Collaborative Multimedia Source-Protocol Coordination: A Cross-Layer QoE Study in Modern Wireless Networks

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***Abstract*—Multiple image/video source neighbors in modern wireless systems such as device-to-device (D2D) networks can significantly improve multimedia quality of experience (QoE) in content sharing. However, the exploration of multisource diversity in multimedia communications has largely been overlooked in the past. In this paper, we propose a new scheme to improve user equipment's (UE) multimedia QoE by optimizing the source traffic dispatching and resource allocation strategies from multiple UE sources in cross-layer wireless D2D networks while assuring the latency constraint. This approach results in two major contributions. First, the proposed approach optimally controls the source server traffic for each multimedia packet with regard to distortion reduction (e.g., quality contribution) and the channel conditions. Second, optimal packet retry limits are adjusted on each direct D2D communication link to achieve effective but unequal resource allocation. Simulation results show that the cross-layer collaborative source-level traffic control and protocol-level resource optimization strategy improve D2D multimedia transmission quality.**

***Index Terms*—Cross-layer multimedia communications, image/video packet coordination.**

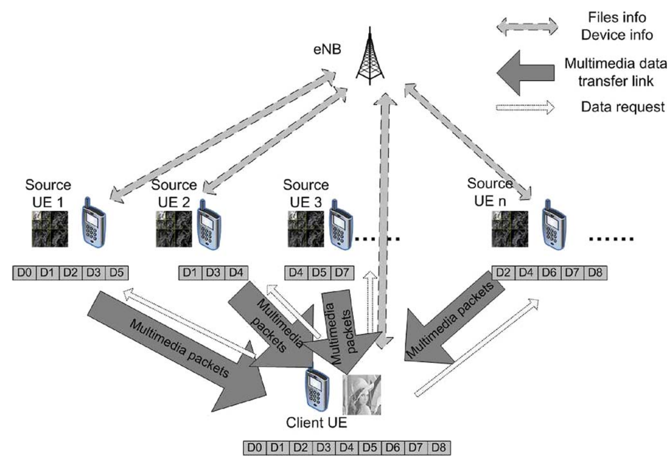

Fig. 1. Illustration of the quality-driven multisource coordination in D2D communications.

I. Introduction

MULTIMEDIA has been dominating the traffic in a wide variety of modern networking systems and applications [1], such as device-to-device (D2D) and point-to-point (P2P) communications [2], IPTV [3], video on demand [4], and social media content sharing [5], etc. According to a recent technical report released by Cisco [1], the multimedia traffic will quickly outpace mobile webpage data and put enormous strain on already overburdened cellular channels. Traditional physical layer research focused on three techniques to accommodate such huge traffic requirement: MIMO-OFDM, cognitive radio, and small-cell communications. However, the close-to-channel-capacity performance of MIMO-OFDM, the available new spectrum resource shortage of cognitive radio, and the high costs of establishing new tower sites for small cell communications become fundamental limitations of the aforementioned solutions [8]. Recently, D2D communication was proposed to offload cellular traffic by taking advantage of physical proximity of client devices defined as user equipment (UE) [6], [7]. Unfortunately, the quality of experience (QoE) solutions for wireless multimedia transmission of D2D networks are still in their infancy. Wireless multimedia applications have two unique characteristics: stringent multimedia QoE requirement and real-time streaming latency requirement. Thus, how to provide quality multimedia service and experience with bounded latency performance over D2D channels becomes a key research challenge.

Furthermore, multiple UE sources can work coordinately to provide extra data delivery reliability. For example, the same video frames stored on different video servers can be transmitted simultaneously via different D2D links. Even if some video frames are lost in the wireless channel or are delayed over the decoding deadline, the video can still be reconstructed when duplicated video frames arrive at the receiver UE, on time, and without transmission errors. In this paper, we explore such multisource diversity in conjunction with multimedia unequal importance to improve multimedia D2D communication quality while satisfying the latency requirement.

The quality-driven multisource coordination problem studied in this paper is illustrated in Fig. 1. As this figure shows, a user UE requests a multimedia file which contains certain multimedia frames with different quality contributions (i.e., distortion reduction), and parts of these frames are stored on several source UEs in geographic vicinity. The same multimedia frame could be stored on multiple source UEs (e.g., several friends

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may all have a local copy of a popular football video). In order to maximize the multimedia quality, multiple available frames on these source UEs are transmitted to the end user UE, coordinated by the evolved node B (eNB or base station in general). In addition, error control method is applied in the data transmission to reduce the packet loss probability. We address two key issues for improving the D2D multimedia QoE while satisfying the latency requirement: 1) improving the coordination of participating source UEs in the D2D networks by applying the optimal transmission scheduling and 2) allocating optimal network resource parameters (e.g., transmission power, retransmission, and modulation) to different multimedia frames with regard to the frame importance and channel error rates.

Similar studies in the multisource traffic coordination can be found in [9]–[13]. In [9], the feasibility of multisource video streaming in a wireless vehicular network is examined with regard to the channel conditions, traffic mobility, and road layouts. The realistic network modeling is considered as a key factor for achieving wireless video streaming by multisource coordination. In [10], a restless-bandit-based multisource selection scheme is proposed to improve the data rate in the wireless mobile P2P networks. In [11], a distributed entity called information plane that helps the network collaborate multimedia content transmission is proposed in the wireless multimedia application. In [12], the authors propose a distributed resource exchange algorithm for the P2P multimedia content collaboration, enabled by video scalable coding and optimal network resource management. Another distributed resource management algorithm is proposed in [13], in which authors investigate the delay and cost of the information exchange for each network node in the multihop cognitive radio networks. All of the aforementioned work mainly considered the multisource coordination for multimedia applications in terms of network architecture and protocol. The optimal traffic control to increase the multimedia transmission quality with latency constraints has been overlooked and is addressed in this paper.

On the other hand, most of the current research on D2D communications has been focused on traditional throughput maximization, power efficiency, or interference management; however, consideration of providing multimedia QoE has largely been ignored. Current solutions for D2D communication are typically focused on OFDM/OFDMA time-frequency resource block allocation, in conjunction with power control [19], admission control [20], interference mitigation [17], [21], and adaptive communication mode selection [16], [22]. In typical resource allocation schemes, the D2D communication acts as an underlay to long-term evolution (LTE) advanced networks [14], and the base station defined as (i.e., the eNB) is typically the controller of resource allocation and transmission coordination [8]. The authors in [14] utilized a 3GPP LTE system as a baseline and proposed a solution to increase the spectrum and energy efficiency of traditional cellular networks. Similarly, authors in [15] proposed a resource sharing optimization approach to improve cellular network throughput. Optimal resource allocation and power control schemes were presented for different resource sharing modes, concluding that optimal power control and resource allocation for the considered resource sharing modes can either be solved in closed form or searched from a finite set. The research in [17] focused on uplink channel optimization with regard to interference management, in which they introduced methods for receivers to improve D2D data-receiving reliability. Simulation results showed a remarkable enhancement, after applying the receive mode selection. The research in [18] introduced a new operator-controlled D2D network framework, in which the geographic proximity could improve data rate performance and reduce communication cost simultaneously. From the aforementioned literature, we can see that the consideration of exploring multiple source diversity in D2D multimedia transmission has largely been ignored.

TABLE I
SYMBOLS FOR EQUATIONS USED IN THIS PAPER

Symbol	Notation
$\varepsilon[D]$	Expected receiver-end QoE, e.g. the total distortion reduction
Si	The application layer optimal source UE selection set for the *i-th* packet
Mi	The link layer optimal retransmission limit for *i-th* packet
N	Number of multimedia packets
$\varepsilon[T]$	Expected transmission delay for the complete multimedia content
$Tmax$	Latency constraint of transmitting the multimedia data
L	The length of each multimedia packet
ρ_0	The packet loss ratio without retransmission mechanism
ρ	The average packet loss ratio after applying ARQ method
$\overline{m}$	The expectation of actual retransmission times for one packet
e	The PHY layer bit error rate

Fundamentally different from the aforementioned research, in this paper, we propose a novel algorithm that maximizes the multimedia QoE while assuring the latency constraint by improving the coordination of participating UEs and allocation of communication resources in wireless multimedia D2D networks. The proposed approach considers end-to-end multimedia quality (either through a direct D2D link or relayed by eNB), delay constraint, channel condition, available bandwidth, and error control mechanism. Specifically, the proposed optimal scheduling algorithm defines which multimedia frame on which source UE will be transmitted during the next time slot and then allocates the optimal retransmission limits to each multimedia frame in the process of D2D data transmission.

The rest of this paper is organized as follows. In Section II, we formulate the quality-driven D2D problem with latency constraint. In Section III, we analyze the receiver UE distortion and the delay cost numerically. In Section IV, we present the proposed optimal transmission scheduling and network resource allocation with a simplified solution. The simulation results are shown in Section V. In Section VI, we conclude this paper. Table I summarizes the symbols used in this paper.

II. Problem Statement

In this paper, we focus on improving the QoE of real-time D2D multimedia applications. Assume that N multimedia frames with various quality contributions are requested by the UE $u*$. We assume that a certain number of data source UEs (i.e., servers) in the geographic vicinity of $u*$ store at least one complete copy of these frames in combination. The eNB is assumed to coordinate the transmission path along which each frame is transmitted from different source servers to the UE $u*$. The cellular network is used to collect low rate control information such as which frames are stored on each source UE, the channel conditions for possible D2D links, etc. The feedback information is used to specify which multimedia frames will be transmitted on each server and to allocate the optimal packet retry limits on each path for maximizing the overall multimedia quality with low-latency requirement. Thus, the multimedia QoE maximization can be formulated as

$$\left\{S_{i|i\in[0,N-1]}, M_{i|i\in[0,N-1]}\right\} = \arg\max\left\{\varepsilon[D]\right\}. \quad (1)$$

Subject to the latency constraint

$$\varepsilon[T] \leq T_{\max} \quad (2)$$

where $\varepsilon[D]$ denotes the expected QoE perceived on user-side $u*$ and S_i denotes the optimal source selection for the ith packet, i.e., from which source UE the ith multimedia frame will be transmitted to the UE $u*$ during the next time slot. M_i denotes the optimal retransmission limit, i.e., the max retry time, of the ith multimedia frame. $\{S_{i|i\in[0,N-1]}, M_{i|i\in[0,N-1]}\}$ is the optimal transmission scheduling strategy which leads to the maximal service quality obtained by the UE $u*$. In the constraint equation (2), $\varepsilon[T]$ denotes the delivery time expectation of transmitting the total N frames, and $T_{\max}$ denotes the latency constraint of a specific multimedia application.

III. Transmission QoE Analysis

In this section, we derive the mathematical relationship between three factors, i.e., the network resource allocation parameter, the distortion reduction during transmission, and the corresponding communication delay. The distortion reduction is defined as the amount by which the distortion of the multimedia content is reduced, when the multimedia packet is successfully delivered and decoded at receiver UE $u*$. In the following two sections, we will express the expected total distortion reduction and the transmission delay.

A. Total Distortion Reduction Expectation

Here, the objective function of the proposed optimization algorithm is derived. Let D_i denote the distortion reduction for frame (i) and ρ_i denote the packet error rate (PER) for frame (i); thus, the total expected distortion reduction can be expressed as

$$\varepsilon[D] = \sum_{i=0}^{N-1} D_i(1-\rho_i). \quad (3)$$

For each multimedia packet, either image or video, in order to make contribution to the decoding process, the packet must be received without error and decoded successfully. As a result, the distortion of the decoded picture or video will be reduced if a packet is successfully received and decoded, for the amount of distortion reduction measured in mean square error (MSE). Equation (3) shows a summation model which is suitable for a realistic environment. Once the source finishes compressing a packet, a distortion reduction estimation value and a packet length will be available for the transmission scheduling process. The scheduling process will handle the packet transmission with resource allocation optimization, which takes count in the packet distortion reduction and packet length as inputs. Thus, in a realistic setting, two vectors will be passed to the scheduling algorithm: a vector of packet distortion reduction and a vector of packet length. They are both easy to be presented as simple data structures, suitable for low-level multimedia D2D transmission design.

The QoE metric and the wireless channel bit error rate (BER) are strongly correlated. The QoE metric is typically expressed in terms of distortion reduction, a reduced amount of MSE when a packet is successfully received and decoded. In order for a packet to make contribution to the multimedia visualization, the PER should be as low as possible. In addition, the PER is directly affected by the packet size and the channel BER. Shorter packets and lower BERs will reduce the PER and thus improve QoE. However, excessively short packets will introduce unnecessary header overheads, which increases the total transmission cost. From the aforementioned analysis, we can see that the total distortion reduction expectation is dominantly affected by the average packet loss ratio ρ. We assume that the channel BER e is known on the basis that the condition of D2D communication links can be measured at the eNB by examining the control messages that continuously flow between the base station and the users in the LTE-A networks.

Thus, the baseline packet error probability ρ_0 without any network resource allocation can be expressed as

$$\rho_0 = 1 - (1-e)^L. \quad (4)$$

Due to multipath-fading, mobility, and cochannel interference, the D2D communication links are usually unreliable and time-varying. To overcome the high packet loss rate, a network resource allocation scheme is generally considered to be a solution for protecting the data from wireless channel errors. Such techniques include forward error correction (FEC), flexible and adaptive modulation, retry adaptation mechanism, and variable data rate control. To deal with the fluctuating packet loss rate in the D2D communication link, we focus on the MAC layer retransmission strategy. According to the simple stop-and-wait ARQ protocol, a lost packet in the multimedia data will be repeated until the positive acknowledgment is received by the sender. After reaching the given retry limit, the source user abandoned retransmission, and the packet is dropped.

The retransmission mechanism requires a certain retry limit M for determining the packet loss. After that, the sender UE abandons retransmitting the packet and removes the data from the buffer to prevent the buffer overflow. Thus, the packet error after ARQ only occurs when it reaches the retry limit. Therefore, we can calculate the average PER after ARQ according to [23]

$$\rho = \rho_0^{M+1}. \quad (5)$$

In a D2D communication environment, on one hand, the random nature results in an uncertain channel condition; on the other hand, the distortion reduction contribution of each frame varies. Therefore, to overcome the difficulties and maximize the overall end user distortion reduction, network resource, e.g., the allocated retry limit, is distributed unequally to different frames. In the next section, we will provide the cost function expression.

B. Average Transmission Delay Estimation

The cost function of the proposed optimization algorithm is formed by the expected delay to receive the N multimedia frames at $u*$, which can be determined as the summation of the expected transmission delay of each multimedia frames, under the assumption of sequential transmission. After applying the ARQ method in the proposed approach, the expectation of the actual retry time $\overline{m}$ can be approximated according to [23] as a function of M and ρ_0

$$\overline{m} = \frac{1-\rho_0^{M+1}}{1-\rho_0}. \tag{6}$$

We assume that the acknowledgment is transmitted through the control messages in the cellular network, so that the delay of transmitting the control messages is not counted in the total transmission delay. Therefore, the expected transmission delay is

$$\varepsilon[T] = \sum_{i=0}^{N-1} \overline{m}_i T_S \tag{7}$$

where T_s is the frame duration for one UE in the LTE-A uplink transmission scheme. From (5)–(7), we can see the tradeoff between the retry limit and the transmission delay: to maximize the distortion reduction quality, one would like to set a high retry limit; however, it would increase the expected transmission delay. In order to maximize the expectation of distortion reduction while maintaining the delay constraint, we propose the optimal source scheduling and retry limit adaptation algorithm in the following section.

IV. Proposed Quality-Driven Scheduling and Network Resource Allocation Approach

Due to the characteristics of multisource opportunity, limited bandwidth, and latency constraint of real-time multimedia applications in D2D networks, the coordination of source UEs is an ideal approach to improve multimedia communication quality. Thus, the total workload should be optimally distributed to each source UE to avoid sending identical frames excessively, which wastes limited resource. In addition, due to different packet lengths and quality contributions of multimedia data frames, the limited bandwidth should be smartly utilized by the multimedia frames with higher quality contribution.

Algorithm 1 describes how to find the optimal source UEs and set the retry limits to each D2D link. The highlight of our proposed approach is to adapt the retry limit according to the importance of the multimedia data and the real-time channel condition. In order to achieve this purpose, the proposed approach improves the multimedia quality in D2D networks with three steps. First, find all possible multimedia frame combinations on available source UEs; second, evaluate the expected multimedia quality for all possible arrangements with frame combinations and optimal retry limit allocation; and third, obtain the optimal frame allocation strategy for each source UE and the optimal retry limit for each D2D multimedia communication link.

Algorithm 1: Joint S-Q Transmission Strategy.

```
Step 1. BER-adaptive source selection:
SortedSourceIndex = sort(sourceBER)
For i = 1 to packetCount
    For j = 1 to serverCount
        k = SortedSourceIndex[j];
        If (source k has packet i)
            S[i] = k;
            Break;
        End If
    End For
End For

Step 2. Transmission efficiency calculation:
maxARQ = 4;
For i = 0 to maxARQ
    For j = 1 to packetCount
        tranDR[i, j] = PERaftARQ(S_BER, Len[j], i)
        * DR[j];
        tranCst[i, j] = Len[j] * ExpRetrans(S_BER,
        Len[j], i)/rate;
        tranEff[i, j] = tranDR[i, j]/tranCst[i, j];
    End For
End For

Step 3. Apply greedy algorithm:
R = int array of [packetCount];
    For element in R
element = −1;
End For
TimeRemain = TimeConstrain;
[Sorted_i, Sorted_j] = Sort(transEff,"descend");
For index = 1 to packetCount * (maxARQ + 1)
    i = Sorted_i[index];
    j = Sorted_j[index];
    If (R[j] > −1)
        continue;
    End If
    If (tranCst[i, j] > TimeRemain)
        continue;
    End If
    R[j] = i;
    TimeRemain− = tranCst[i, j];
End For

Step 4. Record Outputs:
S[i]: Source Selection
R[j]: MaxARQ Selection
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The source packet selection for each source UE to the $u*$ is decided by a greedy algorithm described in Algorithm 1. The complexity is reduced by solving the coordination problem with a greedy choice since a large number of potential source users can provide the content.

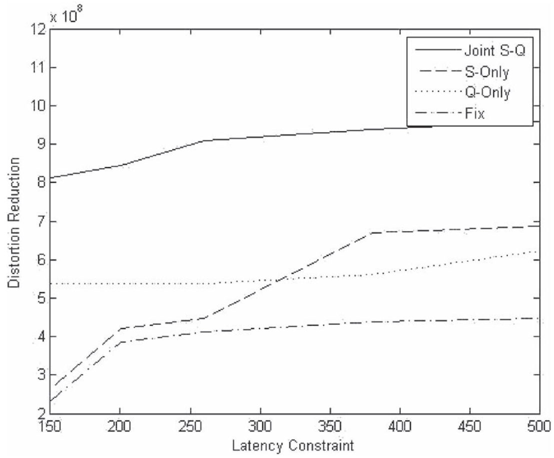

Fig. 2. Distortion reduction performance under different latency constraints (in milliseconds).

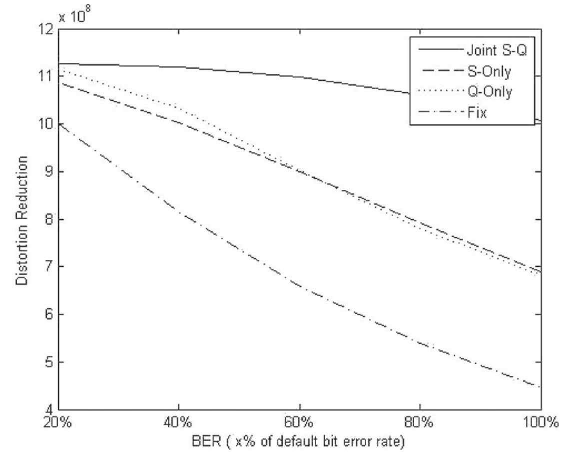

Fig. 3. Distortion reduction performances as a function of BER.

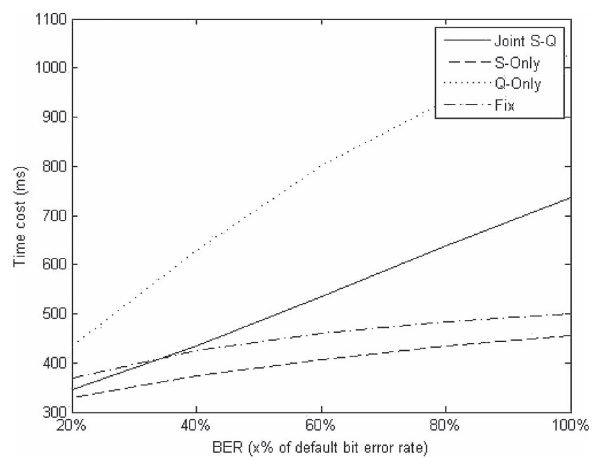

Fig. 4. Transmission delay performances under different BERs.

V. Simulation and Results

In this section, the transmission delay and the transmission quality performance are evaluated (e.g., distortion reduction) for the D2D communication overlaying cellular networks in a realistic simulation setup. We assume that the D2D users communicate directly with each other with the coordination of the centralized base station in the cellular networks. Also, the D2D users use the resources (e.g., the frequency and the time slots) not allocated for cellular users at the time. The distortion reduction is calculated in terms of the MSE. The parameters of network communication are listed as follows. The uplink data rate is 50 Mb/s. The default BER of the D2D links between the source UE and the client UE $u*$ is $1\mathrm{e}-3$. The duration of an uplink subframe in the LTE-A network protocol is 10 ms. The proposed multisource scheduling and ARQ retry limit adaptation approach (i.e., Joint S-Q) is compared to the traditional approach (i.e., Fix) that use fixed source UE and ARQ resources. Moreover, the multisource UE scheduling only (i.e., S-only) and the ARQ retry limit adaptation only approaches (i.e., Q-only) are also evaluated for comparison.

Fig. 2 demonstrates the effectiveness of the proposed joint source UE selection and network ARQ resource allocation approach. It is observed that the proposed scheme achieves a significant performance gain with various latency constraints. In each approach, the distortion reduction performance is improving as the latency constraints increase. Notably, the performance gain of the proposed scheme is especially high under low latency constraints. This is because, in the scenarios under strict latency constraints, the proposed Joint S-Q approach can find the links with better channel conditions and allocate the ARQ communication resources more efficiently, i.e., packets with more distortion reduction are assigned with higher retry limits. With higher ARQ retry limits, the average packet loss ratio will be decreased with higher transmission reliability.

Fig. 3 demonstrates the distortion reduction performances under different channel conditions. In this figure, it is observed that the proposed approach maintains a high-quality performance even with a very high channel BER. This figure shows that the proposed joint source UE scheduling and retry limit adaptation approach is more robust against channel errors because it always chooses the robust links and dynamically allocates retry limits according to the channel condition. Such performance gain is more prominent in higher channel BERs (i.e., worse channel conditions). This is because, in higher channel BER conditions, packet loss probability is higher, and the expected distortion reduction of the multimedia stream is lower. This provides more potential working spaces for ARQ resource allocation and source packet dispatching to improve the service quality. In good channel conditions with lower BERs, the performance of using or not using resource allocation and source packet dispatching becomes relatively close.

In terms of actual transmission delay cost, Fig. 4 compares the performance of the proposed "Joint S-Q" scheme against the other three schemes with different BERs in different scenarios. This figure shows that the "Q-only" scheme has the largest delay cost and our proposed "Joint S-Q" scheme has the second largest delay cost in different scenarios at different BERs. Some of the reasons for the transmission delay cost overhead are summarized as follows. First, due to the nature of the ARQ scheme, every lost packet is retransmitted before positively acknowledged, so the expected time cost is also increased to achieve better distortion reduction performance in the time-varying

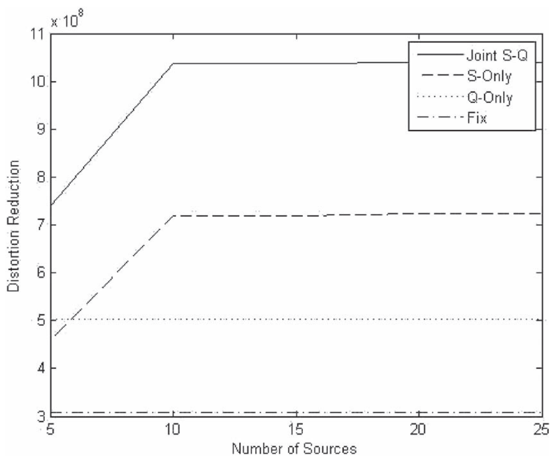

Fig. 5. Distortion reduction performances with different numbers of sources.

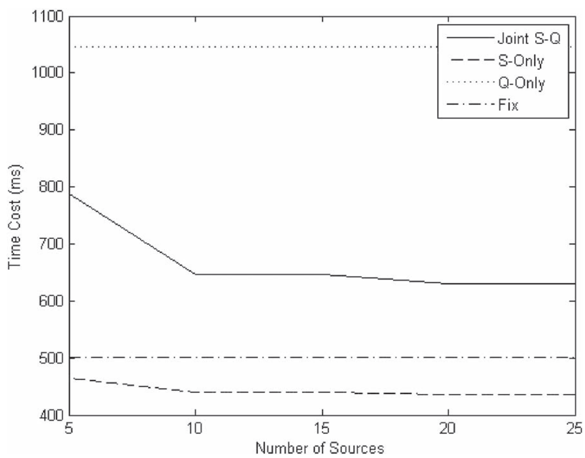

Fig. 6. Transmission delay performances with different numbers of sources.

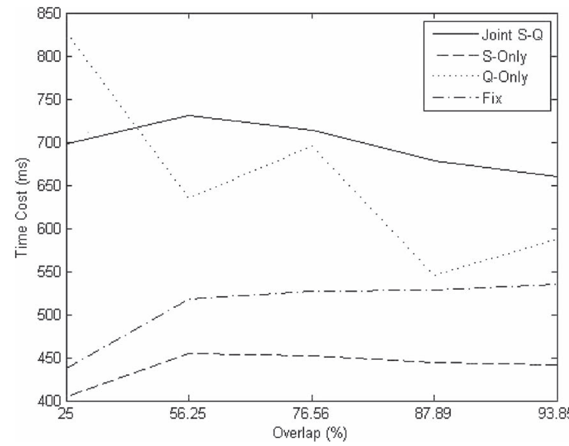

Fig. 7. Transmission delay performances with different overlapping ratios among sources.

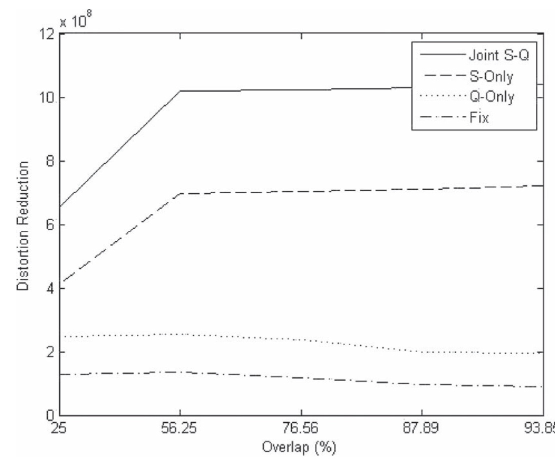

Fig. 8. Distortion reduction performances with different overlapping ratios among sources.

lossy channel conditions. Second, our proposed "Joint S-Q" scheme achieves lower time cost than the "Q-only" scheme because the greedy optimal source scheduling algorithm selects the links with better channel conditions all of the time. Last but not the least, even though, compared with the "S-only" and "Fix" approaches, the ARQ-based schemes require more transmission time, the distortion reduction performance is guaranteed while maintaining the latency constraint.

Figs. 5 and 6 illustrate the distortion reduction performances and the transmission delay performances under different numbers of UE sources. Intuitively, more UE sources provide more choices for the proposed D2D source-retry scheduling, and thus, the multimedia quality performance should also increase. In the meanwhile, more choices of UE sources incur higher computation complexity in choosing the best source UEs, and they will increase the scheduling overhead. From Fig. 5, we note that the source selection scheduling approaches "Joint S-Q" and "S-only" improve the distortion reduction performance as the number of source increases, while that of "Fix" and "Q-only" schemes remain the same. Fig. 6 shows the time cost of the four schemes with different numbers of sources. Still the "Q-only" scheme needs the highest transmission time due to its retransmission scheme. Also, observe that the time cost of "Joint S-Q" and "S-Only" decreases as the number of sources increases. This is because the greedy algorithm makes better choice with more combinations.

Figs. 7 and 8 show the distortion reduction performance and delay cost under different content overlap ratios. Content overlap ratio is the parameter that determines whether and how imedia content is shared by more than one source UE in a small-scale D2D communication system covered by a single eNB. The higher the overlap ratio, the more redundancy of multimedia packets is on different source UEs. Thus, the higher the overlap ratio, the more choices the proposed approach can select to find the best source UEs to transmit the packets. Fig. 7 shows the time delay of the four comparison schemes in D2D communications. The proposed approach has a relatively higher latency overhead due to resource allocation optimization, where more time is allocated to retransmission of important multimedia packets at various sources. In Fig. 8, we can see that the distortion reduction increases as more content is shared among the users. This matches our intuitive expectation that more choices will be available when a higher redundancy exists among multiple source UEs. When the overlap ratio is higher than 56%, then the performance cannot grow more because there are enough choices for the greedy algorithm to achieve the maximized performance.

VI. Conclusion

In this paper, we have proposed a joint multimedia source-protocol optimization strategy for quality-driven multimedia communications in modern wireless D2D overlaying cellular networks. The proposed strategy maximizes the client UE-end QoE in terms of distortion reduction with strict latency constraints by optimally dispatching the packet content from each source UE and allocating optimal retry limit for each transmission link. The greedy-based algorithm presented in this paper reduces computational complexity and can be easily implemented for the real-time multimedia services. The simulation results demonstrate the effectiveness of the proposed joint source-protocol scheduling strategy in various practical scenarios, which significantly improves the multimedia QoE with limited resource constraints.

VII. Future Works

With the steady development of emerging multimedia intensive applications, such as cloud-based video gaming and social media image sharing, big-data transportation over bandwidth-constrained wireless last mile access becomes a critical challenge. D2D has been identified as an ideal candidate to offload cellular data and increase the total capacity of the 5G system, by exploring geographic proximity of user devices to improve wireless communication quality. The discussion of how to improve multimedia QoE in D2D environment has largely been ignored in literature. In addition to the proposed source-retry codesign, we will investigate more effective resource allocation strategies, such as power control, rate adaptation, fragmentation control, FEC, and a combination of them, to achieve better QoE within strict latency constraints. We will also formulate an energy-constrained QoE optimization problem for D2D multimedia, since energy consumption becomes a more important challenge for smart-phone user devices.

The proposed joint source dispatching and retry control could also be applied to machine-to-machine communications and Internet of Things (IoTs) with QoE requirements, e.g., video surveillance IoTs, or acoustic intrusion detection systems, and wearable body sensor network healthcare systems. Different packet prioritization schemes will be developed for specific applications, and various lower level wireless communication protocols and resource allocation schemes will be designed to accommodate various QoE requirements.

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