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Device-to-Device assisted wireless video delivery with network coding

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Broadcasting popular data content such as videos to multiple users is widely used in mobile wireless networks. We consider a group of mobile users, within proximity of each other, who are interested in the same video or cloud services. In this scenario, users are able to use device-to-device (D2D) connections, e.g., WiFi or Bluetooth, to get the video in a cooperative way. In this paper we consider the D2D-assisted wireless network coded video broadcast problem for users with multiple interfaces to minimize the number of transmission slots. In order to obtain all needed videos, user can receive encoded packet according to cellular link and local cooperative D2D links simultaneously. We analyze the lower bound and upper bound of number of transmission slots under two different receiver models. In the first model, receiver just drop the encoded packet which cannot be decoded immediately, and we propose a joint broadcast and D2D encoding solution based on the clique partition in the graph. In the second model that receiver can buffer all received encoded packets and decode when enough packets are received, we propose an optimal solution using an integer linear programming (ILP) formulation, and we also propose an effective heuristic encoding solution based on random linear coding. Simulation results show that the proposed transmission strategy can significantly reduce the number of transmission slots in most cases, which is an important performance metric in wireless video delivery.

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1. Introduction

With the increasing popularity of smart mobile devices, mobile communication is rapidly evolving into a global commodity, which has led to the introduction of truly pervasive, anytime, anywhere wireless communications [1]. The rise of online services for hand-held devices (e.g., Youtube, Facebook, online gaming) has significantly increased the frequency of the users' online activities. The latest market research [2] indicates that that global mobile data traffic will increase sevenfold between 2016 and 2021. In particular, much of todays traffic consists of large user-created videos and images shared across many social media services. Mobile video traffic accounted for 55% of total mobile data traffic in 2016, and over three-fourths (78%) of the world's mobile data traffic will be video.

An important ongoing trend accompanying the mobile video streaming tremendous growth is the popularity of high definition mobile video services (e.g., cloud online gaming, live sports program). If mobile users are engaging in a group activity and are within proximity of each other, then users can establish device-to-device (D2D) links and make it naturally amenable to cooperation. D2D based cooperation is a possible scenario which has many advantage, such as offloading the video traffic of base station, and the state-of-the-art smartphones are able to support such concurrent multi-path transmission. The recent works [3–7] show that this group-aware mobile social video streaming is popular and has gained lots of interest in academic and industry community. For example, a football stadium can serve live content to supporters' devices, and a group of users would be watching the same real-time video content at the same time on their personal devices individually. Another example is the multi-user online gaming, where a group of friends may play an online game together on their personal devices while at a remote location, such as a camping or skiing site. They need to play the online game at the same time, and thus the same related data and video information of the game should be delivered to the group of users at the same time. In this paper, we consider the scenario that there are a small group of mobile users, within proximity of each other, who are interested in the same multimedia (such as online video, etc.) at the same time.

Broadcasting live media streaming is in fact a challenging application because reduced delays and constant throughput are required to achieve smooth playback. By combining different source

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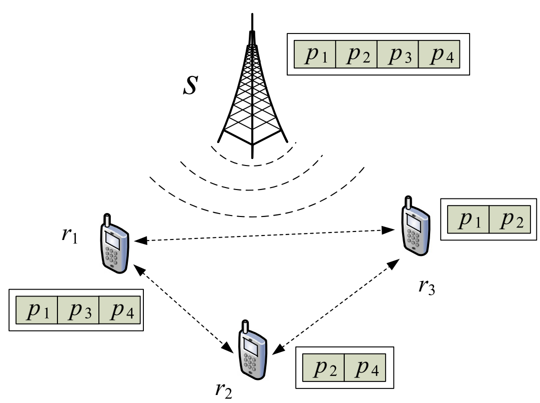

Fig. 1. Example for D2D-assisted wireless network coded broadcast.

packets in a single coded packet, network coding can improve transmission efficiency, throughput, and reduce delay over broadcast channels [8–11]. In particular, jointly determining the optimal coding strategy and the scheduling decisions when receivers obtain layered video data with random linear network coding was studied in [10]. A random linear network coding (RLNC) based multimedia delivery services in LTE/LTE-Advanced was implemented in [11]. Recently, Instantly Decodable Network Coding (IDNC) attracts a significant number of works [12,13] according to its fast decoding potential, which is essential for real-time applications, such as multimedia streaming [14]. In IDNC, sender decides how to encode and transmit based on the cached information at receivers. To guarantee fast decoding, coded packets in IDNC are encoded using XOR coding, and are designed to offer instantaneous, low complexity packet decoding.

On the other hand, when several users which are in proximity of each other need the same multimedia content which the sender wants to broadcast, they may be able to use device-to-device (D2D) connections, e.g., WiFi or Bluetooth, to get the data in a cooperative and/or opportunistic way [15]. More specifically, each mobile device can simultaneously use two network interfaces, one is the cellular link to download parts of the data contents and the other one is the D2D link to connect to the rest of the group and exchange data contents. Proximate D2D communication generally promises its users higher data rates, lower transfer delays, and higher energy efficiency with multimedia content sharing [16]. Network coding also brings several benefits to cooperative media streaming [17–20]. In particular, finding a suitable asynchronous packet scheduling policy in network coding driven live peer-to-peer streaming was studied in [19]. Joint optimization problem for wireless live free viewpoint video (FVV) streaming with network coding based collaboration was studied in [20]. However the aforementioned work in cooperative network coding did not consider utilizing multiple interfaces simultaneously.

Cooperative multimedia delivery using multiple interfaces simultaneously is an emerging and powerful solution that can overcome the limitation of traditional use of a single wireless interface on a smart mobile device, especially for multimedia distribution to a group of users that are within proximity in mobile wireless networks [21]. Le et al. [4] implemented the cooperative system which leverage cellular link and D2D connections simultaneously to effectively download video. However, they did not study the encoding and transmission strategy for server and cooperative users.

Consider a single hop broadcast scenario similar as in [4]. Suppose that the base station s needs to send four packets p_1, p_2, p_3, p_4 to receivers. As shown in Fig. 1, receivers already have some packets in the buffer due to overhearing or prior transmissions. Since users are close to each other, which means that the channel distribution across users are similar. However, even with the same packet loss probability, different users may have different buffer states. Consider the case that we only use the cellular connection. Without coding, base station can simply rebroadcast all needed packets, and s needs 4 transmissions. Using the IDNC encoding strategy introduced in [14], all needed packets can be decoded at all receivers by transmitting the following two encoded packets $p_1 \oplus p_2 \oplus p_4$, p_3. Let us consider the case that packets are obtained according to local D2D links among different receivers such as WiFi. With cooperative IDNC encoding [17], r_3 broadcasts $p_1 \oplus p_2$, and then r_1 broadcasts p_3, p_4 in sequence, and all receivers can decode required packets. The above example shows the benefit of network coding when we use only the cellular connection or D2D links among users. If we can use cellular and local D2D links simultaneously as shows in [4], then the number of transmission slots can be further reduced. The base station can broadcast $p_1 \oplus p_2 \oplus p_4$ via cellular links, and at the same time mobile device r_1 broadcasts p_3 via local area links. Only one time slot is needed so the number of transmission slot is reduced to one. Therefore, mobile devices with cooperation in Device-to-Device assisted wireless broadcast can improve throughput significantly, we can get gain from combined spectrum resource and joint broadcast and D2D encoding methods.

Inspired by the above example, we consider the D2D-assisted wireless network coded broadcast problem for users with multiple interfaces in mobile wireless networks, and users can access data according to cellular and local D2D links simultaneously. Our work mainly focuses on the encoding and transmission strategy for base station and cooperative users, aiming at minimizing the number of transmission slots to obtain all data content under two user models. In the first model which is referred to as the *memoryless model*, the memory size of user device is small. The user just drops the encoded packet which cannot be decoded immediately. In the second model which is referred to as the *memory model*, user device has enough memory. The user will buffer all received encoded packets and decode out their wanted packets when enough packets are received. The contributions in this paper are summarized as follows:

- We study the D2D-assisted wireless network coded broadcast problem for users with multiple interfaces under two receiver models, and we analyze the lower bound and upper bound of the number of transmission slots.
- We introduce a clique partition model for joint broadcast and D2D scheduling under the *memoryless model* and presents an encoding algorithm based on maximum clique in the graph.
- We propose an optimal solution under the *memory model* using an integer linear programming (ILP) formulation, and we also propose an effective heuristic encoding solution based on random linear coding.
- Simulation results show that the proposed transmission strategy can significantly reduce the number of transmission slots in most cases.

The remainder of this paper is organized as follows. Section 2 introduces the related work. In Section 3, we give the system framework and problem statement. Section 4 analyzes the lower bound of network coding gain in terms of number of transmission slots. Section 5 introduces a clique partition model for scheduling problem under the memoryless model and presents an encoding algorithm based on maximum clique. In Section 6, we study the scheduling problem under the memory model with an integer linear programming formation, and propose a heuristic solution using random linear coding. We analyze the upper bound of number of transmission slots in Section 7. Simulation results are shown in Section 8. Finally, we conclude the paper in Section 9.

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