SoCast: Social Ties Based Cooperative Video Multicast

Yang Cao[1], Xu Chen[2], Tao Jiang[1], and Junshan Zhang[2]
[1]Department of Electronics and Information Engineering,
Huazhong University of Science and Technology, Wuhan, 430074, China
[2]School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, AZ, 85287, USA

***Abstract*—In this paper, we propose SoCast - a cooperative video multicast framework to stimulate effective cooperation among mobile users (clients), by leveraging two types of important social ties, i.e., social trust and social reciprocity. By using SoCast, clients can form groups to restore incomplete video frames by obtaining missing packets from other clients, according to the unique video encoding structure. In return, the user perception video quality of mobile video multicast can be improved. Specifically, we first cast the problem of social ties based group formation among clients as a coalitional game, and then devise a distributed algorithm to obtain the core solution (group formation) for the formulated coalitional game. Further, a resource allocation mechanism is proposed for the base station to handle radio resource requests from client groups. Extensive numerical studies with real video traces corroborate the significant performance gain by using the SoCast.**

I. Introduction

With the explosive popularity of smartphones and other mobile devices, the past few years have witnessed a tremendous growth of multimedia applications in wireless systems. Recent studies predict that wireless video/audio applications, including VoIP, video streaming and real-time surveillance, will dominate the wireless traffic in a near future. For instance, Cisco Visual Index reports that mobile video traffic is expected to grow over 26 times from 2010 to 2015 [1]. Such an explosive growth in the mobile video traffic poses a significant challenge for future 4G mobile broadband networks (e.g., LTE-Advanced networks). It is therefore of great interest to study efficient video streaming mechanisms for 4G mobile broadband networks.

Multicast is an efficient video streaming paradigm by leveraging the broadcasting nature of wireless transmissions to deliver video traffic to multiple mobile users (clients) simultaneously. Due to its effectiveness, video multicast is now playing a more and more important role in multimedia services. Important application scenarios for the video multicast include 1) live sport videos: in US, numerous sport programs are broadcast live on the Internet and can be watched on mobile devices. 2) Breaking news videos: when breaking news happens, many people click on the same news video on mobile devices. These requests made around the same time can be batched and fulfilled via multicast transmissions. In fact, one important design target of 4G mobile broadband standards such as the 3GPP LTE and the IEEE 802.16e is to implement the video multicast for mobile TV programs and other commercial video programs [8].

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Although mobile video multicast is capable to boost performance of 4G mobile network for multimedia services, it remains quite challenging to achieve efficient multicast mechanism design. One key challenge is how to cope with diverse fading channels of multiple clients [2]. Suppose there are two clients, one is with a "good" channel and the other one is with a "bad" channel. When the base station (BS) multicasts video stream according to the "bad" channel, resulted low transmission rate would degrade the video quality[1]. Otherwise, the client with a "bad" channel may fail to decode packets. To address this challenge, we can leverage the peer-to-peer cooperation among clients such that they can share packets among each other [2]. Towards this end, there are two critical issues involved in the cooperative video multicast: *1) how to stimulate a client to help others?* Since the packet sharing typically incurs overheads such as energy consumption, a client may not be willing to help others for free without proper incentive. *2) How to coordinate clients' cooperation according to the unique encoding structure of a video stream?* This is because that boosting the transmission rate may not lead to a significant gain in the user perception video quality when the video encoding structure is not considered. To answer the above two questions, we propose a novel cooperative video multicast framework termed as *SoCast* for mobile clients. The salient feature of SoCast is to stimulate cooperation among clients via utilizing social ties, meanwhile taking into account the video encoding structure.

As illustrated in Fig. 1, SoCast can be projected onto two domains: the physical domain and the social domain. In the physical domain, a BS multicasts a video stream to multiple clients, and these clients can share packets among each other via network assisted device-to-device (D2D) communications [3]. In the social domain, client users have diverse cooperation relationships due to their social ties. The underlying rationale of considering social ties is that the mobile devices

[1]An Internet video server can prepare multiple copies of a video with different qualities. When the transmission rate is higher, a higher quality copy would be used in the multicast. Otherwise, a lower quality one would be used.

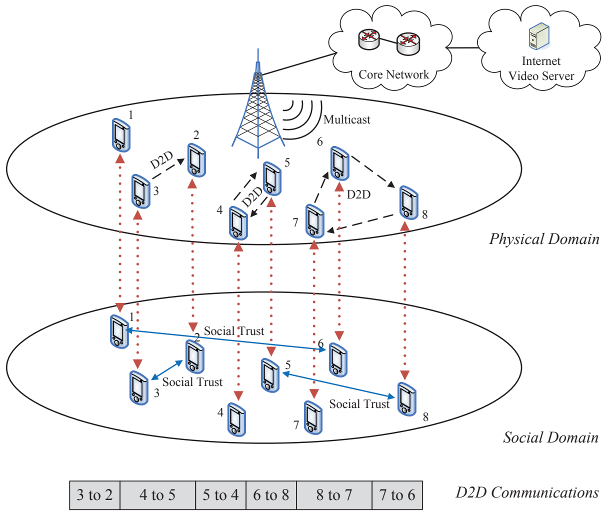

Fig. 1. An illustration of cooperative video multicast based on social ties.

are carried by human beings and the knowledge of human social ties can be utilized to enhance the performance of the video multicast. Here, we consider two important types of social ties. The first type is the *social trust*, which is a mutual trust widely observed among family members, friends and colleagues. In Fig. 1, client 3 is willing to help client 2 (or *vice versa*) without any immediate return when they are friends (social trust). Another type is the *social reciprocity*, which is a powerful mechanism for promoting mutual beneficial cooperation among unfamiliar clients. In Fig. 1, client 4 and client 5 who do not have social trust with each other are willing to help each other (social reciprocity) to improve the quality of the video streaming. By leveraging the social trust and the social reciprocity, SoCast can stimulate clients to help each other for restoring their incomplete video frames, and thus the overall user perception video quality can be greatly improved.

The contributions of this paper are summarized as follows:

- We propose SoCast - a cooperative video multicast framework to stimulate effective cooperation among clients, by leveraging two types of social ties, i.e., social trust and social reciprocity. Unique video encoding structure is taken into consideration in SoCast.
- We cast the problem of social ties based group formation among clients for cooperative video multicast, as a coalitional game. We devise a distributed algorithm to obtain the core solution (group formation) for the formulated coalitional game. Further, a resource allocation mechanism is proposed for the BS to handle radio resource requests from client groups.
- Extensive numerical studies with real video traces corroborate that SoCast improves the average video PSNR (Peak Signal-to-Noise Ratio) by up to 12.7 dB compared to a baseline scheme, and the user perception video quality is improved by up to 2 grades.

There has recently been much effort on the video multicast over wireless networks. DirCast [4] applies association control to minimize the total multicast delay, and within each access point, DirCast chooses the transmission rate based on the channel condition of the "worst" client in the multicast group. Clearly, DirCast still suffers from "the curse of the worst one". In [5], Deb *et al.* studied the problem of multicasting scalable videos through WiMAX with the goal of maximizing the system utility. They developed a greedy algorithm to allocate radio resources and adaptively decide the data rate for each transmitted video layer. SoftCast [6] proposed a joint channel encoding and video source coding scheme for mobile video transmissions. FlexCast [7] modified the MPEG-4 video codec and incorporated rateless coding for efficient video streaming in wireless systems. In [8], MuVi was proposed to improve the overall performance of the mobile video multicast, which operates on a gateway between the Internet video server and the base station. MuVi resorts the order of video frames or even drops some frames according to channel qualities of clients. Most of above approaches require heavy modifications to video encoding schemes or the air interface, or add new component to the system, which may be quite challenging to be implemented in practical systems. By contrast, SoCast is compatible with existing video encoding schemes and air interfaces, and mainly modifies the client side applications for easy implementations.

II. Mobile Video Multicast System Model

In this section, we give a brief introduction to the mobile video multicast system model. As illustrated in Fig. 1, we consider the mobile video multicast over an orthogonal frequency division multiple access (OFDMA) based mobile broadband network[2]. The BS operates in the multicast function, and a set of mobile users (clients) $\Psi = \{1, 2, \cdots, N\}$ are in the same multicast group, where N is the total number of clients. The BS allocates a channel (e.g., a number of OFDM tones) to support the video multicast for the clients. Moreover, to enable fast and reliable packet sharing among clients, we consider the network assisted D2D communications. Specifically, a group of clients who would like to conduct D2D communications among each other will send their requests to the BS. Then the BS carries out the admission control (i.e., deciding which D2D communication requests to be accepted) and allocates radio resources accordingly.

To achieve an efficient mobile video multicast mechanism design, we next discuss the unique features of mobile video multicast.

A. Video Encoding Structure

We first introduce the video encoding structure and the video streaming. We consider that an Internet video server provides video streams for the clients in the multicast group via multicast. In general, the video is encoded using a Group-of-Picture (GOP) structure [9], which is a typical codec of MPEG-4 or H.264 to reduce the total bandwidth demand of video streaming. As illustrated in Fig. 2 (a), a GOP is formed by a number of encoded video frames, i.e., I frame, P frame and B frame. There is usually an I frame at the beginning

[2] OFDMA is widely adopted in 4G mobile broadband standards.

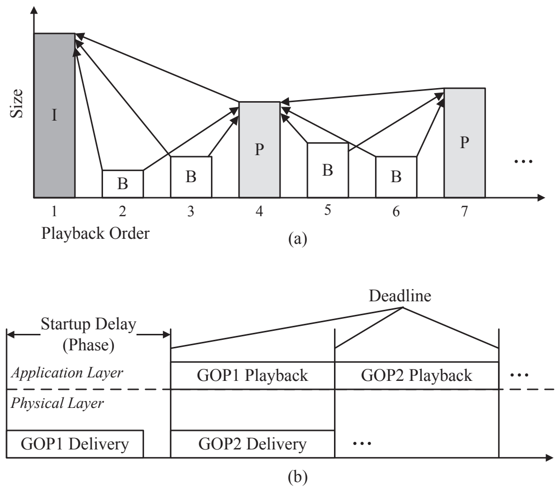

Fig. 2. (a) The structure of a GOP. A line directed from frame x to frame y indicates that the decoding of frame x depends on frame y. (b) An illustration of video streaming. In the physical layer of each client, packets in a GOP are received before the deadline; In the application layer of each client, GOP playback occurs.

of a GOP. The I frame typically has the largest size and is intra-coded. Hence it does not depend on other frames (e.g., P frames and B frames). By contrast, P frames and B frames within a GOP have a much smaller size than that of the I frame and are encoded interdependently using motion estimation and etc. In general, every P frame depends on the preceding I or P frame, and every B frame depends on the preceding I or P frame, as well as on the succeeding I or P frame.

In the video streaming, each encoded video frame is processed into a number of packets for delivery. Unlike data transmissions for the web browsing or the file downloading, video streaming could be a strict real-time application [10]. Clearly, once video playback starts, mobile users expect the video frames to be displayed continuously and smoothly, i.e., there is no rebuffing of packets. To this end, a packet or a batch of packets are associated with a delivery deadline. If a packet misses the deadline, it will be dropped. More specifically, as illustrated in Fig. 2 (b), we consider that the video streaming is tolerable with a maximum startup delay, which equals the playback duration of a GOP. The BS buffers packets in a GOP and attempts to deliver them to clients before the deadline (equals the playback duration). When the deadline is due, undelivered packets in the GOP will be dropped by the BS. As a result, each client has to rebuild video frames with received packets and plays them accordingly. In the sequel, we define the duration from the beginning of multicasting packets in a GOP, to the delivery deadline, as a *phase*.

B. Modulation-and-Coding Scheme (MCS)

We next introduce the concept of MCS. For ease of exposition, we assume that the channel quality of each link is quasi-static, i.e., the channel quality keeps unchanged for the duration of an OFDMA frame that lasts for several milliseconds. In LTE-Advanced networks, the channel quality can be measured by each client as the Channel Quality Information (CQI). Based on CQI, the MCS selected by the transmitter

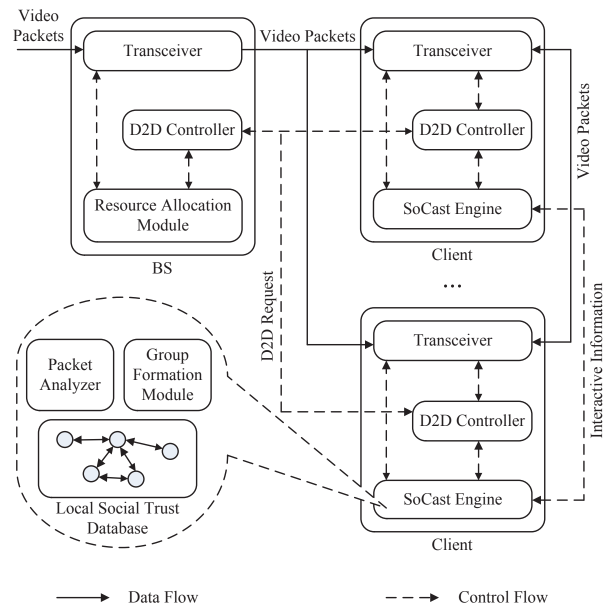

Fig. 3. System components of SoCast.

(BS or client) determines the data transmission rate of a link. For a specific link, a MCS of low transmission rate with a good channel quality would lead to the radio resource under-utilization, while a MCS of high transmission rate with a bad channel quality may render high bit error rate, thus degrade the goodput[3]. By using the channel feedback of a receiver and a CQI-MCS mapping table, a transmitter can choose an appropriate transmission rate, thus the receiver can decode received packets correctly [8].

When the BS attempts to multicast packets to clients in Ψ with heterogeneous channel qualities, one MCS should be chosen for all the clients. We denote $\gamma_i(t)$ as the channel quality of client i during OFDMA frame t, and denote $\bar{\gamma}$ as the minimum channel quality in order to decode a packet transmitted with a specific MCS correctly. When $\gamma_i(t) \geq \bar{\gamma}$, client i can decode packets during OFDMA frame t successfully, otherwise, we consider that these packets are lost.

III. A SoCast Framework

In this section, we propose a SoCast framework for mobile video multicast, which stimulates cooperation among clients via utilizing social ties, while taking into account the video encoding structure.

A. An Overview of SoCast

As depicted in Fig. 3, SoCast highlights the application of network assisted D2D communications to enable beneficial cooperation among clients in the multicast scenario. There is a D2D controller in each node (BS or client), which is in charge of establishing and managing D2D communications among clients. Moreover, we assume that there are two multi-user sharing modes for D2D communications. The first mode is based on the random access such as CSMA, which is used

[3]Goodput is the number of useful information bits delivered by the link to the receiver, per unit of time.

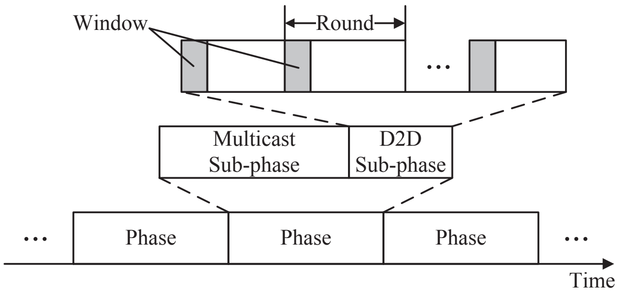

Fig. 4. System workflow of SoCast.

to self-organize interactive information transmission among clients, and does not require the coordination by the BS. The second mode is similar to the time-division multiple access, which is used for transmitting shared video packets among clients, and requires the coordination by the BS to achieve a high system throughput.

As illustrated in Fig. 4, the time structure of SoCast is organized based on the phases. Each phase can be divided into two parts, i.e., *multicast sub-phase* and *D2D sub-phase*. At the beginning of a phase, the BS multicasts packets in a GOP of video streams during the multicast sub-phase. During the following D2D sub-phase, clients would like to share missing packets among each other via D2D communications, in order to increase the quality of video streams. More specifically, the D2D sub-phase can be divided into multiple *rounds*. There is a *window* at the beginning of each round, in which the following actions are executed sequently:

- Clients first determine how to obtain missing packets from other clients based on social ties, and then send D2D communication requests to the BS;
- BS then determines the radio resource allocation policy for multiple D2D communication requests. We assume that the minimum radio resource allocation unit for the BS-coordinated D2D is a *slot*.

The remaining part of a round is to conduct D2D communications among clients to exchange missing packets according to the allocated transmission slots by the BS. In what follows, we will introduce key components of the client and the BS - *SoCast engine* and *resource allocation module*, respectively.

B. SoCast Engine

We first introduce the SoCast engine for the clients. At each client, the transceiver buffers video packets in the same GOP, and then provides packet information to the SoCast engine. SoCast engines at multiple clients can coordinate with each other via interactive information, in order to restore incomplete video frames by sharing packets.

As depicted in Fig. 3, a SoCast engine mainly consists of a *packet analyzer*, a *group formation module* and a *local social trust database*.

1) Packet Analyzer: By using a packet analyzer, the SoCast engine knows which packets are missing for a specific video frame during the multicast sub-phase. Accordingly, in the D2D sub-phase, the SoCast engine attempts to restore incomplete video frames by obtaining missing packets from other clients. Based on the video encoding structure introduced in Section II, we know that different video frames play different roles in the video streaming. We hence introduce the following two definitions:

TABLE I
AN EXAMPLE OF INFORMATION TABLE.

Helper	Frame	Social Trust	Required Resource
1	3 (B Frame)	No	5 Slots
3	7 (P Frame)	Yes	15 Slots
5	7 (P Frame)	No	10 Slots
5	3 (B Frame)	No	3 Slots

Definition 1. A video frame is *valuable* if and only if the video frames it depends on and itself are complete (there are no missing packets).

Definition 2. A video frame is *potentially valuable* if and only if it has missing packets, while the frames that it depends on are complete.

Clearly, once a potentially valuable frame is restored, it will become valuable. Intuitively, each client should only attempt to restore potentially valuable frames in each round to improve the video quality.

2) Local Social Trust Database: The underlying rationale of using social trust is that the mobile devices are carried by human beings and the knowledge of human social trust can be utilized to achieve effective and trustworthy assistance for video frame restoration in the video multicast.

More specifically, we introduce the social trust graph $\boldsymbol{G}^{\mathbf{T}} = \{\Psi, \mathcal{E}^T\}$. Here the set of clients Ψ is the set of vertices, and the set of edge $\mathcal{E}^T = \{(ij) : e_{ij}^T = 1, \forall i, j \in \Psi\}$, where $e_{ij}^T = 1$ if and only if client i and client j have social trust towards each other, which can be kinship, friendship, or colleague relationship between two clients. Based on $\boldsymbol{G}^{\mathbf{T}}$, we have $\Psi_i^T = \{j : e_{ij}^T = 1, \forall j \in \Psi\}$ as the set of clients having social trust with client i. Clearly, client j in Ψ_i^T is willing to help client i due to the social trust between them.

We note that each client can obtain Ψ_i^T based on its own local social trust database, which can be built by adopting the private set intersection technique in [11] to locally identify the social relationship between two clients in a privacy-preserving manner and such a operation can be done before the video multicast.

3) Group Formation Module: At the beginning of a window in the D2D sub-phase, each client broadcasts a request that contains the IDs of missing packets for potentially valuable frames, to other clients over the channel via a random access manner. Through a matching and feedback process, each client can obtain an *information table*, which contains the information of candidate helpers for video frame restorations, the video frames to be restored, required resources (i.e., number of slots) of delivering missing packets for each video frame, and social trust relationship (through local social trust database). Suppose that frame 3, 5, 6, 7 in a GOP (see Fig. 2 (a)) are incomplete for client i, then, it requests missing packets for two potentially valuable frames, i.e., frame 3 and 7. The information table for this case is shown as Table I.

When all clients have obtained information tables, they will form *groups* among them by using group formation modules. Clearly speaking, there are two types of groups, *social trust group* and *social reciprocity group*. On one hand, a social trust group has two members, which has social trust towards each other, and one member (helper) will help the other one (taker). On the other hand, a social reciprocity group can be formed among the set of clients without social trust. A social reciprocity group has at least two members, which forms a *reciprocal circle*, in which a client will provide assistance to other client and receive assistance from another client, making all of them better off. For example, in Fig. 1, client 2 and 3 form a social trust group, client 4 and 5, client 6, 7, 8 form two social reciprocity groups, respectively. At the end of a window in the D2D sub-phase, multiple groups are formed, and each group has a *leader* to send D2D communication request to the BS. The number of totally required slots by the group would be contained in the request. For the purpose of ensuring the fairness and accounting for the resource limitation to support D2D communications, each client can restore at most one of its video frames per round. Since there can be multiple rounds during a D2D sub-phase, it is possible that a client restores multiple incomplete video frames. The objective of the SoCast engine is to stimulate effective cooperation among clients to restore as many as possible potentially valuable video frames through forming groups based on social ties.

C. Resource Allocation Module

We next discuss the radio resource allocation module for supporting D2D communications among clients in the BS [12]. For each round of the video frame restoration, the resource allocation module receives requests from multiple groups and allocates radio resources to them accordingly. Notice that, the BS does not required to know the video encoding structure and the social ties among clients when allocating radio resources. For example, client 6, 7, 8 in Fig. 1 expect to establish D2D communications among them to form a reciprocity group, in which client 7 helps client 6, client 8 helps client 7 and client 6 helps client 8. Client 6, 7, 8 requires 6 slots, 8 slots, 6 slots to help the other client, respectively, thus totally 20 slots are required to establish D2D communications. When the resource allocation module decides to accept the request from client 6, 7, 8, it should allocate 20 slots to them for this round. The objective of the resource allocation module is to maximize the utilization of radio resources for supporting D2D communications among clients.

IV. Scheduling for SoCast

Based on the SoCast framework in Section III, we now address the following two key challenges: *1) How to form clients to proper groups based on social trust and social reciprocity in a distributed manner, so that the user perception video quality is improved? 2) How to allocate radio resources to different groups, so that the radio resource utilization can be maximized?*

A. Social Ties Based Group Formation

Since each client can restore at most one video frame per round for the purpose of ensuring the fairness and accounting for the resource limitation to support D2D communications, a client may need to choose between a social trust group (as a taker) or a social reciprocity group. We first generalize the concept of social reciprocity group, i.e., we consider that the taker in a social trust group, or a client not in any group (single client), forms a special social reciprocity group with a self-circle. Then a key challenge is how to efficiently divide the clients into multiple social reciprocity groups such that the clients can significantly improve the user perception video qualities. We will propose a coalitional game framework to address this challenge.

1) An Introduction to Coalitional Game: For the sake of completeness, we give a brief introduction to the coalitional game [13]. Formally, a coalitional game can be represented by a tuple $\Omega = \{\Psi, \mathcal{X}_\Psi, V, (\succ_i)_{i\in\Psi}\}$, where

- Ψ is a finite set of players;
- $\mathcal{X}_\Psi$ is the space of feasible cooperation strategies of all players;
- V is a characteristic function that maps from every nonempty subset of players $\Delta \subseteq \Psi$ (a coalition) to a subset of feasible cooperation strategies $V(\Delta) \subseteq \mathcal{X}_\Psi$. This represents the possible cooperation strategies among the players in the coalition Δ, given that other players out of the coalition Δ do not participate in any cooperation;
- $(\succ_i)_{i\in\Psi}$ is a strict preference order (reflexive, complete and transitive binary relation) on $\mathcal{X}_\Psi$ for each player $i \in \Psi$. This captures the idea that different players may have different preferences over different cooperation strategies.

In the same spirit as the Nash equilibrium in a non-cooperative game, the "core" plays a critical role in the coalitional game. Here we have the following definition:

Definition 3. The core is the set of $\mathbf{x} \in V(\Psi)$ for which there does not exist a coalition Δ and $\mathbf{y} \in V(\Delta)$ such that $\mathbf{y} \succ_i \mathbf{x}$ for all $i \in \Delta$.

Clearly, the core is a set of cooperation strategies such that no coalition can deviate and improve for all its members by cooperation within the coalition [13].

2) Coalitional Game Formulation and Core Solution: We now formulate the social ties based group formation for the cooperative video multicast as a coalitional game.

(1) **Preference Order Construction:** First of all, we consider the critical part of the coalitional game formulation, i.e., constructing the preference order $(\succ_i)_{i\in\Psi}$. To this end, we take the video encoding structure and the goal of improving the video quality into consideration. Let v_m denote the value of video frame m as follows:

$$v_m = \begin{cases} 1 + N_d^m, & \text{if the video frame is valuable,} \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

where N_d^m is the maximum number of video frames that depend on this frame in a GOP. For example, there are one I frame, two P frames and four B frames in the GOP depicted in Fig. 2. We can find that, the I frame has $N_d^m = 6$ because two P frames and four B frames depend on it directly or indirectly. The P frame on the left has $N_d^m = 5$ while the P frame on the right has $N_d^m = 2$. All B frames have $N_d^m = 0$.

Intuitively, the preference of a helper is determined by two aspects: 1) v_m when a video frame m is restored in the assistance of the helper (the larger, the better); 2) the required slots by the helper to deliver missing packets (the less, the better). Accordingly, we construct a preference order list as follows. First, if a helper can assist to restore multiple video frames, then choose the video frame with the highest value when it is restored in this round. Next, assign a higher priority to the helper who can restore a video frame with a higher potential value, regardless of the required radio resources. If multiple helpers can restore video frames with a same potential value, than the one with less required slots is of a higher priority. To support self-circle reciprocity groups (taker in a social trust group or single client), find the best helper that has social trust towards client i (termed as client j), then replace client j with client i in the preference order list. If there is no helper that has social trust towards client i, add client i to the end of the preference order list. For example, for client i, the preference order list for the case in Table I is $\{5, i, 1\}$ (client 5 is the most preferred helper, client 3 that has social trust with client i is replaced by client i). Elements in the preference order list of client i forms a set Ψ_i^P.

(2) **Coalitional Game Formulation:** Based on the preference order introduced above, we then cast the social ties based group formation problem as a coalitional game $\Omega = \{\Psi, \mathcal{X}_\Psi, V, (\succ_i)_{i\in\Psi}\}$ as follows:

- the set of players Ψ is the set of clients;
- the set of cooperation strategies $\mathcal{X}_\Psi = \{(h_i)_{i\in\Psi} : h_i \in \Psi_i^P, \forall i \in \Psi\}$, which gives the set of possible helpers for all clients;
- the characteristic function $V(\Delta) = \{(h_i)_{i\in\Psi} \in \mathcal{X}_\Psi : (h_i)_{i\in\Delta} = (j)_{j\in\Delta}$ and $h_k = k, \forall k \in \Psi\backslash\Delta\}$ for each coalition $\Delta \subseteq \Psi$. The condition $(h_i)_{i\in\Delta} = (j)_{j\in\Delta}$ represents the possible packets exchange among the clients in the coalition Δ. The condition $h_k = k, \forall k \in \Psi\backslash\Delta$ represents that the clients out of the coalition Δ would be a taker in a social trust group or not in any group;
- the preference order $(\succ_i)_{i\in\Psi}$ is defined as $(h_k)_{k\in\Psi} \succ_i (h'_k)_{k\in\Psi}$ if and only if $h_i \succ_i h'_i$. Clearly speaking, client i prefers the group formation $(h_k)_{k\in\Psi}$ to another group formation $(h'_k)_{k\in\Psi}$ if and only if helper h_i in $(h_k)_{k\in\Psi}$ is preferred by client i than helper h'_i in $(h'_k)_{k\in\Psi}$, according to the preference order list.

The core of this coalitional game is a set of $(h_i^*)_{i\in\Psi} \in V(\Psi)$ for which there does not exist coalition Δ and $(h_i)_{i\in\Psi} \in V(\Delta)$ such that $(h_i)_{i\in\Psi} \succ_i (h_i^*)_{i\in\Psi}$ for all $i \in \Delta$. That means, no coalition of clients can deviate and obtain better helper by cooperation in coalition Δ. The objective is to find the core solution $(h_i^*)_{i\in\Psi} \in V(\Psi)$.

(3) **Obtaining Core Solution:** We then study the core solution. Given the preference order lists of all clients, a preference graph $G^{\mathbf{P}}_{\mathcal{M}} = \{\mathcal{M}, \mathcal{E}^P\}$ can be constructed for a given set of clients $\mathcal{M} \subseteq \Psi$. Specifically, the given set of clients $\mathcal{M}$ is the set of vertices, and the set of edge $\mathcal{E}^P = \{(ij) : e_{ij}^P = 1, \forall i, j \in \mathcal{M}\}$. There is an edge directed from client i to client j ($e_{ij}^P = 1$) if and only if client j is the most preferred helper (MPH) among the set of clients $\mathcal{M}$ according to the preference order list of client i. Based on the preference graph, we have the following definition:

Definition 4. Given a preference graph $G^{\mathbf{P}}_{\mathcal{M}}$, a client sequence $\mathcal{C} = \{i_1, \cdots, i_L\}$ is termed as a *reciprocal circle* of length L if and only if $e^P_{i_l, i_{l+1}} = 1$ for $l = 1, \cdots, L-1$ and $e^P_{i_L, i_1} = 1$.

Based on the concept of the reciprocal circle, we can then compute the core solution for our coalitional game formulation by identifying the reciprocal circles in an iterative manner. More specifically, we denote the set of clients at the t-th iteration as $\mathcal{M}_t$, and identified reciprocal cycles are denoted by $\mathcal{C}_1^t, \cdots, \mathcal{C}_{Z_t}^t$, where Z_t is the number of identified reciprocal cycles. For the first iteration $t = 1$, we set $\mathcal{M}_1 = \Psi$ and find the reciprocal cycles as $\mathcal{C}_1^1, ..., \mathcal{C}_{Z_1}^1$ on the preference graph $G^{\mathbf{P}}_{\mathcal{M}_1}$. For the second iteration $t = 2$, we can then set that $\mathcal{M}_2 = \mathcal{M}_1 \backslash \cup_{i=1}^{Z_1} \mathcal{C}_i^1$ (i.e., remove the clients in the cycles in the previous iteration) and find the new reciprocal cycles as $\mathcal{C}_1^2, ..., \mathcal{C}_{Z_2}^2$ based on the preference graph $G^{\mathbf{P}}_{\mathcal{M}_2}$. This procedure repeats until the set of nodes $\mathcal{M}_t = \varnothing$ (i.e., no operation can be further carried out).

For a similar problem in the context of the cooperative relay selection problem, [14] showed that the relay selection based on the reciprocal cycles is the core solution. Similarly, for our coalitional game formulation for the cooperative video multicast, the derivation based on the reciprocal cycles can also obtain the core solution. The key idea is that a reciprocal cycle is a mutually best outcome for the clients within the cycle, among the possible coalitions at each iteration. More specifically, for the first iteration $t = 1$, clients in each identified reciprocal cycles as $\mathcal{C}_1^1, ..., \mathcal{C}_{Z_1}^1$ receive the assistance from the MPH among all the clients $\mathcal{M}_1 = \Psi$ and hence they do not have any incentive to deviate. Given this fact, at the second iteration $t = 2$, clients in each identified reciprocal cycles as $\mathcal{C}_1^1, ..., \mathcal{C}_{Z_2}^2$ receive the best available helper among the remaining clients $\mathcal{M}_2$ and they also can not improve by deviation. Such an argument holds for all the reciprocal cycles.

We should emphasize that, different from [14], the proposed coalitional game is formulated in the context of cooperative video multicast, and we construct the preference order based on the unique video encoding structure. Moreover, [14] mainly considered to implement the core solution in a centralized manner. While in this paper, we propose a distributed implementation of the core solution - the distributed group formation algorithm for the cooperative video multicast, which would not incur extra communication overheads between a client and the BS during the group formation process.

(4) **Distributed Group Formation:** We now introduce the distributed group formation algorithm. Based on the preference graph, a reciprocal circle can be found by a *path*, which is a client sequence started from an arbitrary client in the preference graph. Each client (besides the first one) in the path is the MPH of the client previous to it in the path. We have the following observation.

Theorem 1: A path beginning from any vertex in preference graph $G^{\mathbf{P}}_{\mathcal{M}_t}$ results in one and only one cycle.

Proof: We construct the preference graph based on the MPH in the preference order list, and hence each vertex has an out-degree of one. This implies that we can construct a path of an infinitely large length if the path does not induce a cycle. This contradicts with the fact that the number of vertices on the graph is finite. On the other hand, if the path induces multiple distinct cycles, there must exist a vertex with more than one outward directed edge. This contradicts with the fact that each vertex has an out-degree of one. ■

Based on Theorem 1, we propose a distributed social reciprocity group formation algorithm. The key idea is that clients locally send probing messages to detect the reciprocal cycles. Specifically, a client i first sends the probing message to its MPH, client j. Client j then forwards this message to its MPH. Such a process continues until client i receives this message from another client if a reciprocal cycle exists. The detailed steps of the distributed group formation mechanism are given as follows.

1) Each client $n \in \Psi$ with flag $F_n = 1$ (i.e., client n has not involved in any reciprocal cycle) contends for the reciprocal cycle discovery via a random access manner.
2) When client i wins the contention, client i first broadcasts BUSY message to declare it will do reciprocal cycle discovery, and other clients would not do reciprocal cycle discovery until it finishes. Then client i transmits message MESG to its MPH, client j.
3) For the client j who receives the MESG, it first records the client from whom the message comes, and then checks F_j's value. In particular, if $F_j = 0$ (i.e., client j has involved in some reciprocal cycle), client j sends REJ message to client i, then client i sends the message MESG to the next preferable client according to the preference order. If $F_j = 1$ (i.e., client j has not been involved in any reciprocal cycle), then client j attaches its ID to the message MESG. Next, it transmits the MESG to its MPH.
4) The process continues until there is a client k who has received the MESG message before (i.e., a reciprocal cycle is identified). Client k sets its flag $F_k = 0$, then it can obtain the list of clients from the cycle (because of step 3). Next client k broadcasts feedback message including the clients who form the reciprocal cycle to all the clients in the system. Client k is also the leader to the cycle.
5) All the clients whose flags still equal one repeat steps 1 to 4 until a new reciprocal cycle is discovered. Such a reciprocal cycle discovery process ends until all the clients' flags are marked zero.

We next consider the computational complexity of the distributed group formation mechanism. We show in Theorem 2 that the proposed group formation mechanism has a very low computational complexity in practices.

Theorem 2: The distributed group formation mechanism has a computational complexity of at most $\mathcal{O}(N^2)$, where N is the total number of clients.

Proof: According to the process of the reciprocal cycle identification, the computational complexity is $\mathcal{O}(|\mathcal{C}_t|)$ after t-th contention for reciprocal cycle discovery, where $|\mathcal{C}_t|$ denotes the number of cycles in t-th round. Therefore, the overall computational complexity of all iterations is $\mathcal{O}(\sum_{t=1}^{T}|\mathcal{C}_t|)$, where T is the total number of contentions. Although we cannot estimate the number of clients in each iteration, we can estimate the lower bound and upper bound. The lower bound is $\mathcal{O}(N)$ which corresponds to the case that all the clients form a cycle in one contention. The upper bound represents the case that in each contention each client forms a self-cycle and we need to visit all the clients to identify it, this means that the computational overhead is $\mathcal{O}(\sum_{t=1}^{T}|\mathcal{C}_t| = \sum_{i=1}^{N} i = \frac{N(N+1)}{2})$. Thus, the mechanism has a computational complexity of at most $\mathcal{O}(N^2)$. ■

B. Resource Allocation for D2D Communications

When the social ties based group formation is completed, the BS needs to allocate slots to carry out the D2D communications for the groups.

Due to the resource limitation, it is possible that not all the D2D communication requests can be satisfied. In this case, the BS needs to carry out the admission control to decide which requests to be accepted in order to maximize the system resource utilization. Specially, we denote the D2D requests by each group as $s \in \{1, 2, \cdots, S\}$ where S is the total number of requests. The transmission slots required from the group request s is denoted by R_s. The total available slots is denoted by W. The resource allocation policy is denoted by x_s, such that $x_s = 1$, the BS accepts the request s; otherwise, the BS rejects the request s. We can model the resource allocation problem for the BS as follow:

$$\begin{aligned} \text{maximize } & \textstyle\sum_s R_s x_s \\ \text{subject to } & \textstyle\sum_s R_s x_s \le W, \\ & x_s \in \{0,1\}, \forall s. \end{aligned} \tag{2}$$

Problem (2) can be viewed as a knapsack problem by regarding that each request s is an item with the identical weight and profit of R_s and the capacity of the knapsack is W. It is well-know that the knapsack problem can be solved by dynamic programming with a computational complexity of $\mathcal{O}(SW)$. Due to space limitation, interested readers can refer to [15] for the details of dynamic programming. Then the BS will feedback the obtained optimal resource allocation solution to the leaders of all groups and schedule the D2D transmissions accordingly.

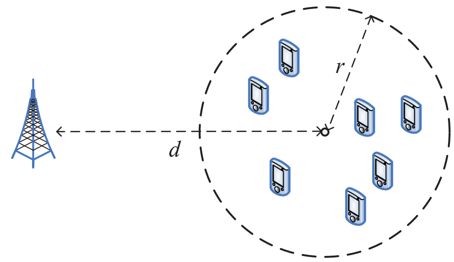

Fig. 5. Multicast distance between the BS and the client cluster center is denoted by d, and the radius of the client cluster is denoted by r.

TABLE II
RELATIONSHIP BETWEEN MOS AND PSNR RANGE.

Video Quality (MOS)	PSNR Range
Excellent	> 37
Good	31 - 37
Fair	25 - 31
Poor	20 - 25
Bad	< 20

V. NUMERICAL STUDIES

In this section, we evaluate the performance of the proposed SoCast by numerical studies. As illustrated in Fig. 5, we consider that a cluster of multicast clients are scatted in a round area with a radius of r = 100 meters, which ensures that all clients are within the D2D communication ranges with each other. The multicast distance between the BS and the cluster center is denoted by d.

The path losses of a multicast channel between the BS and a client, and the D2D channel between two clients are calculated based on the COST-231 Type E (Walfish-Ikegami) and Type F models, respectively [16]. Channel models also take the large-scale shadowing and the small-scale fading into consideration. A 5 MHz wide channel is allocated to the video multicast, which is centered around 2000 MHz with a white noise power density -174 dBm/Hz. Over the allocated channel, the maximum transmit power of a client is 200 mW, and the maximum transmit power of the BS is 1 W. An OFDMA frame is 5 milliseconds long and contains 10 slots.

For video streaming, we consider the MPEG-4 video codec with a G16B3 structure, i.e., there are totally 16 encoded video frames in a GOP and there are at most three B frames between successive I or P frames. The video encoding bitrate is defined as the bits of encoded video frames to be displayed per second. In general, a higher video encoding bitrate renders a better video quality. Moreover, we generate social trust graphs according to the friendship network of the real data trace Brightkite [17].

We evaluate and compare the performance of the proposed SoCast and the baseline scheme - DirCast [4]. Based on the client channel qualities, DirCast uses the highest MCS that can be supported by all clients in the video multicast. For SoCast, the BS reserves 20% of a phase as the D2D sub-phase, then determines the transmission rate that can deliver all video frames during the multicast sub-phase. We implement the experiments with default client number equals 10, the default multicast distance between BS and client cluster center being 800 meters, and the default video encoding bitrate as 500 kbps. We consider the following three evaluation metrics:

- *Valuable video frame ratio:* it is the ratio of the number of valuable video frames obtained by a client, to the number of all delivered video frames during the video multicast. This metric can be averaged over all multicast clients.
- *PSNR:* PSNR (Peak Signal-to-Noise Ratio) is a standard metric of video quality and is a function of the mean square error between the original and the received video frames.
- *MOS:* MOS (Mean Opinion Score) is a metric of user perception video quality. The relationship between the MOS and the PSNR is summarized in Table II [8].

A. Experiments Using Simulated Video Data

To better understand the performance of SoCast, we conduct a series of sensitivity experiments by using simulated video data. Specifically, we generate simulated encoded video data based on [9]. As depicted in Fig. 6, SoCast achieves significant gain in terms of valuable video frame ratio, compared with DirCast, for a variety of video encoding bitrates. For example, when the video encoding bitrate is 500 kbps, DirCast only results in 32% valuable video frames, while SoCast results in 80% valuable video frames. We also observe that the performance of DirCast degrades sharply as the increase of the video encoding bitrate, while SoCast is more robust to the increase of the video encoding bitrate. Similar findings can be observed from Fig. 7, in which curves of valuable video frame ratios versus multicast distance d are plotted. We see that, SoCast outperforms DirCast significantly.

Next, we evaluate the benefits of using social trust, as well as the impact of the client number. From Fig. 8, we observe that, for different client numbers, using social trust in SoCast is better than not to use social trust. Moreover, client number has great impact on the performance, and a proper client number can further improve the performance gain of SoCast. This is due to the fact that the total amount of resources for supporting D2D communications is limited.

B. Experiments Using Real Video Traces

We next evaluate the performance of SoCast using real video data. In this part, we use two standard sample video sequences, i.e., “Foreman” and “Bus” [18]. Both videos have an image size of 352×288. Since video “Bus” has a faster changing background than video “Foreman”, it has larger video encoding bitrate.

As depicted in Fig. 9 and Fig. 10, we choose three typical clients from all clients to show the performance comparisons, where “weak client” is with the worst average multicast channel quality, “strong client” is with the best one, and “moderate client” is with the middle one. We observe that, SoCast improves the average video PSNR by up to 12.7 dB compared to DirCast, and the user perception video quality, i.e., MOS, is also greatly enhanced. For video “Foreman”, the

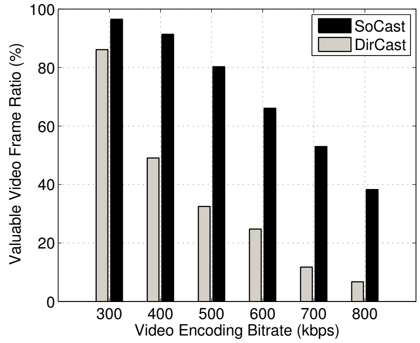

Fig. 6. Valuable video frame ratio versus video encoding bitrate by using SoCast and DirCast.

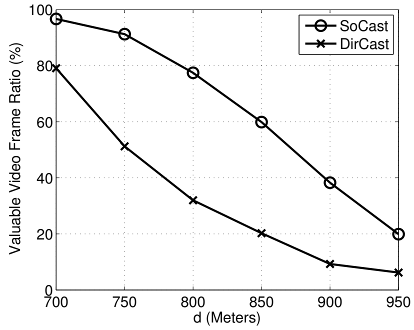

Fig. 7. Valuable video frame ratio versus d by using SoCast and DirCast.

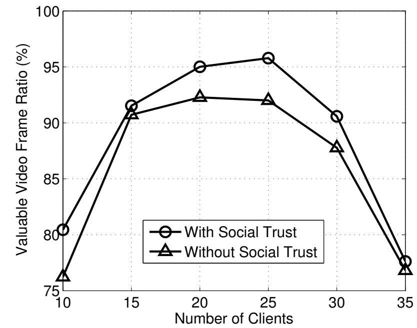

Fig. 8. Valuable video frame ratio versus client number with or without social trust.

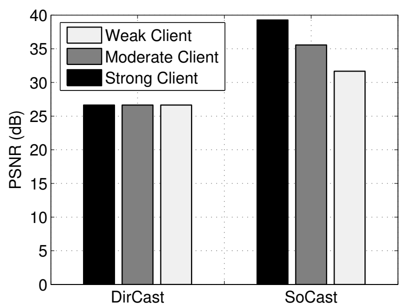

Fig. 9. Average video PSNRs ("Foreman") for three typical clients by using SoCast and DirCast, respectively.

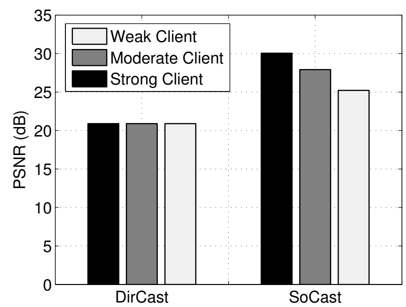

Fig. 10. Average video PSNRs ("Bus") for three typical clients by using SoCast and DirCast, respectively.

MOSs of weak client and moderate client upgrade from "Fair" to "Good", and the MOS of strong client upgrades from "Fair" to "Excellent" (two grades). Similarly, the PSNR and MOS are greatly improved for video "Bus".

VI. Conclusions

This paper presented SoCast - a cooperative video multicast framework based on social trust and social reciprocity. Extensive numerical studies with real video traces have corroborated the significant performance gain by using SoCast. SoCast provides stimulation for clients to share video packets with each other based on social ties, while taking into account the video encoding structure. SoCast's distributed group formation algorithm based on coalitional game theory, and resource allocation mechanism for the BS, help to improve the user perception quality of mobile video multicast effectively. Moreover, SoCast is compatible with existing video encoding schemes and air interfaces, and mainly modifies the client side applications for easy implementations.

References

[1] "Cisco Visual Networking Index: forecast and methodology, 2010-2015." [Online] Available:http://www.cisco.com.

[2] J. Vella and S. Zammit, "A survey of multicasting over wireless access networks," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 2, pp. 718-753, 2013.

[3] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Communications Magazine,* vol. 47, no. 12, pp. 42-49, 2009.

[4] R. Chandra, S. Karanth, T. Moscibroda, V. Navda, J. Padhye, R. Ramjee, and L. Ravindranath, "DirCast: a practical and efficient Wi-Fi multicast system," in *IEEE ICNP*, 2009, pp. 161-170.

[5] S. Deb, S. Jaiswal, and K. Nagaraj, "Real-time video multicast in WiMAX networks", in *IEEE INFOCOM*, 2008, pp. 2252-2260.

[6] S. Jakubczak and D. Katabi, "A cross-layer design for scalable mobile video," in *ACM MobiCom*, 2011, pp. 289-300.

[7] S. Aditya and S. Katti, "FlexCast: graceful wireless video streaming," in *ACM MobiCom*, 2011, pp. 277-288.

[8] J. Yoon, H. Zhang, S. Banerjee, and S. Rangarajan, "MuVi: a multicast video delivery scheme for 4G cellular networks," in *ACM MobiCom*, 2012, pp. 209-220.

[9] A. Al-Tamimi, C. So-In, and R. Jain, "Modeling and resource allocation for mobile video over WiMAX broadband wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 28, no. 3, pp. 354-365, 2010.

[10] L. Yang, Y. Sagduyu, and J. Li, "Adaptive network coding for scheduling real-time traffic with hard deadlines," in *ACM Mobihoc*, 2012, pp. 105-114.

[11] R. Zhang, Y. Zhang, J. Sun, and G. Yan, "Fine-grained private matching for proximity-based mobile social networking," in *IEEE INFOCOM*, 2012, pp. 1969-1977.

[12] H. Luo, S. Ci, D. Wu, J. Wu, and H. Tang, "Quality-driven cross-layer optimized video delivery over LTE," *IEEE Communications Magazine*, vol. 48, no. 2, pp. 102-109, 2010.

[13] R. Myerson, *Game theory: analysis of conflict.* Harvard University Press, 1997.

[14] X. Chen, B. Proulx, X. Gong, and J. Zhang, "Social trust and social reciprocity based cooperative D2D communications," in *ACM Mobihoc*, 2013, pp. 187-196.

[15] H. Kellerer, U. Pferschy, D. Pisinger, *Knapsack problems.* Springer, 2004.

[16] "Multi-hop relay system evaluation methodology." [Online] Available: http://ieee802.org/16/relay/docs/80216j-06_013r3.pdf

[17] "Brightkite dataset." [Online] Available: http://snap.stanford.edu/data/loc-brightkite.html.

[18] "Video traces for network performance evaluation." [Online] Available: http://trace.eas.asu.edu/tracemain.html