Cooperative Multicast for Mobile IPTV over Wireless Mesh Networks: The Relay Selection Study

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Abstract—Recently, there has been a growing interest in Internet Protocol TeleVision (IPTV) technologies from both academic and industrial communities. To meet this trend, we study the mobile IPTV deployment across wireless mesh networks (WMNs) in this paper. IPTV services require the support of reliable multicast to ensure the stable packet transmission across WMNs. In our work, we employ multicast cooperative communications to achieve this goal. Specifically, we first identify the relay selection as a critical issue for cooperative multicast; we then develop the concept of in-group/out-group cooperation as well as a distributed relay selection algorithm for the mobile computing environment. Extensive simulation results show that our approach can efficiently mitigate multicast transmission errors and guarantee reliable IPTV data delivery in wireless environment.

Index Terms—Mobile IPTV, wireless mesh network, multicast, cooperative communications.

I. INTRODUCTION

Internet Protocol TV (IPTV) has recently gained momentum as one of the key applications in the telecommunications market [1], [2]. Most researchers believe that IPTV service represents a key opportunity for operators around the world to benefit from video delivery over IP networks. The infrastructure of IPTV is based on personal choices, varying with the needs and interests of different communities. So far, most existing systems are deployed over wired networks, including the 20-Mbps promise of asymmetric digital subscriber line 2+ (ADSL2+), the 50-Mbps capability of very high digital subscriber line (VDSL2), and the 100-Mbps potential of fiber to the x (FTTxs) [3].

With the proliferation of mobile devices, we investigate the mobile IPTV technology that allows users to enjoy TV programs anytime anywhere. The mobile TV solutions using 3G network and WiMAX usually require considerable network construction investment from service providers, as well as high monthly charge from users. Therefore, it is practically attractive to develop a low-cost mobile TV technology. In the past few years, wireless mesh network (WMN) has drawn significant attention from research community and industry as a fast, easy, and inexpensive solution for broadband wireless access [4]–[6]. Motivated by this trend, we propose a novel approach of supporting mobile TV service over IEEE 802.11 based WMNs.

One of the most challenging issues in our solution is to efficiently support reliable multicast communication in wireless environment. Multicast is a network addressing method for the delivery of information to a group of destinations simultaneously. It uses the most efficient strategy to deliver the messages over each link of the network only once, creating copies only when the links to the multiple destinations split. IPTV service in WMNs is usually Internet oriented, and thus the traffic is directed from the Internet gateway (IGW) to the mesh clients. Once the multicast data travel though the WMN backbone and reach a destination mesh router, the destination mesh router will transmit the data to the mesh clients in its coverage.

In WMNs, the reliable multicast scheme should involve both WMN backbone and mesh router coverage (data transmission from mesh router to mesh clients). In our work, we consider WMN backbone in general error immune with the help of underlying infrastructures and reliable multicast protocols. Therefore, we mainly address the support of reliable multicast in mesh router coverage by using cooperative communications.

In the literature, comprehensive investigation has been given on the unicast cooperative communications to improve the performance of point-to-point wireless links [7], [8]. These existing approaches allow different users or nodes in a wireless network to create collaboration through distributed transmission and processing, in which each user’s information is transmitted not only by the user, but also by collaborating users.

In our work, we utilize cooperative communications to improve the performance of WMN multicast, which is drastically different from previous point-to-point scenarios. We investigate the cooperative multicast in the range of a mesh router, where channel instability and user mobility are two salient features. In such a research context, we further consider relay selection as one of the major challenges. In unicast cooperative communications, relay selection aims at grouping terminals into cooperating pairs. Choosing pairs of cooperating terminals is an instance of matching problem in graph theory [9]. In multicast cooperative communications, however, the main objective of relay selection is to find the least number of relays while covering as many erroneous receivers as possible.

To optimize the relay selection, we study two types of multicast cooperation, i.e., in-group cooperation and out-group cooperation. In-group cooperation means employing a multicast group member as relay to other multicast members under the same mesh router. Out-group cooperation means finding...
a non-multicast group member to relay information to the multicast members. Clearly in-group cooperation is more efficient than out-group cooperation in terms of cooperative cost. Nevertheless, out-group cooperation is a necessary supplement to in-group cooperation especially when in-group relays could not totally cover the error-prone multicast receivers. Based on above considerations, we develop a hybrid relay selection algorithm that integrates both in-group and out-group cooperation. Moreover, our hybrid relay selection algorithm is implemented in a distributed manner, so that user mobility could be easily dealt with.

In addition to mobile IPTV, the approach of cooperative multicast proposed in this paper can also be extended to support other group-oriented multimedia applications in WMN, such as multimedia conferencing and so on. It is also possible to apply our approach to clustered mobile ad hoc networks (MANETs) and wireless sensor networks (WSNs). Nevertheless, additional measures have to be taken to assure the reliable communication amongst cluster heads, since MANETs and WSNs do not have underlying infrastructure.

The rest of the paper is organized as follows. We first introduce the mobile IPTV deployment over WMNs in Section II. We then propose a framework of multicast cooperative communications for mobile IPTV service in Section III. In Section IV, we develop a distributed algorithm to optimize the relay selection for a multicast session. In Section V, we present numerical results to demonstrate the performance of our scheme. Finally, Section VI concludes the paper.

II. MOBILE IPTV OVER WMN

A. Wireless Mesh Networks

As shown in Fig. 1, a WMN consists of two types of nodes: mesh routers and mesh clients. The mesh routers form an infrastructure of mesh backbone for mesh clients. In general, mesh routers have minimal mobility and operate just like a network of fixed routers, except being connected by wireless links through wireless technologies such as IEEE 802.11. We observe from Fig. 1 that a WMN can access the Internet through a gateway mesh router, which is connected to the IP core network with physical wires.

In a WMN, each mesh router is equipped with a traffic aggregation device (similar to an 802.11 access point) that interacts with individual mesh clients. The traffic aggregation device and backbone use different wireless channels, so that they do not interfere with each other. The mesh router relays aggregated data traffic of mesh clients to and from the IP core network. Typically, a mesh router has multiple wireless interfaces to communicate with other mesh routers, and each wireless interface works corresponding to one wireless channel. These wireless channels have different characteristics, because wireless interfaces are running on different frequencies and built on either the same or different wireless access technologies, e.g., IEEE 802.11a/b/g/n. It is also possible that, directional antennas are employed on some interfaces to establish wireless channels over long distance.

WMNs in general have the support of infrastructure [10], characterizing a significant difference from other wireless networks, such as MANETs and WSNs. In other words, a backbone can be built amongst wireless mesh routers. Therefore, it is reasonable to assume that the wireless link between two mesh routers is error immune. Even if there exists minor transmission error, we can still employ reliable multicast protocols to mitigate it [11], [12].

B. Mobile IPTV Deployment in WMN

IPTV defines the way of provisioning real-time television services over IP networks with various mechanisms implemented to ensure the appropriate level of quality [13]–[16]. Originally, IPTV was proposed to serve the users of fixed terminals, such as set-top box and desktop computer. As the requirement of mobility rises up, it is an inevitable trend to extend IPTV technology from wired networks to wireless networks. In this paper, we investigate the mobile IPTV deployment in WMNs, which enables roaming users to receive TV programs anywhere on their handhelds or laptop computers.

A variety of delivery architectures have been proposed to support IPTV service in wired network. These architectures can be roughly classified into the following categories [17]: 1) native IP multicast; 2) application-level infrastructure overlays advocated by CDN companies, e.g., Akamai; and 3) peer-to-peer technologies, such as P2P multicast tree and mesh-pull P2P streaming. So far, in terms of the number of simultaneous users, the most successful IPTV deployments in the Internet utilize mesh-pull P2P streaming architecture.

In WMNs, however, we consider native IP multicast as the optimal architecture for mobile IPTV service. As an example, we could deploy in Fig. 1 several content servers right behind gateway mesh routers, from which the TV programs are delivered to WMN users using native IP multicast. The major advantage of native IP multicast comes from its capability of saving network resources. Particularly, native IP multicast allows the source to send a packet only once, even if it needs to be delivered to a large number of receivers. It is well known that, native IP multicast is generally not considered as practical in the Internet, because it requires router updates across the whole network. However, native IP multicast becomes a feasible solution in WMNs, because the service provider can control all the mesh routers in the network.

Success of mobile IPTV services relies on QoS guaranteed IP multicast. Corresponding metrics include packet loss rate, delay, jitter, channel zapping time, and so on [3]. In the following, we propose an approach of cooperative multicast to address the metric of packet loss. Additionally, we also take into account the delay and spectrum efficiency in our design.

III. COOPERATIVE MULTICAST IN WMN

A. Motivation

Previous study on unicast cooperative communications aimed at improving the performance of point-to-point links in wireless networks [7], [8]. This pioneering work realized a new form of space diversity to combat the effects of severe fading, and thus created a novel communication paradigm that
Cooperative communications in multicast environment are seldom discussed in the open literature. It is worth noting that unicast usually means two-way communication where a pair of users exchange messages interactively. Multicast, on the other hand, is a one-way data delivery where all group members receive the same message. In the coverage of a mesh router, we classify mesh clients into two categories: 1) error-prone nodes and 2) error-immune nodes. In the following, we present the formal definition of our classification.

We study the coverage of a mesh router that involves $N$ mesh clients $M_1$, $M_2$, ..., $M_N$. We denote each wireless node by $i$ ($i = 0, 1, 2, ..., N$), where 0 represents the mesh router and $i$ ($i > 0$) represents mesh client $M_i$. Then, each $i$ has the baseband equivalent discrete time transmitted signal $X_i[n]$ and received signal $Y_i[n]$, where $n$ is the time sample. Hardware limitations of IEEE 802.11 introduce the so called “half-duplex” constraint, by which the received signal of node $M_i$ at time sample $n$ can be modeled as [18]

$$Y_i[n] = \begin{cases} \sum_{j=0}^{N} H_{j,i} X_j[n] + W_i[n], & \text{if } M_i \text{ receives at time } n \\ 0, & \text{if } M_i \text{ transmits at time } n \end{cases}$$

(1)

where $H_{j,i}$ captures the combined effects of symbol asynchronism, fading, quasi-static multipath fading, shadowing, and path-loss between nodes $M_j$ and $M_i$; $W_i[n]$ is a sequence of mutually independent, circularly symmetric, complex Gaussian random variables with common variance $N_0^i$ that models the thermal noise and other interference received at node $M_i$.

Based on above model, the signal-to-noise ratio (SNR) between mesh router and mesh client $M_i$ is given by

$$SNR_{0,i} = P_0 |H_{0,i}|^2 / N_0^i,$$

(2)

where $P_0$ denotes the transmitted power of mesh router.

According to Shannon theorem, the channel capacity or the theoretical upper bound of the data rate from mesh router to
where $B_{0,i}$ is the physical bandwidth of the channel.

In real system, Shannon limit is not reachable and practical channel capacity is decided by the modulation mechanism. For example, IEEE 802.11 employs Orthogonal Frequency Division Multiplexing (OFDM) in the PHY layer. Each OFDM subcarrier further adopts M-ary QAM to achieve high bandwidth efficiency. We assume that $H_{j,i}$ is frequency-flat and each subcarrier takes the same modulation scheme. Then the bit error ratio (BER) performance of OFDM is exactly the same as the underlying modulation of each subcarrier. If the OFDM subcarrier adopts Gray mapping, the BER expression for QAM for the coherent (optimum) receiver in an additive white Gaussian noise (AWGN) channel is given by [19]

$$P_e \approx \frac{\sqrt{M} - 1}{\sqrt{M} \log_2 \sqrt{M}} \erfc\left(\sqrt{\frac{3E_b \log_2 M}{2N_0 (M-1)}}\right),$$

where $E_b/N_0 = SNR \times (B/f_b)$, $B$ and $f_b$ are the channel bandwidth and channel data rate (net bitrate) of OFDM subcarrier respectively.

Then we formulate the multicast BER or the BER from mesh router to mesh client $M_i$ as

$$P_e^{0,i} \approx \frac{\sqrt{M} - 1}{\sqrt{M} \log_2 \sqrt{M}} \erfc\left(\sqrt{\frac{3B \cdot SNR_{0,i} \log_2 M}{2f_b (M-1)}}\right).$$

Usually, error correcting codes are added to the multicast data stream to counteract channel errors. Without loss of generality, we assume block codes are employed with length $K$ and error correcting capability $s$. Then, we define

$$\begin{cases} M_i \text{ is error prone,} & \text{if } KP_e^{0,i} > s; \\ M_i \text{ is error immune,} & \text{if } KP_e^{0,i} \leq s; \end{cases}$$

In the range of a mesh router, we study a typical scenario that the wireless channel from mesh router to mesh client is subject to Log-Distance Path Loss model [20]. Path loss (or path attenuation) is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space. Log-Distance Path Loss model is widely accepted to predict the path loss that a signal encounters inside a building or densely populated areas over distance. Particularly, it has been used to formulate the radio propagation for WLAN, mobile ad hoc network, and wireless sensor network in recent years [21]–[24]. Log-Distance Path Loss model states that the received power over a wireless channel is given by

$$PL = PL(d_0) + 10 \gamma \log_{10}(d/d_0),$$

where $PL$ is the path loss in dB, $PL(d_0)$ is the path loss at a reference distance $d_0$, $\gamma$ is the path loss exponent, and $d$ is the distance from transmitter to receiver. Assuming $d_0 = 1$, we integrate Eq. (7) into Eq. (2) and obtain the following result in dB

$$|H_{0,i}|^2 = -PL(1) - 10 \gamma \log_{10}(d_{0,i}), \quad d_{0,i} > 1,$$

where $d_{0,i}$ represents the distance from mesh router to mesh client $M_i$. Eq. (8) implies $P_e^{0,i}$ is increasing with $d_{0,i}$, and thus there exists a multicast error threshold $d_M^e$ that makes a mesh client $M_i$ an error prone node if $d_{0,i} > d_M^e$. Particularly, when a mesh router adopts 2D omni-directional Log-Distance Path Loss model in the range, the circle of radius $d_M^e$ becomes the threshold boundary. The error-immune nodes are all inside the threshold circle whereas the error-prone nodes are all outside the threshold circle.

C. Cooperative Multicast Relaying Model

The goal of cooperative multicast is to prevent error-prone nodes from transmitting errors by using some error-immune nodes as relays. In our study, we investigate two types of multicast cooperation, i.e., in-group cooperation and out-group cooperation.

**In-group Cooperation:** Multicast is a network addressing method for the delivery of information to a group of destinations simultaneously. In our study, we assume that a multicast group has a number of error-prone and error-immune nodes in the range of a mesh router. Considering the computation and transmission overhead, it is more efficient for error-prone nodes to use, whenever possible, the error-immune nodes in the same multicast group as relays. Once an in-group error-immune node is selected to be a relay, it broadcasts the cooperative signals to its neighborhood.

**Out-group Cooperation:** It is possible that the error-prone nodes could not be completely covered by the in-group relays. In this case, we have to rely on the help from some error-immune nodes out of the multicast group. Clearly, an out-group node will introduce more overhead to serve as a relay, since it has to receive and forward the multicast data not useful to itself. Despite this disadvantage, out-group relays may considerably reduce the number of total relays. For example, one out-group relay may be more effective than several in-group relaying nodes due to its special topology position. In the rest of the paper, relaying node refer to both in-group relay and out-group relay, if not explicitly stated.

In the literature, previous study proposed three cooperative methods, i.e., Amplify and Forward, Detect and Forward, and Coded Cooperation [25]. In Amplify and Forward, the relay receives a noisy version of the signal transmitted by the sender and then simply amplifies and retransmits this noisy version to the receiver; in Amplify and Forward, the relay attempts to detect the sender’s bits and then retransmits the detected bits; in Coded Cooperation, the relay detects the sender’s bits and then transmits the additional parity bits only. In our work, we employ Coded Cooperation in multicast environment since it involves the least amount of relaying bits [26].

To apply Coded Cooperation to multicast, we adopt the concept of incremental redundancy. As shown in Fig. 3, at the transmitter, the information bits are encoded by a systematic “mother” code. Initially, only the systematic part of the codeword and a selected number of parity bits are transmitted during the multicast session. Then the relay sends additional parity bits to the error-prone nodes in the neighborhood. In the literature, incremental redundancy has been
extensively investigated in hybrid automatic repeat request (ARQ). Corresponding coding schemes can be implemented by using Reed-Solomon codes, convolutional codes, and low-density parity-check (LDPC) codes [27]–[29].

We employ frequency division multiplexing (FDM) to allow mesh router and multiple relays transmitting data at the same time. Specifically, we rearrange the OFDM data subcarriers of IEEE 802.11 to three portions: 1) multicast data sub-channel, 2) cooperative signalling sub-channel, and 3) cooperative data sub-channel. Here, multicast data sub-channel refers to the subcarriers allocated to the downlink data transmission from mesh router to mesh clients, cooperative signalling sub-channel refers to the subcarriers allocated to signaling exchange, and cooperative data sub-channel refers to the subcarriers allocated to data relaying. These three sub-channels work at the same time due to the orthogonality of OFDM subcarriers. In our design, we let multiple relays transmit the additional parity bits through different OFDM subcarriers independently. It is notable that these relays actually are transmitting the same information. We consider, however, not to allow them sharing the same OFDM subcarriers, since the unsynchronized multiple copies of signal will lead to severe multipath fading.

As a cost of transmission reliability, our proposed subcarrier allocation scheme will lower the spectrum efficiency (throughput) from mesh router to the mesh clients during a multicast session. Let \( N_s \) be the numbers of IEEE 802.11 data carrying subcarriers, and \( N_m, N_s, N_c \) be the number of multicast data subcarriers, cooperative signalling subcarriers, cooperative data subcarriers, respectively. Then we define the spectrum efficiency of cooperative multicast as

\[
\eta = \frac{N_s}{N_m + N_s + N_c} = 1 - \frac{N_s}{N_s + N_c}.
\]

Above definition shows that the growth of \( N_c \) will decrease the spectrum efficiency (throughput), though it can also accelerate the deliver of cooperative data (additional parity bits) and thus shorten the delay of whole multicast transmission.

As shown in Fig. 4, we define a multicast packet as a vector of \( K \) bits denoted by \( s_M = (S_M[0], S_M[1], \ldots, S_M[K-1]) \). \( s_M \) involves some parity bits to obtain error correcting capability \( s \). The mesh router sends \( s_M \) to its coverage during the multicast session. After receiving \( s_M \), the relays generate and broadcast the additional parity bits \( s_C = (S_C[0], S_C[1], \ldots, S_C[L-1]) \) with the length of \( L \) and the error correcting capability of \( t \).

Assume that node \( M_i \) is error-prone and node \( M_j \) is error-immune. In the following, we study the relationship between node \( M_i \) and node \( M_j \), and judge whether \( M_j \) can serve as relay to \( M_i \).

The SNR between node \( M_j \) and node \( M_i \) is given by

\[
SNR_{j,i} = P_j |H_{j,i}|^2 / N_0^j,
\]

where \( P_j \) denotes the transmitted power of node \( j \). With similar derivation as in Eq. (2)- Eq. (5), we formulate the relay BER, or the BER from relay \( M_j \) to error-prone node \( M_i \) as

\[
P_{e,j} = \frac{\sqrt{M-1}}{\sqrt{M \log_2 M}} \text{erfc} \left( \sqrt{\frac{3B SNR_{j,i} \log_2 M}{2 f_b (M-1)}} \right).
\]

We say error-immune node \( M_j \) is an appropriate relay to error-prone node \( M_i \) or \( M_i \) can be covered by \( M_j \), if

\[
s + t \geq KP_{e,j}^{0,i} + LP_{e,j}^{1,i}.
\]

Moreover, to mitigate unexpected channel fading or interference, we define the cooperative channel quality between \( M_j \) and \( M_i \) as

\[
q_{j,i} = (s + t) - (KP_{e,j}^{0,i} + LP_{e,j}^{1,i}).
\]

We assume the wireless channel between \( M_j \) and \( M_i \) is subject to Log-Distance Path Loss model and we conduct the similar derivation as in Eq. (7) - Eq. (8) to estimate the cooperative radius. For the error-prone nodes whose multicast BER is lower than \( P_r^{M} \) \((s < KP_{e,j}^{0,i} < s + t)\), there exists a relay error threshold \( d_{R}^{p}(P_{r}^{M}) \); if the distance from relay to error-prone node is less than \( d_{R}^{p}(P_{r}^{M}) \), then error-prone node can be covered.

D. Tradeoff Strategy for Transmission Overhead

Cooperative multicast introduces signalling and transmission overhead to WMNs, as the cost of reliability and capacity gains. Here, signalling overhead comes from the message exchange to construct the relaying relationship, whereas transmission overhead comes from the relaying information propagation. Since signalling overhead mainly relies on the given
relay selection algorithm, we will give it intensive investigations in the next section. Transmission overhead, on another hand, is decided by the cooperative methods, such as Amplify and Forward, Detect and Forward, and Coded Cooperation. Coded Cooperation has less transmission overhead than the other two, because it only propagates the additional parity bits.

With the model in Fig. 4, we define the normalized transmission overhead of cooperative multicast as \( O_T = L/K \). On one hand, the growth of transmission overhead can increase the cooperative coverage, i.e., the number of covered error-prone nodes. Given a chosen type of incremental redundancy codes (IR codes) for a relaying message, let \( t = f_{IR}(L) \) be the function from length \( L \) to error correcting capability \( t \). Then, \( f_{IR}(OT/K) (L = OT/K) \) is monotonically increasing with \( O_T \), implying that larger transmission overhead yields larger cooperative coverage. On the other hand, high value of \( O_T \) has negative impact on the cooperative delay, which is a sensitive metric to multimedia multicast applications. During cooperative multicast, the mesh router transmits the multicast data first, and the relays append the additional parity bits after. In our study, we assume each relay is assigned an equal number of \( N_r^s \) OFDM subcarriers. Then we define the cooperative delay as the time to transmit additional parity bits, which is calculated by \( d_c = \frac{O_T K}{N_r^s b_c} \), with \( b_c \) representing the data rate of a single OFDM subcarrier. Above definition shows that cooperative delay is linearly increasing with the transmission overhead.

In a practical system, we have to make a tradeoff between cooperative coverage and delay when configuring transmission overhead \( O_T \). Specifically, we first determine the bound of cooperation delay according to the overall delay requirement of an IPTV application. That is, we achieve cooperative delay bound \( d_c \) by subtracting the routing delay and the en/decoding delay of IR codes from overall delay requirement. With \( d_c \), we then calculate transmission overhead by \( O_T = \frac{N_r^s b_c d_c}{K} \) and cooperative coverage by Eq. (11)- Eq. (12).

Numerical results are given in Fig. 5 to demonstrate the tradeoff curve between cooperative delay and coverage. In our simulation, we adopt the linear IR codes proposed in [30], where each block consists of 16 information bits, 6 initial parity bits, and an adjustable number of additional parity bits \((K = 22, L \geq 1)\). A number of blocks are further packed into one IEEE 802.11 frame to facilitate the data transmission from mesh router to mesh clients. We assume the error-prone nodes have a fixed multicast BER of \( P_{err}^M = 0.12 \) from mesh router, and thus the error correcting capability of initial parity bits, \( s = 1/22 \approx 0.0455 \), cannot guarantee a reliable data reception. We assign each relay with one OFDM subcarrier and apply Log-Distance Path Loss model to the wireless channel between relay and error-prone nodes. For each value of cooperation delay bound, we first calculate transmission overhead \( O_T \) and then derive the cooperative radius \( d_R^c(P_{c}^M) \) from \( f_{IR}(OT/K) \) based on Eq. (12), so that the relay can cover all the error-prone nodes within the distance of \( d_R^c(P_{c}^M) \). The value of cooperative radius in Fig. 5 is normalized at the cooperative delay bound of 50ms. It shows that cooperative radius is increasing with the compromising of delay metric.

IV. DISTRIBUTED RELAY SELECTION FOR MULTICAST COOPERATIVE COMMUNICATIONS

A. Centralized Relay Selection Algorithm

In multicast cooperative communications, one of most important issues is to select the relaying nodes. A straightforward approach is to conduct relay selection in a centralized way. As the coordinator, mesh router exchanges monitoring messages with each mesh client to collect the channel state information (CSI), bit error rate (BER), and topology relationship of in-group and out-group wireless terminals. Then, Mesh router employs a certain algorithm to choose the most appropriate multicast relays and sends the cooperative command to ignite the relays. The basic goal of relay selection algorithm is to minimize the number of relays while covering all error-prone multicast members. In our scheme, we assign each relay the same number of cooperative data subcarriers. Therefore, minimizing the number of relays is equivalent to minimize the number of cooperative data subcarriers or to maximize the spectrum frequency. Next, we theoretically define the centralized optimal relay selection solution, using the terms developed in Section III.

When selecting relaying nodes, we prefer in-group error-immune nodes to out-group ones. With the notations in Table I, we define the optimal in-group relay selection \( \Omega_{in} \) as the one that can cover all nodes in \( S_{in-cv} \) with the least number of in-group relays. To take care of the multicast receivers in \( S_{err} \), as well, we define the integrated optimal in-group/out-group relay selection \( \Omega_{in-out} \) as the one that can cover \( S_{cv} \) with 1) the least number of out-group relays and 2) the least number of in-group relays. Here, condition-1 has higher priority than condition-2. In the rest of the paper, we employ \( \Omega_{in-out} \) as a theoretical comparison reference, and shortly refer it as centralized algorithm.

<table>
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<tr>
<th>Table-I Notations</th>
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<tbody>
<tr>
<td>( S_{in} ): the set of in-group error-immune receivers.</td>
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<tr>
<td>( S_{out} ): the set of out-group error-immune receivers.</td>
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<tr>
<td>( S_{imm} ): the set of all error-immune receivers, ( S_{imm} = S_{in} + S_{out} ).</td>
</tr>
<tr>
<td>( S_{err} ): the set of all error-prone multicast receivers.</td>
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</table>
\( S_{\text{cov}} \): the set of error-prone multicast receivers that can be covered by the relaying nodes in \( S_{\text{in-mm}} \).

\( S_{\text{in-cov}} \): the set of error-prone multicast receivers that can be covered by the relaying nodes in \( S_{\text{in-mm}} \).

The centralized relay selection algorithm mentioned above can be mathematically formulated as weighted set covering problem (WSCP), which has been proved to be NP-hard [31]. In the literature, weighted set covering problem (WSCP) is defined as follows. Given a set of elements \( E = \{ e_1, e_2, ..., e_m \} \) and a set of \( m \) subsets of \( E \), \( S = \{ S_1, S_2, ..., S_m \} \), find a "least cost" collection \( C \) of sets from \( S \) such that \( C \) covers all elements in \( E \). That is, \( \bigcup_{S_i \in C} S_i = E \). Set Cover comes in two flavors, unweighted and weighted. In unweighted Set Cover, the cost of a collection \( C \) is the number of sets contained in it. In weighted Set Cover, there is a nonnegative weight function \( w(S_i) \) for each \( S_i \), and the cost of \( C \) is defined to be \( \sum_{S_i \in C} w(S_i) \). Regarding this definition, each error-prone node is viewed as an element of \( E \) and each error-immune node is viewed as subset from \( S \). Moreover, we consider out-group error-immune nodes have much higher weight than the in-group ones. Then, \( \Omega_{\text{in-out}} \) comes to be the optimal solution to weighted set covering problem.

In centralized relay selection, mesh clients have to report the state information to mesh router periodically. On the contrary, mesh router may send mesh clients the cooperation command. The signalling overhead therefore consists of two portions: uplink overhead \( O_{S}^{U} \) (mesh clients to mesh router) and downlink overhead \( O_{S}^{D} \) (mesh router to mesh clients). In our study, we consider downlink signalling overhead is negligible compared to the uplink signalling overhead, since mesh router only sends cooperative command to renew the relays with respect to significant change in its coverage. Let \( N \), \( u \), \( f_u \) be the number of mesh clients, the number of uplink signalling messages per report, and the state updating frequency (1/sec) respectively. The uplink signalling overhead is given by

\[
O_{S}^{U} = Nu f_u. \tag{14}
\]

To achieve satisfying cooperative gain, \( f_u \) must be high enough to catch up the change of channel condition and network topology in the mobile environment.

**B. Distributed Relay Selection Algorithm**

In practice, centralized optimal relay selection is not applicable due to the frequent user movement, and thus is mainly considered to be a theoretical reference in our study. In the following, we develop a distributed relay selection algorithm as the realistic solution. Our distributed algorithm covers eight different cases, where Case 1-3 address the variation of channel condition, Case 4-6 address the change of multicast membership, and Case 7-8 address the relay handoff problem.

**Case-1: Uncovered Error-prone Multicast Receiver**

1. Error-prone node scans for the existing relays whose received signal strength indicators (RSSIs) are higher than a given threshold;
2. if relays are available then
3. Error-prone node sends available relays a “relay query” message;
4. Each relay replies with its cooperative state information, such as 1) in-group or out-group, 2) the number of registered error-prone nodes;
5. Error-prone node selects the most appropriate relay with the following rules: 1) preferring in-group relays to out-group relays, 2) preferring the relay with more registered error-prone nodes, 3) preferring the relay with higher RSSI;
6. Error-prone node sends the selected relay a relaying request;
7. The selected relay confirms the request and increases the number of registered error-prone nodes by one;
8. Error-prone node starts to process the cooperative signal from selected relay;

**Case-2: Covered Error-prone Node Becoming Error-immune**

1. State-changing node sends its relay a “quitting” request;
2. Relay confirms the request and reduces the number of registered error-prone nodes by one;
3. State-changing node sets its role as the error-immune node;

**Case-3: Relay Becoming Error-prone**

1. State-changing relay broadcasts a message of “relay disabled” to its registered error-prone nodes;
2. Error-prone nodes try to find new relays;
3. if the state-changing relay used to be an in-group one then
4. The state-changing relay tries to find a new relay for itself;
5. end if

**Case-4: Covered Error-prone Node Quitting the Multicast Session**

1. Quitting node sends its relay a “quitting” request;
2. Relay confirms the request and reduces the number of registered error-prone nodes by one;

**Case-5: In-group Relay Quitting the Multicast Session**

1. Quitting relay changes to be an out-group relay;
2. Quitting relay broadcasts a message of “in-group to out-group” to its registered error-prone nodes;
3. The registered error-prone nodes try to find new in-group relays;
4. if new in-group relay is available then
5. Error-prone node makes relay handoff;
6. else
7. Error-prone node sends a message of “in-group relay not available” to the quitting relay and continues the cooperative relationship;
8. end if
Case-6: Out-group Relay Joining the Multicast Session
1: Joining relay turns to be an in-group relay;
2: Joining relay broadcasts a message of “out-group to in-group” to its registered error-prone nodes;

Case-7: Out-group to In-group Relay Handoff
1: Let \( M_i \) be an error-prone node currently registered with out-group relay \( M_j \);
2: \( \text{Set} \ R = \emptyset \); // initializing the handoff-relay pool.
3: Fill \( \text{Set} \ R \) with the in-group relays that have covered \( M_i \) for a certain period;
4: Let \( M_k \) be the relay in \( \text{Set} \ R \), which has the largest number of registered error-prone nodes;
5: \( M_i \) makes a relay handoff from \( M_j \) to \( M_k \);

Case-8: Other Relay Handoff
(in-group to in-group and out-group to out-group, but not in-group to out-group)
1: Let \( M_i \) be an error-prone node currently registered with relay \( M_j \);
2: \( \text{Set} \ R = \emptyset \); // initializing the handoff-relay pool.
3: Fill \( \text{Set} \ R \) with the in/out-group relays that are other than \( M_j \) but have involved \( M_i \) in range longer than a certain period;
4: Let \( M_k \) be the relay in \( \text{Set} \ R \), which has the largest number of registered error-prone nodes; let \( N_j \) and \( N_k \) be the numbers of error-prone nodes registered with \( M_k \) and \( M_j \), respectively.
5: If \( (N_j - N_k) \) is greater than a given threshold then
6: \( M_i \) makes a relay handoff from \( M_j \) to \( M_k \);
7: \end if

In distributed relay selection, signalling exchange is triggered by events, such as the aforementioned eight cases. Therefore, we can calculate the signalling overhead of distributed algorithm by

\[
O_S = \sum_{i=1}^{8} O_S^i f_i, \tag{15}
\]

where \( O_S^i \) and \( f_i \) represent the signalling overhead (number of messages) per Case \( i \) event and the frequency of Case \( i \) event (1/sec) respectively. Eq. (15) indicates that the moving speed and pattern have significant impact on \( f_i \) and \( O_S \).

V. NUMERICAL RESULTS

In this section, we present Matlab simulation results to illustrate the performance of our proposed distributed relay selection schemes. We investigate our approach mainly from three perspectives, including error-countering capability, number of relays, and signalling overhead. Moreover, we employ centralized optimal relay selection as the reference for comparison.

A. Simulation Model

In our simulations, we emulate the multicast in a mesh router’s coverage, where the coordinates of the mesh router are (0,0), and \( N \) mesh clients, represented by \( M_1, M_2, \ldots, M_N \), are randomly placed on a unit disk centered at the mesh router (see Fig. 6). We assume that all mesh clients have the identical receiving capability and all relays have the indential transmitting power and IR codes. We also assume that \( x\% \) out of all mesh clients are the members of multicast group, uniformly distributed according to the distance between mesh client and mesh router.

To formulate the wireless channel, we mainly apply Log-Distance Path Loss model to the unit disk while simplifying other factors, e.g., shadowing and multipath fading, as a possibility. Assuming that the distance inside the unit disk is logarithmized, we make the following configuration in our simulation.

1) Error-prone/Error-immune Nodes: We define three areas in the unit disk, i.e., \( M_i \) belongs to the area of near range, medium range, or far range respectively, if \( 0 < d_{0,i} < 1/3 \), \( 1/3 < d_{0,i} < 2/3 \), or \( 2/3 < d_{0,i} < 1 \). We randomly choose \( y_{n\%}, y_{m\%}, y_{f\%} \) of mesh clients from near range, medium range, far range as error-prone nodes while configuring other nodes as error-immune. Log-Distance Path Loss model requires \( y_{n\%} \ll y_{m\%} \ll y_{f\%} \).

2) Cooperative Relationship: Let \( M_i \) be an error-prone node and \( M_j \) be an error-immune node. Then, we define a threshold for relay distance as \( d^t_R \). We say \( M_j \) can cover \( M_i \) with the possibility of \( z\% \), if the distance between \( M_j \) and \( M_i \) is less than \( d^t_R \). In this model, \( d^t_R \) represents the transmission power of relay \( M_j \), and \( z\% \) represents the shadowing, multipath fading, as well as other random factors between \( M_j \) and \( M_i \). We configure \( d^t_R = 0.18, z = 80 \) in our simulation, which implies \( M_j \) has much less transmission power than the mesh router and there is 20% chance of anomaly in the relay channel.

We study both static model and Brownian motion model [32] to achieve a comprehensive evaluation of our distributed relay selection scheme. In the static model, mesh clients are randomly placed on the unit disk with uniform distribution according to the radius. In the Brownian motion model, we adopt position update equation: \( \text{New}\_\text{Position} = \text{Old}\_\text{Position} + \text{Random}\_\text{Movement} \). We emulate the indoor environment and configure each mesh client moving slowly on the unit disk.

With above definitions, we further program two scenarios

![Fig. 6. Our simulation model of Log-distance unit disk](https://example.com/fig6.png)
in our simulation study:

Scenario-1: Varying the number of mesh clients, or N, in the coverage of a mesh router: \( N = 30 - 60, x = 30, y_n = 15, y_m = 30, y_f = 60, d_R^h = 0.18, z = 80 \)

Scenario-2: Varying the number of multicast receivers, or \( \% \), in the coverage of a mesh router: \( N = 50, x = 30 - 60, y_n = 15, y_m = 30, y_f = 60, d_R^h = 0.18, z = 80 \)

Above two simulation scenarios are applicable to both static model and Brownian motion model. In the rest of this section, we refer Scenario-1 as varying total number of mesh clients and Scenario-2 as varying the percentage of multicast receivers, unless explicitly stated otherwise.

In our simulation study, we take the centralized algorithm \( \Omega_{in-out} \) as the comparing reference to our distributed relay selection algorithm. Here, centralized algorithm \( \Omega_{in-out} \) is the theoretical optimal solution or upper bound for static model. When applying \( \Omega_{in-out} \) to Brownian motion model, the topology of mesh clients is captured and stored each time interval of \( (1/f_u) \). Then the centralized algorithm runs on the stored topology to obtain a relay selection result that keeps valid until the next topology is captured. Moreover, for our distributed relay selection algorithm, we present the converged results in static model and average results in Brownian motion model.

B. Error-countering Capability

Error-countering capability is a prominent advantage of cooperative multicast communications. In the simulation model mentioned above, there are \( N \times x\% \times (y_n \% + y_m \% + y_f \%)/3 \) error-prone multicast receivers, which are considered to be out of multicast range in conventional WMN. Or put differently, without multicast cooperative communications, zero percentage of error-prone nodes can be covered. However, as shown in the following, most error-prone multicast receivers are able to survive with cooperative communications.

Numerical results are presented in Fig. 7 and Fig. 8 to illustrate the error-countering performance of our proposed approaches while varying \( N \) and \( x\% \). For the simulation of Brownian motion model, we assign the centralized algorithm a special value of \( f_u \) so that it has the same overhead as distributed algorithm.

Fig. 7 illustrates the error-countering capability of centralized and distributed relay selection under static model and Brownian motion model. In this metric, centralized and distributed relay selection algorithms have similar performance under static model, explaining that our distributed relay selection converges to the centralized optimal relay selection when mesh clients are not moving. Under Brownian motion model, however, our distributed relay selection takes clear advantage over its centralized counterpart, implying that distributed approach is more feasible than centralized approach in mobile computing environment due to its quick adaptiveness.

Fig. 8 shows that the error-countering capability of centralized and distributed relay selection algorithms are robust with the percentage of multicast receivers. Although the number of error-prone nodes grows with the size of multicast group, most multicast receivers are still able to be reached when enough relays are ignited. The reason is that increasing number of multicast receivers lead to more error-prone nodes and more error-immune nodes (available relays) at the same time.

C. Number of Relays

The number of relays is a straightforward performance indicator of relay selection algorithms. Corresponding simulation results are presented in Fig. 9 - Fig. 12 to illustrate the in-group and out-group scenarios respectively. For Brownian motion model, we apply the criterion that centralized algorithm has the same overhead as distributed algorithm.

Fig. 9 illustrates the number of in-group relays required by different algorithms while varying the total number of mesh clients - \( N \). As the theoretical upper bound, centralized algorithm costs the least relays under static model and Brownian motion model. The distributed relay selection algorithm, compared to centralized algorithm, has similar performance under static model and slightly worse performance under Brownian motion model. It reveals that the distributed algorithm takes a little more relaying cost to handle the mobile computing environment. Above principles of in-group relays rule again
when we investigate the required out-group relays in Fig. 10 while varying the total number of mesh clients - $N$.

Fig. 11 and Fig. 12 show that the growth of multicast receivers increases the average number of in-group relays for all algorithms, whereas out-group relay number keeps relatively stable. This feature is reasonable, since relay selection algorithms address that out-group relays cost more than in-group relays. As a result, the overhead of our multicast cooperative approach mainly depends on the in-group relays when multicast group is highly populated.

D. Comparison of Signalling Overhead

Relay selection, no matter centralized algorithm or distributed algorithm, will involve message exchanges during the cooperative relationship build-up. From a high-level view, these message exchanges are the signalling overhead of cooperative multicast, serving as a necessary cost of reliability and capacity gains. In the following, we compare in Fig. 13 the performance of centralized algorithm and distributed algorithm under Brownian motion model of indoor speed, while varying the total number of mesh clients.

In the simulation, we configure the state updating frequency $f_u$ of centralized algorithm high enough to catch up with the topology change, so that centralized algorithm has equivalent relaying gain as its distributed counterpart. For the message exchange, we set $u$ of the centralized algorithm proportional to the number of error-prone and error-immune nodes; we set $O_i^S$ of the distributed algorithm proportional to the complexity of Case $i$ event.

In Fig. 13, the overhead is quantified by the number of signalling messages dispersed per time unit. To make the numerical results easy to understand, we assume the overhead of centralized algorithm is unit one at $N = 30$, and then normalize other values using it. Fig. 13 shows that the signalling overhead of both centralized and distributed algorithms grows with the number of mesh clients in a mesh router’s range. However, distributed algorithm has much less overhead than the centralized one, since event-driven computing outperforms periodical polling in terms of efficiency.
Fig. 13. Comparison of signalling overhead while varying total number of mesh clients - \( N \) (Simulation Scenario-1)

VI. CONCLUSIONS

To successfully deploy mobile IPTV service in WMNs, we address in this paper the support of reliable multicast using cooperative communications. Specifically, we first study the unique features of multicast cooperative communications, and classify relays into in-group and out-group categories accordingly. After that, we consider WMN as a typical mobile computing environment, and develop a distributed relay selection algorithm to accommodate the user mobility. Extensive simulation results show that our approach can significantly improve the error-countering capability of WMN multicast with a small number of relays.

REFERENCES

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