_k} R_{ki}} \right) \qquad (6)$$

where $|\cdot|$ denotes set cardinality.

3.2 Proposed Method

The proposed method consists of an initialization phase, and a coalition formation phase.

Initialization phase: At the start of the proposed method, all the nodes n_k are directly connected to the BS via LR LTE links; i.e. each cluster consists of a single node such that $\mathcal{C}_k = \{n_k\}$ and $|\mathcal{C}_k| = 1$. This is equivalent to the scenario without D2D collaboration. All clusters are in the search space $\mathcal{S} = \{k; \mathcal{C}_k \neq \emptyset\}$.

Coalition formation phase:

- Find the cluster having the highest energy consumption per node: $k = \arg\max_{i \in \mathcal{S}} E_{\mathcal{C}_i}/|\mathcal{C}_i|$.
- Coalition candidate search: Find the cluster $\mathcal{C}_j$ that leads to the lowest energy consumption when merged with cluster $\mathcal{C}_k$: $j = \arg\min\limits_{i \neq k} E_{\mathcal{C}_i \cup \mathcal{C}_k}$.
- Coalition formation: Form a coalition between the members of clusters $\mathcal{C}_j$ and $\mathcal{C}_k$ if the following condition is verified: $E_{\mathcal{C}_j \cup \mathcal{C}_k} \leq E_{\mathcal{C}_j} + E_{\mathcal{C}_k}$. This condition indicates that a coalition between two clusters is formed only if it is more energy efficient than having the two clusters operate independently.
- If the merger condition is satisfied, Set $\mathcal{C}'_j = \mathcal{C}_j \cup \mathcal{C}_k$. The new cluster has n_j as cluster head since it has the lowest energy consumption on the link with the BS. Thus, it is the cluster head of the coalition cluster.
- Update the clusters by setting $\mathcal{C}_j = \mathcal{C}'_j$ and $\mathcal{C}_k = \emptyset$. If the merger condition is not satisfied, keep clusters $\mathcal{C}_k$ and $\mathcal{C}_j$ separate since this scenario turned out to be more energy efficient than collaboration. In both cases, remove k from the search space: $\mathcal{S} = \mathcal{S} \backslash \{k\}$.

- Repeat the process until no improvement can be made, i.e., until $\mathcal{S} = \emptyset$. This means that $\forall k, j$ such that $\mathcal{C}_k \neq \emptyset$ and $\mathcal{C}_j \neq \emptyset$, we have: $E_{\mathcal{C}_j \cup \mathcal{C}_k} > E_{\mathcal{C}_j} + E_{\mathcal{C}_k}$.

3.3 LTE Resource Allocation

To avoid interference between MTs during D2D operation, we consider that the BS allocates an RB to each MT to be used for transmission on the SR links using D2D communication. This BS intervention is done at the beginning of the communications to avoid interference between MTs on the SR.

We assume that the same video is sent to all users. This corresponds to an application where users are subscribed to a real-time streaming service, e.g., broadcasting of a news channel, or a sports channel during the World Cup, etc. Using LTE MBMS, we dedicate a single RB in the cell to multicast the same video stream to the MTs. With multicasting, transmission on a given RB is limited by the rate achieved by the MT having the worst channel conditions on that RB [13]. Thus, the BS selects the RB having the highest minimum rate, i.e., according to the following:

$$z^* = \left\{ \arg\max_z \left(\min_k R_{0k}^{(z)} \right) \right\} \quad (7)$$

After determining z^* according to (7), we set:

$$R_{0j} = \min_k R_{0k}^{(z^*)} \quad (8)$$

In the non-cooperative scenario without D2D communications, all MTs are involved in the minimization of (7). In other words, all MTs interested in the streamed video form a single multicast group for LTE MBMS. Thus, the achievable multicasting rate on the LR is affected by the MT having the worst channel conditions. However, in the collaborative approach, coalitions are formed according to the method described in Section 3.2. Afterwards, only the cluster heads are involved in the minimization in (7). Consequently, cluster heads form a single multicast group that does not include the other members of their clusters. Since cluster heads are selected as such because they have relatively higher achievable LR rates, then the outcome of (7) is expected to lead to significantly higher LR multicasting rates, since multicasting is performed on a subset of the participating MTs, with the members of the subset having better LR channel conditions (and hence higher rates) than the others.

It should be noted that we consider that one RB is allocated on the LR for the investigated MBMS service. The other MTs are used to serve the other users not participating in the real-time streaming subscription, or subscribed in other MBMS streaming applications (e.g. watching other videos that are multicast simultaneously).

4. RESULTS AND DISCUSSION

The simulation model is displayed in Fig. 1. We consider an LTE bandwidth $W_{LR} = 5$ MHz, subdivided into $N_{\mathrm{RB}} = 25$ RBs of 12 subcarriers each [4]. We consider a 5 W BS transmit power, subdivided equally among all RBs, and an MT transmit power of 125 mW. Channel parameters are obtained from [3], whereas energy consumption parameters are taken as in [9]: we set $\kappa = -128.1$ dB, $\upsilon = 3.76$, $\sigma_\xi = 8$ dB, $P_{\mathrm{Rx},0k} = 1.8$ Joules/s, $P_{\mathrm{Tx},kj} = 1.425$ Joules/s and $P_{\mathrm{Rx},kj} = 0.925$ Joules/s, for all $k > 0$ and $j > 0$. To simulate the video transmission, the Foreman sequence, encoded in QCIF format, is used. GOPs consisting of 15 frames, one I-frame and 14 P-frames, are used, with the duration of a GOP being 0.5s. The results are averaged over 2500 iterations. We consider scenarios where MTs interested in the same video file are uniformly distributed in an area of size 200m $\times$ 200m, whose origin is at a distance d_{LR} m from the BS. In addition, we consider the traditional scenario where MTs are uniformly distributed in the cell, with a 1km $\times$ 1km cell having the BS at its center.

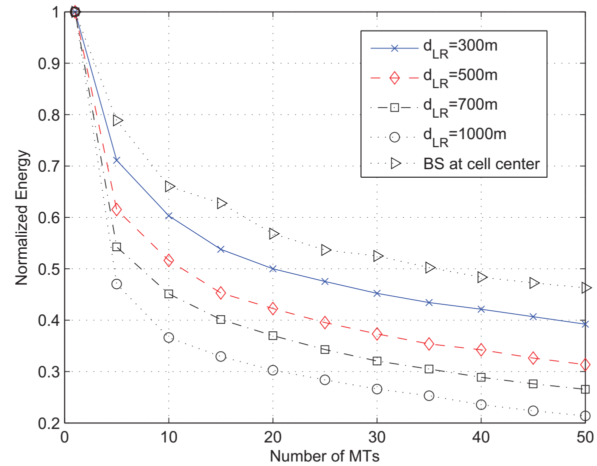

Figure 2: Normalized energy consumption.

Fig. 2 shows the normalized energy consumption during video streaming. The normalized energy is defined as the ratio of the energy consumed in the cooperative approach to the energy consumed without cooperation. Thus, a value lower than one indicates energy savings due to the cooperative technique. Consequently, Fig. 2 shows that the proposed cooperative D2D approach leads to considerable savings compared to the traditional non-cooperative case. In addition, the savings increase as the distance to the BS increases. In fact, as the distance increases, the achievable rates on the LR links decrease, which leads to longer times to receive the data and increased energy consumption. With D2D collaboration, cluster heads are selected to have relatively higher rates on the LR and thus can receive the video content faster via MBMS, then distribute it on the SR where high rates are achievable due to the short distances between MTs of the same cluster. The scenario with the BS at the cell center has relatively worse performance, although significant gains are still achieved. The reason is that, with this scenario, MTs are more scattered in the cell and thus it is harder to build coalitions with MTs that are close enough to communicate at high rates using D2D communications.

Fig. 3 shows the average video loss distortion results in dB, which gives an indication of QoS performance of the proposed approach. Huge gains are achieved compared to the non-collaborative scenarios, since a lower distortion corresponds to less lost frames and better streaming performance. Furthermore, with the exception of the scenario with the BS at the cell center, the distortion goes to $-\infty$ in dB in all scenarios with a hotspot area located at a distance d_{LR} from the BS when the number of cooperative MTs increases,

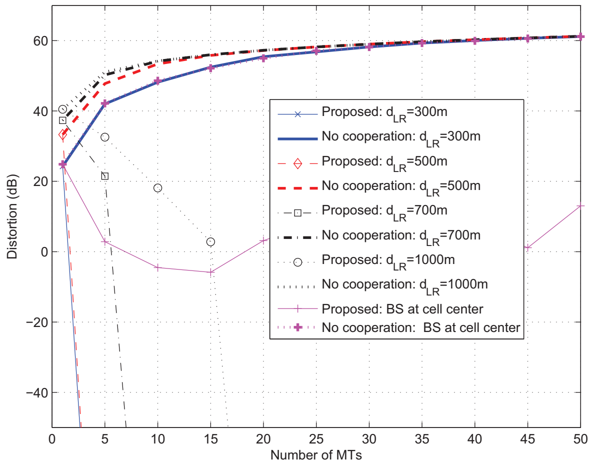

Figure 3: Video loss distortion.

which corresponds to zero loss distortion. This indicates that all the subscribers receive the video correctly without losses caused by wireless transmission, which is highly desirable in real-time video streaming applications. Hence, the formation of coalition clusters with D2D multicasting can enhance the QoS performance of real-time video streaming over LTE MBMS.

5. CONCLUSIONS AND FUTURE WORK

Real-time video streaming over LTE multicast and broadcast multimedia services was investigated. Cooperative clusters were formed using a proposed coalition formation technique. Device-to-device communications were used for short range communications in these clusters. Significant energy savings were achieved with the proposed approach compared to the non-collaborative case, and considerable enhancements in the quality of service were achieved.

The scenario investigated in this paper assumed the MTs have comparable stored energies. An interesting direction for future research would consist of taking the available energy in the battery of each MT into account. This would guide the coalition formation process based on the available residual energy in the battery of each MT and avoid selecting the MTs with little remaining energy as cluster heads.

6. ACKNOWLEDGMENTS

This work was made possible by NPRP grant # 09-180-2-078 from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

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