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MULTI-PATH LIVE VIDEO STREAMING OVER WI-FI DIRECT MULTI-GROUPS

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ABSTRACT

This paper proposes a method to realize a reliable live video streaming over mobile ad hoc networks (MANETs) consisting of several Wi-Fi Direct groups. The proposed method uses a multi-path routing with two disjoint routes connecting a source to several subscribers so that if the primary route temporally becomes unavailable, the source immediately switches to the secondary route, which is regarded as a new primary route, and starts the exploration of a new secondary route by invoking a variant of AODV protocol. The result of experiments with twelve Android tablets indicates that it could stably deliver a live video stream of QVGA quality to a subscribing node located at 200 m away from the source node, and quickly recovers from link failures in 100 ms which is significantly shorter than the original AODV.

KEYWORDS

MANET; Wi-Fi Direct; AODV; live video streaming,; connected domatic partition.

1. INTRODUCTION

Recently, it arises a demand for live video streaming in a region in which cellular and/or Wi-Fi networks are not available, as in the relief activities in the areas affected by large scale disasters. If such infrastructure *were* available, we could take a standard approach so that a live video taken by a user is uploaded to a media server through WebRTC [24] and is disseminated to the subscribers after being converted to HLS [6] (in fact, YouTube Live takes such a two-step approach). However, if such an infrastructure is not available, the video stream should be delivered to the subscribers by repeating data transmission via wireless links among nearby devices. The main contribution of the current paper is the proposal of a way of realizing such an *ad hoc live video streaming* merely with functions installed on standard Android devices. More specifically, we use Wi-Fi Direct as the underlying wireless communication technology. Although the original Wi-Fi Direct does not support multi-hop communication, the proposed method realizes a multi-hop video streaming in the following manner:

(1) At first, with the mechanism of Wi-Fi Direct we organize given nodes (devices) into groups, so that the communication within a group is conducted in one hop via a node playing the role of virtual access point.
(2) We then select gateway nodes to connect adjacent groups, and transfer RTP packets across groups via those gateways.
(3) A route from the source to each subscriber is explored by using a variant of AODV [18].

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Since we are going to use standard Android devices in the proposed MANET, the wireless network could become unstable due to the node mobility and/or the battery exhaustion. To effectively tolerate such an instability with as small cost as possible, we introduce the following multi-path routing technique to the resulting MANET:

(4) The node set is statically partitioned into two subsets, called red and white, and the entire MANET is configured so that there is a route consisting only of red nodes and another route consisting only of white nodes for any pair of source and destination (in graph theory, such a property is called the *bi-connectivity* of the network);
(5) While conducting video streaming, the source uses routes of different colors as primary and secondary routes to the destination, respectively, and if the primary route becomes unavailable, the source immediately switches to the secondary route, which is regarded as a new primary route, and starts the exploration of a new secondary route by invoking a variant of AODV protocol.

The performance of the resulting live video streaming is evaluated by using a prototype system consisting of twelve Android tablets. Results of experiments indicate that: the proposed method could stably deliver a live video stream of QVGA quality to a subscriber located at 200 m away from the source, which expands the delivery area of the original single-hop Wi-Fi Direct to 16 times. In addition, it could quickly recover from link failures. More specifically it could complete the recovery from the link disconnection on the delivery route in about 100 ms which is significantly shorter than the standard AODV.

The remainder of this paper is organized as follows. Section 2 overviews related work. Sections 3 and 4 describe the details of the proposed method. Section 5 summarizes the results of evaluations. Finally, Section 6 concludes the paper with future work. This paper is an extended version of a paper presented at CANDAR 2019 [9]. The difference to the conference version is summarized as follows: 1) we formalize a vertex coloring problem corresponding to the multi-path routing scheme and propose a heuristic algorithm for solving the problem; 2) we fully rewrite the explanation of the proposed system so that the reader can easily catch the details of the implementation; 3) we improve the performance of system by changing the way of relaying RTP packets; and 4) the performance of the heuristic algorithm for solving the vertex coloring problem is experimentally evaluated by simulation.

2. RELATED WORK

2.1. Wi-Fi Direct

Wi-Fi Direct is a technology to organize a wireless network without deploying an access point (AP) [25]. This technology is available in Android version 4.0 (API level 14) or later. Each of Wi-Fi Direct *compatible* devices incorporates the function of AP as a software, and given a collection of such devices called **nodes**, one node is autonomously selected to serve as a logical AP. The set of nodes configured in this way is called a **group**, and given such a group, the node which plays the role of AP is called the **group owner** (GO) and the other nodes are called group members (GMs). Note that GO simply appears to be a legacy AP to Wi-Fi Direct *incompatible* devices.

Originally, Wi-Fi Direct is designed by extending the infrastructure mode of IEEE 802.11 standard to directly, securely, and rapidly realize inter-device communication [25]. It is secured by WPA2, and has the maximum transmission rate of 250 Mbps and the maximum transmission radius of 150 meters as with legacy WiFi. With those features, Wi-Fi Direct has become a promising candidate for the wireless communication in many application domains including proximity-based advertising, content distribution, alerting, and online games.

2.2. Wi-Fi Direct Multi-Groups

The proposed method realizes MANET by connecting several Wi-Fi Direct groups. Each node in a MANET can freely move in the given area, which causes a random change of the network topology. Thus, a key issue for general MANETs is how to update routing tables to reflect the dynamic change of the network topology. There are many previous works concerned with this issue; e.g., 1) reactive routing protocols such as AODV[18], DSR[4], and ABR[22]; 2) proactive routing protocols such as DSDV[19], OLSR, and Babel; and 3) their hybrid [3] (the details of AODV will be explained later).

Wi-Fi Direct has a *P2P concurrent mode*, in which GM of a group can serve as GO of another group. For example, the reader could consider a situation in which laptop PC in a department is connected to a large Wi-Fi Direct group as a GM and at the same time, serves as GO of another small group consisting of peripheral devices such as Wi-Fi printer and smart TV. With this mode, Liu *et al.* [15] proposed a method to organize a multi-hop network in which the routing over the network is proactively done during organizing Wi-Fi Direct groups. Shahin and Younis proposed a method called EMC (Efficient Multi group formation and communication) [21], in which GO of each group is adaptively selected based on the remaining battery level. Similar methods for the dynamic GO selection have been proposed in the literature; e.g., Menegato *et al.* [17] focus on the node mobility in addition to the battery level, and Khan *et al.* [11] proposed another composite metric for the GO selection. Chaki *et al.* [2] extend the standard group formation procedure so that each device indicates an intention to become an *emergency group owner* (EGO) in addition to the usual intent value to become a GO, where EGO substitutes for the role of GO upon detecting the leave of the GO, to reduce the service suspension time.

Wi-Fi Direct has been used to realize integrated services such as resource sharing and content delivery. Yoon and Kim proposed a collaborative streaming-based media content sharing using Wi-Fi Direct and iDLS (inter-BSS Direct Link Setup) [23]. Jung *et al.* proposed a multi-hop network based on Content-Centric Network (CCN), and realized a storage of contents shared by all Wi-Fi devices [8]. Lee *et al.* [12] implemented a chat application by connecting Wi-Fi Direct groups through Bluetooth or ZigBee, while it is slower (e.g., upto 25 Mbps) than Wi-Fi connection. Khan *et al.* consider the reliable multicast within a Wi-Fi Direct group [10]. They proposed a method called Enhanced Leader Based Multicast (ELBM) and compare it with existing methods. Finally, Je *et al.* experimentally evaluated the performance of Wi-Fi Direct in streaming applications with respect to RTT and the communication bandwidth [7]. More recently, a framework for constructing multihop networks based on Wi-Fi Direct has been proposed in [1,16], and a method to increase the communication bandwidth of Cellular-V2X (vehicle to X) networks with the aid of Wi-Fi Direct is proposed in [20]. However, to the best of our knowledge, there are no studies that attempt to realize live video streaming on MANET based on unstable communication links such as Wi-Fi Direct.

3. BASIC ROUTING SCHEME

This section describes the basic routing scheme over a single path, which is the basis of the proposed system. After providing an overview of the scheme, we describe how the video stream is forwarded to the next node on the delivery path, and then explain how to find such path to the subscribers. As will be explained later, the proposed system adopts AODV protocol for the exploration of delivery paths.

3.1. Overview

Figure 1 illustrates the basic flow of the proposed live video streaming based on RTP/UDP. At first, the source encodes a video stream captured by a camera into a stream of H.264 packets and sends it out to nearby nodes using libstreaming library [13]. The received packet stream is played back at the receiver using libVLC library [14] with the aid of SDP packets [5]. In the following, we will merely consider the delivery of RTP (and SDP) packets from the source to their *final destination*; i.e., subscriber of the live video. Concerned with the delivery of the video stream to

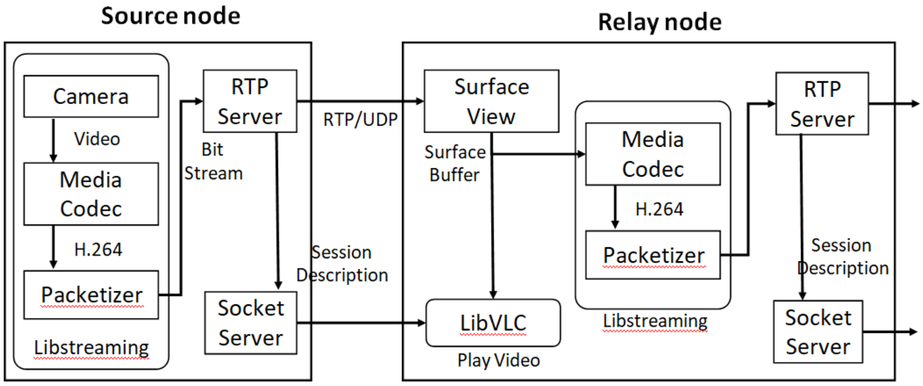

Fig.1. The basic flow of live video streaming. RTP packets generated by the source is delivered to the final destination through intermediate relay nodes.

the final destination, there are four key issues we need to address, which will be discussed in each of succeeding subsections:

- How to forward RTP packets to the successor on the delivery route (Section 3.2).
- How to find a route to the final destination (Section 3.3).
- How to reduce the suspension time of video streaming due to topology changes (Section 4.1).
- How to keep the high multiplicity of routes to the final destination (Section 3.3).

3.2. Relay Packets to the Successor Node

The proposed system assumes that RTP and DHCP servers are installed to all nodes beforehand, so that each node can send RTP packets to another node in the same group, which is called the *tentative* destination of the packets. More concretely, nodes in a group are automatically assigned an IP address by the DHCP server installed on GO (Group Owner), and by using the local RTP server, RTP packets received from a neighbor are forwarded to the next tentative destination which is determined by referring to the routing table as will be explained in Section 3.3. Two groups are connected by a **gateway** (GW) node as is illustrated in Figure 2. GW is a member of a group. It is connected to the owner of its group as a Wi-Fi Direct *compatible* device, and simultaneously, is connected to the owner of another group via legacy Wi-Fi as an *incompatible* device. Note that such a combined use of two Wi-Fi connections is allowed by the specification of Wi-Fi Direct standard.

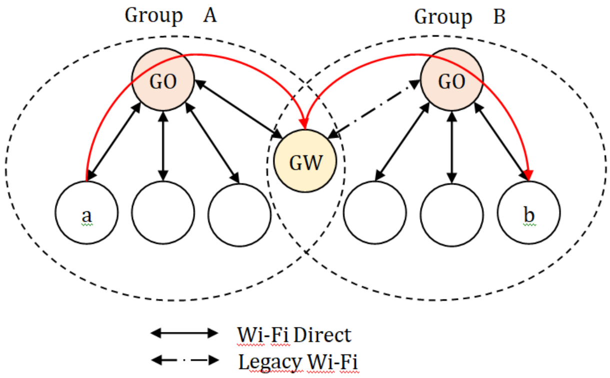

Fig 2. Relay of RTP packets from node a to node b through gateway node (GW is a member of group A and is connected to the GO of group B through legacy Wi-Fi).

The above relay mechanism could certainly realize the delivery of RTP packet stream to the final destination, but to play back the received video at the subscriber, *control packets* should also be delivered to the final destination. To this end, we use the session description protocol (SDP) in the following manner: when a relay node receives an SDP packet, the receiver

1. saves it as an .sdp file,
2. replies an acknowledgement to the sender,
3. starts playback at the node, and
4. forwards the received SDP packet to the next node.

The .sdp file records the predecessor/successor on the delivery route as well as the source/destination pair, which is used to notify the occurrence of link failures to the source node. Such a notification message is propagated to the source along the route in the backward direction, and each node receiving the message *invalidates* corresponding entries in the local routing table.

3.3. Exploring Delivery Route to the Destination

The proposed system uses AODV (Ad hoc On-Demand Distance Vector) [18] to establish a route from the source to the final destination. Note that AODV is a reactive routing protocol designed for general MANETs. More concretely, a source which wishes to find a route to the final destination broadcasts RouteRequest packet to nearby nodes, which contains: source identifier SrcID, destination identifier DestID, source sequence number SrcSeqNum, destination sequence number DesSeqNum, broadcast identifier BcastID and TTL. SrcSeqNum and DesSeqNum indicate the freshness of the route accepted by the source and the freshness of the route to the destination, respectively (the larger the newer). TTL limits the times of packet forwarding.

A node *u* receiving RouteRequest from a neighbor *v* returns RouteReply packet to *v* if either *u* equals DestID or*u* knows a correct route to the destination, where a route is said to be correct if it has a DesSeqNum no smaller than the packet. Otherwise *u* decrements TTL of the received packet by one and forwards it to the other neighbors unless TTL= 0. It then locally caches DesSeqNum and BcastID for a certain period of time to use them for the matching with RouteReply sent back from neighbors. If *u* receives RouteRequest with the same SrcID and BcastID several times, it simply discards later packets to avoid redundant exploration.

RouteReply records the number of hops to the destination and is delivered to the originator of the corresponding RouteRequest (i.e., source) along the route of the packet in the reverse direction.

After receiving RouteReply from neighbors, the node selects the route with the smallest number of hops and updates the routing table so that the next node along the selected route is recorded for each destination.

Our basic routing protocol uses AODV in the following manner (a multi-path extension of the protocol is described in the next section). The idea is to use the set of GWs as the set of AODV nodes; namely, a GW *u* forwards RouteRequest to another GW in the same group or to a GW in the group connected with *u* through legacy Wi-Fi. Since each GW can forward RTP packets to any node in the corresponding group in a single hop, RouteReply can be returned from GW adjacent to the final destination.

4. MULTI-PATH ROUTING SCHEME

4.1. Overview

The proposed method adopts multi-path routing to realize a quick recovery from link failures. More concretely, the given set of GWs is partitioned into two subsets called red and white, and the entire MANET is configured so that there is a route consisting only of red nodes and another route consisting only of white nodes for any pair of source and destination. See Figure 3 for illustration. It then pushes video stream towards subscribers in such a way that the source uses routes of different colors as primary and secondary routes, respectively, and if the primary route becomes unavailable, the source *immediately* switches to the secondary route, which is regarded as a new primary route, and invokes the exploration of a new secondary route. Note that such a switching significantly reduces the suspension time of video streaming even if a link or a node is tentatively unavailable.

A colored route is explored by using a variant of AODV which proceeds as follows. At first, we use *colored* RouteRequest to construct a routing table for each color. More specifically, when the source starts the exploration of a route with color

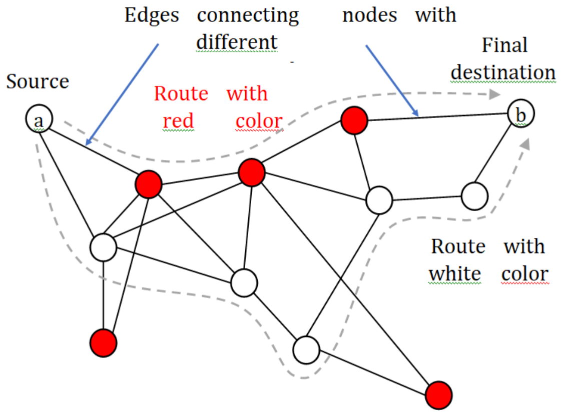

Fig.3. Multi-path routing from node a to node b through routes with different colors (each color induces a connected dominating set for the given graph, and the source and destination can have a different color from the color of the delivery route).

c, RouteRequest of color *c* is sent out to adjacent AODV nodes with color *c*, where the color of the source might *not* be *c*. If a node receiving the packet is adjacent with the final destination, the node replies RouteReply regardless of the color of the destination. In other words, a route with color *c* consists of edges connecting nodes with the same color *except for* the first and the last edges.

4.2. A Vertex Coloring Problem

To enable such a colored routing, the selection and the coloring of AODV nodes should satisfy the following conditions (note that we could not control the physical location of nodes since it is a given parameter, but can control the selection of GWs and their coloring):

1. Each node is adjacent with at least one red node and at least one white node (**Condition A**), and
2. For each color *c*, the subgraph induced by nodes with color *c* is connected (**Condition B**).

In graph theory, a node coloring satisfying those two conditions is called the **connected domatic partition** (CDP) of cardinality two (i.e., with red and white colors). It is known that graph *G* has a CDP of cardinality *k* if and only if the vertex connectivity of *G* is at least *k* (in other words, for any two vertices in *G*, it must contain at least *k* vertex-disjoint paths connecting them). The reader should

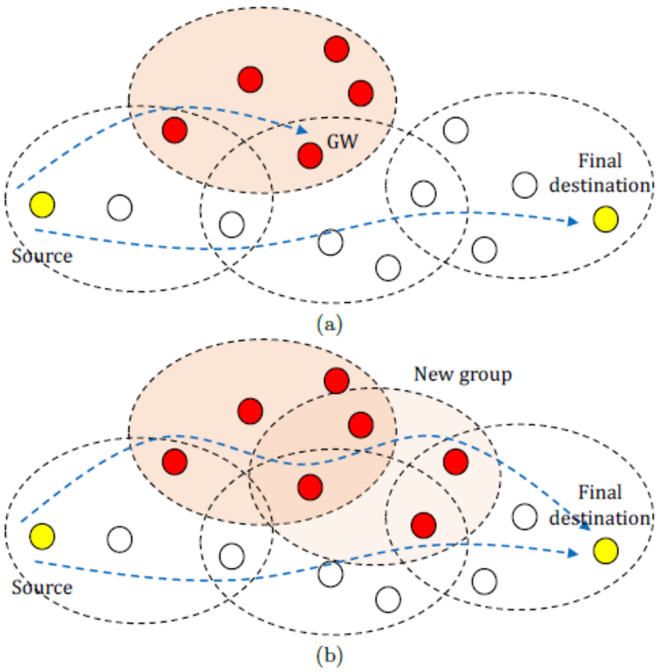

Fig.4. Heuristic method for the node coloring. (a) We could not establish disjoint routes for the initial configuration of Wi-Fi Direct groups, but (b) by generating a new group, we could establish two routes from the source to the final destination. Note that re-organization of Wi-Fi Direct groups increases the number of candidate nodes for the GW.

note that *the target graph G could change in our setting*; namely, we could increase the vertex connectivity of the target graph by recruiting more nodes as an AODV node (i.e., GW) while it would increase the total amount of power consumption.

The problem of *minimizing* the number of AODV nodes by keeping the 2-vertex connectivity of the resulting graph is NP-hard. Thus we use the following heuristic approach in the proposed method:

1. Randomly, independently color each node by red or white with uniform probability (e.g., each node is colored red with probability 1/2).
2. Organize initial Wi-Fi Direct groups so that each group consists of nodes with the same color, where the selection of GO is conducted arbitrarily.
3. By construction, each node is connected with the corresponding GO via Wi-Fi Direct link. Any node which can be connected with GO of another group via legacy Wi-Fi is *marked* as a candidate for GW.
4. Check whether the resulting graph is 2-vertex connected when all candidates are selected as GW. If the answer is YES, go to Step 5; otherwise go back to Step 3 after re-organizing groups so that each group contains less number of nodes.
5. Greedily remove GWs as long as the 2-vertex connectivity of the resulting graph holds (if we wish to remove as large number of GWs as possible, the removal of GW should be done in such a way that *non-critical* nodes concerned with the 2-vertex connectivity are selected earlier).

It is worth noting that Wi-Fi Direct groups organized in the above manner can geometrically overlap. To see this, consider a situation in which a live video stream is going to be delivered from a small village suffered from disaster to a place of refuge. In such a specific situation, intermediate nodes (i.e., mobile devices) can be located along a road connecting the village and the place of refuge and there might not exist a bypass road. However, by increasing the density of nodes located on the road, we could control the number of nodes covered by a group, and then control the vertex connectivity of the resulting graph. Such a control can be independent of the number of delivery hops of the video streaming, since if the node density is sufficiently high, we can control the number of nodes in a group by keeping the geometrical radius covered by the group.

4.3. Enhance the Multiplicity of Delivery Routes

To enhance the sustainability of the proposed method, we develop a procedure to detect a part of the graph in which AODV nodes are lacking, and to repair the graph and its coloring upon necessity.

Recall two conditions introduced in the last subsection. Condition A can be locally checked and fixed by flipping the color of an adjacent node while it would cause a race of flipping in the worst case. As for the check of Condition B, we introduce probe packets in addition to RouteRequest used in AODV. More concretely, we use two probe packets X and Y, where X is a packet relayed by any nodes and Y is a colored packet which is relayed by nodes of the same color with the packet. Those packets are simultaneously emitted by the source and are propagated over the network. Each packet is given TTL to limit the maximum times of forwarding, and a unique ID to avoid duplicated forwarding. If a node receiving X does not receive Y, then the node judges itself to be disconnected from the source with respect to the induced subgraph. In practice, such an unreachability could be identified by using timeout corresponding to the maximum TTL, although it is not equivalent to the unreachability in a strict sense.

A procedure to fix such a disconnection of induced subgraph proceeds as follows. The basic idea is to focus on the boundary of disconnected nodes. In the following, we call a node which judges itself as a disconnected node a *marked* node. Consider the marking of nodes concerned with white color. If node u is not marked but is adjacent with a marked node v (namely, if v is a boundary node), the color of u

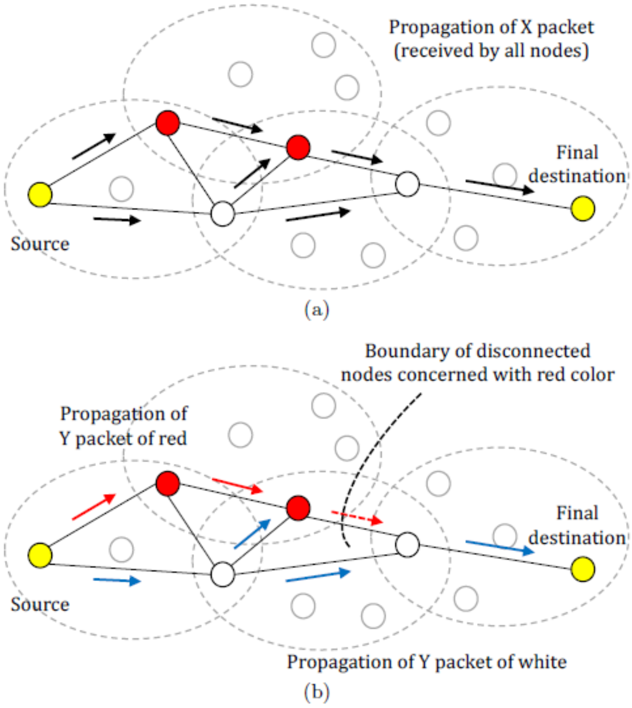

Fig.5. Detection of the boundary of disconnected nodes. (a) Probe packet X reaches all nodes since the graph consisting of gateway nodes is connected. (b) The boundary of disconnected nodes concerned with a color can be identified by propagating Y packets.

(and all nodes in the same group with u) must be red since otherwise, they can forward Y to v in a single hop. Let G_u denote the group containing u. We partition G_u into two non-empty groups G^1_u and G^2_u, and change the color of G^2_u to white so that v can receive Y through GW in G^2_u.

5. Evaluation

5.1. Prototype System

To evaluate the performance of the proposed method, we implement a video streaming system consisting of twelve Android tablets (Zen Pad 10, Android 7.0) and conduct several experiments on it, where CPU of each device is MediaTek MT81638 (1.3 GHz, quad core) and each device has a RAM of 2 GB. All experiments start with a configuration in which all devices are joining the MANET and two disjoint routes from the source to a designated subscriber have been established. The length of delivery route is varied from one to five hops, where we regard the packet transmission to the next GW as one hop.

5.2. Video Quality

At first, we evaluate the *quality of video stream* observed at the subscriber by varying the number of hops from one to five. In summary, it is confirmed that the video quality rapidly degrades after exceeding four hops, and since the result of an auxiliary experiment indicates that *one-hop limit* of video streaming over WiFi Direct is approximately 50 meters, we can conclude that the proposed method covers subscribers within 200 meters away from the source which is 16 times larger than the original Wi-Fi Direct (the reader should note that a node at distance 200 meters cannot correctly receive a video stream transmitted by a node while *radio wave* could reach the node).

The detail of the experiments is as follows. In general, the bit rate of a video stream is not constant and dynamically varies depending on the subject captured in the video in modern codec such as H.264 and MPEG-4. Hence we use two movies with different characteristics; i.e., a water surface in which the entire screen changes little by little (Movie A) and a waveform drawn on a black screen in which only a part of the view changes drastically (Movie B). The source takes a given movie by camera, delivers it towards the subscriber, and the subscriber tries to play it back to check the degree of deterioration. Parameters used in the experiment are as follows:

- Screen size: 176×144 (S), 352×288 (M), or 480 ×360 (L), where in terms of the number of pixels, M coincides with the resolution of video CD, and L coincides with the resolution of iPhone 3 and 3g. Note that the resolution of VGA is 640 ×480 and that of QVGA is 320 × 240.
- The number of hops varies from one to five.
- The source autonomously adjusts the bit rate depending on the subject in the movie.

Table 1 summarizes the results, where △ indicates that the playback is instable while it is not suspended, and × indicates that the playback stops during streaming. For example, when the screen size is 352×288 (M), both movies are correctly displayed at the subscriber as long as the number of hops is no more than four, while it becomes instable depending on the subject shown in the movie. On the other hand, when the screen size is 480×360 (L), the playback of Movie A stops after four delivery hops, whereas that of Movie B did not suspend until five hops.

The above results indicate that in order to enjoy a comfortable live video streaming with the proposed method, we should limit the number of hops to the subscriber to four if we wish to deliver a video stream of screen size 355×288 (M) and should limit to two hops if we wish to deliver a video stream of screen size 480×360 (L).

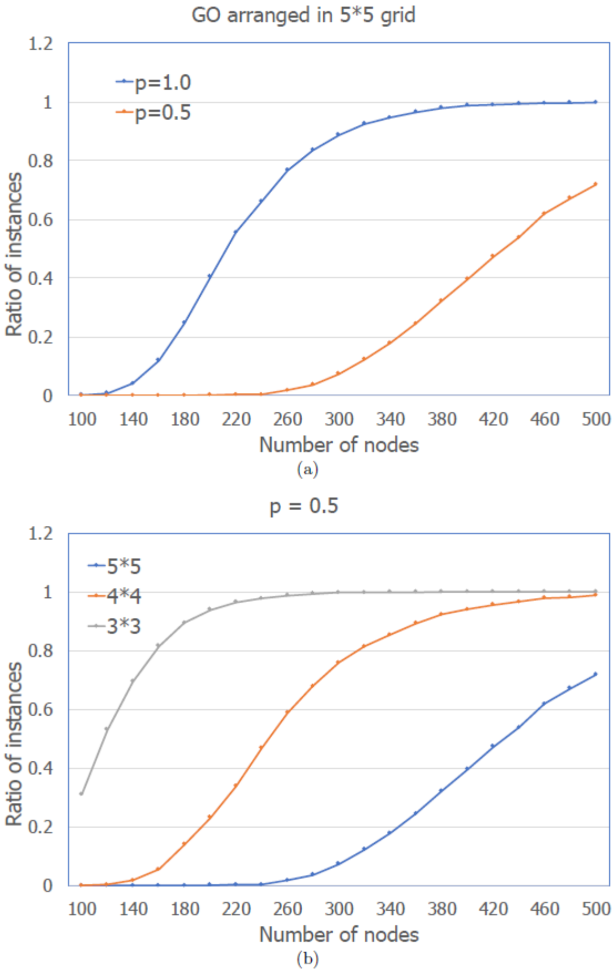

Fig. 6. The ratio of instances satisfying two conditions under a random node coloring.

Table 1. Results of experiment 1.

(a) Movie A.

hops	S	M	L
1	○	○	○
2	○	○	○
3	○	○	△
4	○	△	×
5	△	×	×

(b) Movie B.

hops	S	M	L
1	○	○	○
2	○	○	○
3	○	○	○
4	○	○	△
5	△	△	△

In other words, there is a trade-off between the maximum number of hops and the screen size. Since the area covered with $i \geq 1$ relay nodes is $(i + 1)^2$ times larger than the area covered by the single-hop case, it is 16 times larger if $i = 3$ (i.e., four hops).

5.3. Performance of Multi-Path Routing Algorithm

As for the recovery time of the proposed system, we confirm that the switching to the secondary route completes within one second which is significantly shorter than the time required for the route exploration by the standard AODV.

The performance of the proposed routing algorithm with respect to the multiplicity of delivery route, depends on the location of relay nodes in the given area. In practice, such a node location does not follow a certain probability distribution in a free space due to the existence of prohibited regions such as obstacles and privately owned place. In addition, although Wi-Fi Direct has a connection mode in which nearby peers *autonomously* select a GO, in our setting, it is natural to use another mode in which a pre-designated peer placed at a point plays the role of GO. In the following, we assume that those pre-designated GOs are regularly placed in the given area so that the distance to the closest GO is within the transmission radius of Wi-Fi, and the other peers join the closest group as GM, where the selection of a group follows a uniform distribution. More specifically, we consider three arrangements of GOs, namely 3×3, 4×4 and 5×5, and evaluate the ratio of randomly generated instances in which two conditions are satisfied, by varying the number of nodes from 100 to 500 (more concretely, we generate 10000 instances in which the group and the color of nodes are randomly selected). The probability of being selected as GW is given as a parameter and in all generated instances, each group consists of at least three nodes.

Figure 6 summarizes the results, where (a) fixes the arrangement of GOs to 5×5 and (b) fixes the probability of being selected as GW to 1⁄2. Those results indicate that even under a random coloring of nodes, two conditions (i.e., A and B) are satisfied for sufficiently large number of nodes with high probability. For example, the ratio exceeds 0.99 for 280 nodes if the arrangement is 3×3 and the probability is 1⁄2. The reader should note that this ratio increases if we allow an external authority such as GO to control the coloring of nodes so that each group has at least one red node and at least one white node. The proposal of an optimal placement of GOs for a given map of area is left as a future work.

6. Concluding Remarks

In this paper, we propose a way of realizing a reliable live video streaming without relying on specific communication infrastructure such as the Internet and cellular networks. The proposed method uses Wi-Fi Direct multi-groups of Android devices to organize a MANET and realizes the routing of RTP packets towards the subscriber by using a multi-path variant of AODV. The results of evaluations indicate that the proposed method could cover 16 times larger delivery area than the original (single-hop) Wi-Fi Direct and could realize a quick recovery from link failures within few seconds.

We leave the following issues as future work: 1) to improve the quality of video streams by modifying the way of relaying packets at gateways (without decoding/encoding at relay nodes, for example); and 2) to develop an efficient way to explore colored routes.

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