A Multi-rate Multi-channel Multicast Algorithm in Wireless Mesh Networks

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***Abstract*—Devices in wireless mesh networks can operate on multiple channels and automatically adjust their transmission rates for the occupied channels. This paper shows how to improve performance-guaranteed multicasting transmission coverage for wireless multi-hop mesh networks by exploring the transmission opportunity offered by multiple rates (MR) and multiple channels (MC). We investigate the characteristics and behavior of transmissions with different rates in wireless multi-hop mesh networks. We then propose parallel low-rate transmissions and alternative rate transmissions to explore the advantages of MRMC under the constraint of limited channel resources. A novel link-controlled multi-rate multi-channel multicast algorithm is also designed to extend wireless multicast coverage with high throughput. Our NS2 simulation results demonstrate the improved multicast quality of LC-MRMC in much larger wireless areas as compared to current studies.**

***Keywords*—Wireless multicasting, multiple rates, multiple channels, wireless mesh networks.**

I. Introduction

Multicast in a wireless mesh network (WMN) is promising to efficiently utilize wireless resources in providing flexible and reliable wireless connections to a group of receivers. This paper proposes to improve transmission coverage with high throughput for multicast in a large-scale WMN. Complicated wireless multicasting interference is a major obstacle to achieving this. Such interference is caused by 1) consecutive transmissions on the same multi-hop WMN paths, and 2) parallel delivery of multicast data on paths that have at least one interfering hop. We use the example in Fig. 1 to illustrate the effect of this complicated interference.

While n_0 sends the multicasting traffic to n_1 (labeled by the black arrow lines), n_1 is forwarding data to n_2 (labeled by the light grey arrow lines). Because of the nature of wireless broadcast, the transmission $n_1 \rightarrow n_2$ competes with the transmission $n_0 \rightarrow n_1$ for occupation of the same channel (highlighted by the red circle in the figure). These two concurrent transmissions to consecutive nodes degrade the multicast performance from n0 to n1. Meanwhile, when n_1 receives data, the transmission $n_4 \rightarrow n_5$ also takes place in parallel, which continues degrading the communication performance on the way from n_0 to n_1 (as highlighted by the blue circle in the figure). Weakened wireless multicasting traffic (labeled by the yellow arrow lines) tries to enter n_1, however this then experiences hidden-terminal interference caused by n_2. As highlighted by the green circle, the unexpected detection of the transmission $n_2 \rightarrow n_3$ (labeled by the shadowed arrow lines) further degrades/weakens the quality of multicast that can be transmitted by n_1 (as labeled by the grey arrow line).

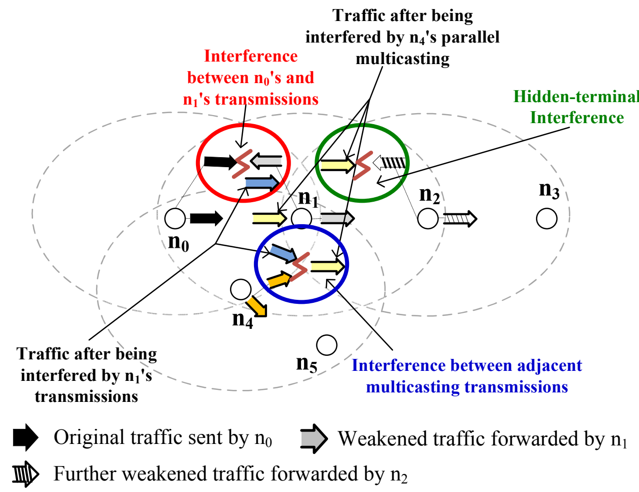


Fig. 1. An example of wireless multicasting interference in a three-hop transmission.

One simple way to address this complicated interference is to employ multiple orthogonal (i.e., non-overlapping) channels at interfering nodes. By attaching orthogonal channels to different radio interfaces, the non-interfering capacity of a WMN may be increased. In the literature, the utilization of orthogonal channels is either in parallel at single nodes to achieve a great accumulated capacity or at successive nodes in series to effectively avoid interfering transmissions. However, with current wireless technology, there is a limited number of orthogonal channels that can be quickly used up in a multi-hop WMN multicast because of the rich connectivity. Hence, it is unfortunately difficult to gain significant improvement in throughput-guaranteed multicast coverage by using orthogonal channels. Apart from operating on multiple channels, devices in a WMN (i.e., gateways, routers, and client nodes) can adjust their transmission rates freely whenever necessary. With the availability of multiple transmission rates, WMN communication performance can be improved either by detouring around bottleneck/interfering nodes or by referring to network conditions to determine an appropriate transmission rate. However, the employment of multiple transmission rates in a WMN multimedia multicast may easily cause a very complicated interference topology. This is because different transmission rates have different coverage - an adaptive change of a transmission rate may incur new interference on a structured multicast tree.

In the literature, research has been carried out to explore multiple transmission rates (MRs) or multiple channels (MCs) separately. Few studies proposed MRMC multicasts to explore the combinational advantages of multiple channels and multiple rates to address the fast performance degradation of multimedia communications in WMNs. This paper is one of the first that investigates efficient MRMC schemes to extend multicast coverage with guaranteed throughput for multimedia applications in WMNs. To start, we conduct simulations to observe the characteristics of and the obstacles experienced by wireless MRMC transmissions. Then, based on the insights and findings achieved from our simulation studies, we propose the following contributions in this paper.

- *The parallel low-rate transmission* scheme (PLT) improves high-capacity wireless coverage by equipping nodes with multiple low-rate channels in parallel. PLT requires simple processes with few overheads and its effectiveness in extending high-performance transmission ranges becomes a key element in our MRMC multicast design.
- *The alternative rate transmission* algorithm (ART) alternatively employs PLT transmissions and regular transmissions to achieve a great throughput-guaranteed extension of coverage under limited channel availability. Such performance is obtained by analyzing a benchmark rate that provides the best balance between throughput and coverage and planning PLT transmissions at the $j(\lceil \frac{\check{d}}{d} \rceil + 1)$th[1] hops to control interference with the available orthogonal channels, where $j \in N$, d and $\check{d}$ are the radii of the wireless coverage of the benchmark rate and the rate used by PLT respectively.
- *The link-controlled multi-rate multi-channel multicast* algorithm (LC-MRMC) constructs a multicast tree by efficiently selecting the minimum number of on-tree forwarders that can reliably connect the multicast source to all group receivers via interference-controlled ART paths.

Finally, we use NS2 simulations to evaluate the proposed LC-MRMC. We observe the average multicast throughput, the average multicast delays, and the multicast transmission coverage in different simulated WMNs. The results show that LC-MRMC carries multimedia traffic with higher rates to areas that are at least 85.7% larger than those existing MRMC WMN multicast schemes can achieve.

II. Related Work

Multi-channel multi-radio multicast. Research on multiple channels has consistently focused on channel assignment with diverse static and dynamic solutions being proposed. O. Karimi *et al.* [1] studied high-throughput WMN multicast by exploring the advantages of channel diversity and multiple mesh gateways. By forming WMN multicast as a mathematical problem, an iterative primal-dual optimization framework is proposed to iteratively switch between solving primal sub-problems for channel allocation and routing. S. Lim *et al.* [2] improved multicast connectivity in a multi-channel WMN. The proposed protocol builds multicasting paths while inviting multicast members. The channel assignment guarantees that neighboring members will have common channels. N. Lan *et al.* [3] presented a channel assignment algorithm that uses both orthogonal and overlapping channels to minimize interference for WMN multicast. H. Chiu *et al.* [4] proposed an integer linear program and an associated heuristic algorithm for WMN multicast to efficiently minimize the carried load on the most-heavily loaded channel and maximize the residual capacity of the most heavily loaded node by using multiple channels.

Multi-rate multicast. Research on multiple transmission rates has investigated rate adaption and rate allocation schemes. J. Choi *et al.* [5] presented algorithms to dynamically control wireless transmission rates based on collision situations. H. Zhu *et al.* [6] proposed to adjust transmission rates by referring to the signal to noise ratio that can be achieved by exchanging control messages. T. Kim *et al.* [7] studied rate adaption on a per path basis. A new metric ETM is studied that takes the relative position of a link on a path and the avoidance of congestion areas into account to adjust transmission rates for WMN routing to achieve reliably high throughput. A. Kakhbod *et al.* [8] considered the decentralized bandwidth/rate allocation problem in multi-rate multicast service provisioning with strategic users. O. Alay *et al.* [9] proposed a method to dynamically adapt the transmission rate and Forward Error Correction (FEC) for video multicast over multi-rate wireless networks.

Multi-channel multi-rate multicast. The advantages of multiple rates and multiple channels in combination have also been explored in the literature. S. Bodas *et al.* [10] studied scheduling algorithms for multi-channel OFDM-based downlink systems. A Markov chain mathematical technique that improves on traditional ON-OFF models is developed for channels with multiple rates. However, this work considers neither multicast nor multi-hop wireless paths. For MRMC in WMNs, J. Qadir *et al.* [11] designed degree-free (DF) transmission. Briefly, a DF node employs multiple channels with each channel using a different rate to transmit data to those neighbors who are located in the coverage of the transmission rate. DF enables closer nodes to receive data with shorter delays (because of a faster transmission rate) instead of compromising for more distant nodes to receive at a lower rate with longer delays. The MRMC transmission has been used by L. Farzinvash *et al.* [12] to develop a multi-gateway multi-rate multicast routing in order to maximize the total achieved data rates at receivers while preserving fairness between them. To the best of our knowledge, the structured DF scheme is the most closely related to our study motivations. However, although DF may be effective when network traffic load is light, it may not be suited to high-rate multimedia communications because multiple DF transmissions of the same high-rate traffic easily causes bottleneck nodes. We are then motivated to develop a new MRMC study that can efficiently utilizes wireless resources to achieve the goal of extended throughput-guaranteed coverage.

III. Multiple rates and multiple channels in WMNs

A. About The Throughput-coverage Tradeoff

The tradeoff between network throughput and transmission coverage introduced in the literature is based on single-hop wireless transmissions. We conduct NS2 simulations to observe the transmission behavior of different rates on a multi-hop wireless path. The simulations use the parameter settings listed in Table I. To set 802.11 MAC and physical wireless parameters, we refer to the specifications of Lucent ORiNOCO11b cards. Also, a probabilistic Nakagami propagation model, representing channel

[1]The expression $\lceil \frac{\check{d}}{d} \rceil$ represents the smallest integer greater than $\frac{\check{d}}{d}$.

fading characteristics of a wide-range urban settings, is employed in the simulations.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Simulator	NS2.33
Frequency	2.4GHz
Propagation Model	Nakagami
MAC Protocol	802.11
Transmission Power	15dBm
Number of Channels	1
Receive Threshold of 1.0 Mbps Transmissions	-94dBm
Receive Threshold of 2.0 Mbps Transmissions	-91dBm
Receive Threshold of 5.5 Mbps Transmissions	-87dBm
Receive Threshold of 11 Mbps Transmissions	-82dBm
Packet Type	RTP/UDP
Packet Size	1400 bytes

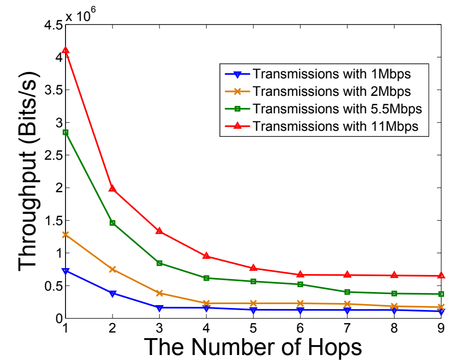
Fig. 2 (a) demonstrates the varying trends of network throughput of different rates. Each curve is plotted based on the effective throughput received at different hops. By the effective throughput (a.k.a the effective capacity in this paper), we mean the maximum transmission capacity achievable without causing an unacceptable data loss rate. In the simulations of this paper, we use 5% as the bound of data loss rates. The results in Fig. 2 (a) agree that a higher transmission rate contributes to a higher network throughput. Moreover, the decrease in network throughput is much greater over the first few hops. This is because the data rates at the first few hops are higher, which likely causes more intensive interference when nodes on this path use a common wireless channel. Hence, our first observation is - *under the same transmission circumstances (e.g., external interference, environmental factors), the traffic with a higher data rate suffers more performance loss than the traffic with a lower data rate does.*

Fig. 2 (b) plots the curves of transmission coverage resulting from this simulation. Indeed, a lower rate transmission can reach a larger area. However, if we combine the results in both figures, it is worth noting that a higher-rate transmission can deliver a higher network throughput to a larger area via a greater number of hops. For example, in this simulation, the 5.5Mbps transmission delivers an effective throughput of 1.46Mbps to an area with the radius of 702m via 2 hops, while the 2Mbps transmission can only deliver an effective throughput of 1.28Mbps to an area with the radius of 369m. This suggests an interesting insight - *the throughput-coverage tradeoff is potentially addressable by transmitting at a higher rate via multiple hops.*

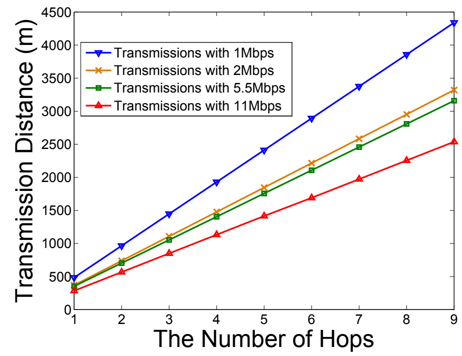
B. Parallel Low-rate Transmission (PLT)

We consider a simple wireless multicast in Fig. 3 in which n_1 is located in the 11Mbps transmission range of n_0 and n_2 is located out of the 11Mbps transmission range but within the 5.5Mbps transmission range of n_0. For the sake of connectivity, it is not unusual for n_0 to transmit at 5.5Mbps in the literature, however this limits the throughput that n_1 can potentially achieve since n_0 is capable of transmitting at 11Mbps. Moreover, when n_1 forwards the received packets to n_3, the already degraded throughput at n_1 may cause unacceptable throughput at n_3 and hence shrinks multicast coverage (as n_3 cannot be admitted into the multicast). Degree-free transmissions (DF) [11][2] solves this problem by equipping n_0 with two channels - one for transmissions at 11Mbps (to n_1) and the other for transmissions at 5.5Mbps (to n_2). In this way, n_1 can achieve throughput as great as its connection allows and n_3 is able to join the multicast with acceptable performance. However, DF inefficiently utilizes resources (e.g., node power, channel bandwidth) as n_0 has to schedule the transmission of the same information twice. In a more complicated topology, when a node has several direct children, this node could easily become a bottleneck in a DF multimedia multicast affecting both throughput and coverage of the multicast.

[2]Please refer to Section II for our introduction to DF.



(a)



(b)

Fig. 2. The network throughput (a) and the transmission distances (b) achieved by different transmission rates in the multi-hop wireless simulation.

We propose the idea of parallel low-rate transmissions (PLT). Instead of employing two channels to transmit at the rates required by individual nodes, as illustrated in Fig. 3 (b), with PLT, n_0 employs two 5.5Mbps orthogonal channels in parallel to transmit half of the traffic via each channel. As a result, both n_1 and n_2 receive the same high network throughput without requiring n_0 to transmit the same traffic more than once. We simulate the two transmission schemes in the multicast topology of Fig. 3 with the same settings in Table I. Fig. 4 shows the comparison of the average throughput: PLT gains an effective throughput of 4.25Mbps for both n_3 and n_4 - a 92% improvement as compared to the average effective throughput achieved by DF. This improvement is achieved without scheduling the delivery at different nodes (the requisite of DF) and hence benefits the real-time performance.

C. Analysis of The Parallel Low-rate Transmission

We now generalize the achieved observations from the above simulations for other transmission rates. Suppose there are $n (n > 0)$

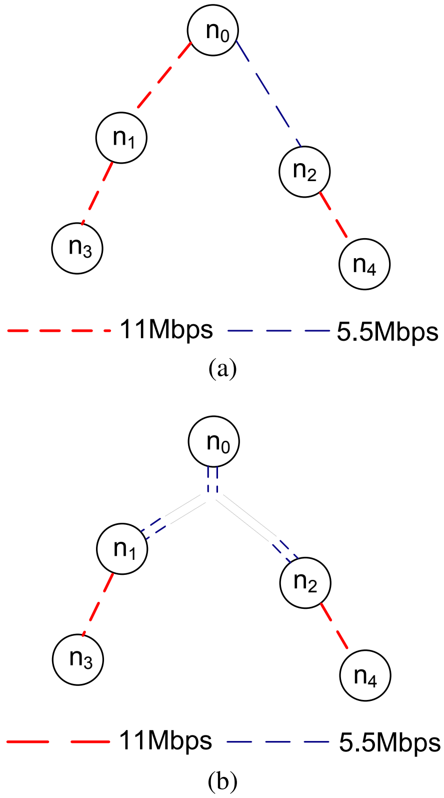


Fig. 3. An example of wireless multicast with DF (a) and with PLT (b).

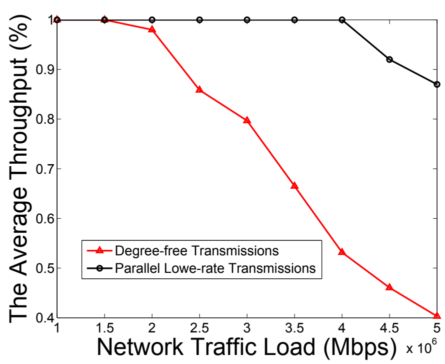


Fig. 4. The average network throughput of DF and PLT achieved from the multicast in Fig.3.

different rates, denoted as $\{r_0, r_1, ..., r_{n-1}\}$, required by DF. Denote the throughput reduction factor of r_i as β_i[3] and the maximum throughput-guaranteed hops that the traffic with r_i can travel as H_i. For PLT, if its transmission rate is $r(r_{min} \leq r \leq r_{max})$, denote the throughput reduction factor of r as β and the maximum throughput-guaranteed hops that the traffic with r can travel as H, where $r_{max} = max\{r_i, i \in [0, n-1]\}$ and $r_{min} = min\{r_i, i \in [0, n-1]\}$.

Theorem 1 *Parallel low-rate transmissions overtake degree-free transmissions in terms of effective output capacity by* $[\frac{nr_{max}\beta}{\sum_{i=0}^{n-1}\beta_i r_i} - 1]$ *in single wireless transmissions, and by* $[\frac{nmin\{r_{max}\beta p_j, j\in[0,H-1]\}}{\sum_{i=0}^{n-1} min\{r_i\beta_{i,j}p_{i,j}, j\in[0,H_i-1], i\in[0,n-1]\}} - 1]$ *in multi-hop wireless transmissions, where* $p_{i,j}$ *is the transmission probability at the* j*th hop of a DF path with rate* r_i*,* p_j *is the transmission probability at the* j*th hop of a PLT path.*

[3]In Section III A, we observed that the effective throughput provided by a transmission rate is reduced from the nominal transmission rate.

Proof. For the n channels (with each associated with a different transmission rate) used by a DF node, we denote the transmission probability of the ith ($i \in [0, n-1]$) channel as p_i^{DF}. When $r_i \leq r_j$ ($j \in [0, i) \cup (i, n-1]$), the transmission coverage of the channel with r_i is larger than the transmission coverage of the channel with r_j, i.e., $p_i^{DF} \leq p_j^{DF}$ as a larger coverage experiences a higher interference possibility. To synchronize data delivery to downstream neighbors via n channels, the DF node should transmit with the probability (p^{DF}) equal to the minimum transmission probability among n channels (i.e., the transmission probability of the channel with r_{min}). Therefore, the effective output capacity of a channel transmitting at r_i is at most $\beta_i r_i p^{DF}$. This means that the average effective throughput of the DF transmission using n rates is $\frac{\sum_{i=0}^{n-1}\beta_i r_i p^{DF}}{n}$. For the PLT transmission, if rate r ($r_{min} \leq r \leq r_{max}$) is employed, a number of $\lceil\frac{r_{max}}{r}\rceil$ channels should be employed in parallel in order to make up the difference between r_{max} and r. Then, the effective output capacity of PLT is $\lceil\frac{r_{max}}{r}\rceil\beta r p^{PLT}$, where p^{PLT} is the transmission probability when the channel is using rate r.

To compare the two transmission schemes, we have $\frac{\sum_{i=0}^{n-1}\beta_i r_i p^{DF}}{n\lceil\frac{r_{max}}{r}\rceil\beta r p^{PLT}} \leq \frac{\sum_{i=0}^{n-1}\beta_i r_i}{nr_{max}\beta} < 1$.[4] More specifically, the effective capacity improvement of PLT on a one-hop wireless path is $\frac{\lceil\frac{r_{max}}{r}\rceil\beta r - \frac{\sum_{i=0}^{n-1}\beta_i r_i}{n}}{\frac{\sum_{i=0}^{n-1}\beta_i r_i}{n}} > \frac{nr_{max}\beta}{\sum_{i=0}^{n-1}\beta_i r_i} - 1$.

We now analyze the PLT improvement in effective capacity in multi-hop transmissions. Assume that traffic experiences H_i hops if DF uses rate r_i ($i \in [0, n-1]$). After transmitting H_i hops, DF's effective throughput should be $\min\{r_i\beta_{i,j}p_{i,j}, j \in [0, H_i - 1], i \in [0, n-1]\}$, where $\beta_{i,j}$ is the throughput reduction factor and $p_{i,j}$ is the transmission probability at the jth hop. This implies that the average effective throughput achieved by DF in a multi-hop transmission is $D = \frac{\sum_{i=0}^{n-1}\min\{r_i\beta_{i,j}p_{i,j}, j\in[0,H_i-1], i\in[0,n-1]\}}{n}$.

For PLT, the effective throughput after transmitting H hops is $P = \min\{\lceil\frac{r_{max}}{r}\rceil r\beta p_j, j \in [0, H-1]\}$, where p_j is the transmission probability of the traffic at the jth hop. Hence, the improvement of PLT in effective capacity is

$$\frac{P - D}{D} > \frac{nmin\{r_{max}\beta p_j, j \in [0, H-1]\}}{\sum_{i=0}^{n-1} min\{r_i\beta_{i,j}p_{i,j}, j \in [0, H_i - 1]\}} - 1.$$

Q.E.D

PLT needs to split the full traffic into several sub-traffic flows and to transmit the sub-traffic flows via multiple channels in parallel to next-hop nodes. Since all PLT channels use the same transmission rate, the flow splitting is simply to schedule packets to be transmitted via different channels in a round robin fashion. Such split allows multiple channels to share traffic load with few overheads or additional processes.

[4] $\frac{\sum_{i=0}^{n-1}\beta_i r_i p^{DF}}{n\lceil\frac{r_{max}}{r}\rceil\beta r p^{PLT}} \leq \frac{\sum_{i=0}^{n-1}\beta_i r_i p^{DF}}{n\lceil\frac{r_{max}}{r}\rceil\beta r p^{DF}}$ because $p^{DF} \leq p^{PLT}$. Since $r < r_{max}$, based on our observations in Section III A, we have that β is less than the throughput reduction factor of r_{max}. That is, $r_{max}\beta$ is larger than the effective capacity provided by r_{max}. As $\beta_j r_j < \beta_i r_i$ if $r_j < r_i$ ($j \in [0, n-1], j \neq i$), we have $nr_{max}\beta > \sum_{i=0}^{n-1}\beta_i r_i$.

IV. Alternative Rate Transmission

Although PLT requires a simple process to effectively improve transmission ranges with high throughput, its significant benefit relies on the availability of orthogonal channels. With the limited channel diversity in practice, we design the alternative rate transmission (ART) that applies PLT alternatively with regular transmissions on multi-hop paths to extend transmission ranges as well as maintain high transmission throughput.

A. Benchmark Rate

To save orthogonal channels for PLT transmissions, regular transmissions employ single channels. Bearing the motivation of improving both throughput and coverage in mind, by referring to our observations in Section III A, in ART, regular transmissions use such a rate that provides the best balance between coverage and performance over multiple hops. We call it the benchmark rate, denoted as R. We now analyze how to achieve R among n available rates.

For a multimedia flow with the burstiness $\sigma > 0$ and the average transmission rate $\rho > 0$, based on [13], the input traffic load meets $\int_t^{t+\tau} R(t)dt \leq \sigma + \rho\tau$,where $R(t)$ is the rate function of multimedia traffic. If the output with rate r_i can travel H_i hops (with guaranteed throughput) and the transmission probability at the jth ($j \in [0, H_i - 1]$) hop is $p_{i,j}$, the achievable output capacity at this hop is $r_i \beta_{i,j} p_{i,j}$. It infers that the one-way delay of the multicast flow at this hop is $\frac{\sigma+\rho\tau}{r_i \beta_{i,j} p_{i,j}}$. Let $\frac{1}{\beta_i p_i} = \frac{\sum_{j=0}^{H_i-1} \frac{1}{\beta_{i,j} p_{i,j}}}{H_i}$. Then, the one-way delay for the multimedia flow to be transmitted on the H_i-hop path is $\sum_{j=0}^{H_i-1} \frac{\sigma+\rho\tau}{r_i \beta_{i,j} p_{i,j}} = \frac{H_i(\sigma+\rho\tau)}{r_i \beta_i p_i}$.

Hence, the greatest coverage for transmissions with rate r_i achieving guaranteed delays in delivery of complete multimedia data has an upper bound of

$$H_i d_i \leq \frac{d_i \bar{D} r_i \beta_i p_i}{\sigma + \rho\tau}, \tag{1}$$

where $\bar{D}$ is the end-to-end delay bound and d_i is the radius of the coverage of rate r_i. ART selects the rate that contributes the maximum value for expression (1) as the benchmark rate R.

B. Alternative Rate Transmission

The ART algorithm classifies wireless mesh nodes as *regular nodes* and *PLT nodes*. Regular nodes transmit at the benchmark rate (denoted as R) via single channels. PLT nodes employ the PLT transmission to send packets at rate $\check{R}$[5].

Theorem 2 *For any path in a wireless multi-hop system, in order to make the most of the throughput and coverage advantage provided by PLT nodes, ART should assign nodes at the $j(\lceil\frac{\check{d}}{d}\rceil+1)$th hops ($j \in N$) as PLT nodes and nodes at all other hops as regular nodes, where d and $\check{d}$ are the radiuses of the coverage of transmission rates R and $\check{R}$ respectively.*

Proof. When ART uses $\check{R}$ at the $j(\lceil\frac{\check{d}}{d}\rceil + 1)$th hops, there are $\lceil\frac{\check{d}}{d}\rceil$ hops of regular transmissions with rate R between two closest PLT nodes. To avoid the interference between these regular nodes, the number of $\min\{\lceil\frac{\check{d}}{d}\rceil, 3\}$ orthogonal channels is required. The reason for introducing 3 into the expression is because neighboring or hidden-terminal interference on a multi-hop path can be avoided if any 3 consecutive hops on the path use orthogonal channels. Then, adding the $\lceil\frac{R}{\check{R}}\rceil$ channels required by a PLT node[6], the total number of channels required by an ART transmission is $(\lceil\frac{R}{\check{R}}\rceil + \min\{\lceil\frac{\check{d}}{d}\rceil, 3\})$.

For a non-ART transmission, assume that there are m regular nodes between the two closest PLT nodes. To avoid interference between m regular nodes, the number of required orthogonal channels is $\min\{m, 3\}$. When $m > \lceil\frac{\check{d}}{d}\rceil$, we have $m \geq 3$ because $\check{d} > d$ implies $\lceil\frac{\check{d}}{d}\rceil \geq 2$. If $m = 3$, the ART transmission is actually employed. If $m > 3$, the non-ART transmission underuses PLT transmissions and hence cannot achieve the best coverage performance.

For a non-ART transmission with $m < \lceil\frac{\check{d}}{d}\rceil$, $3\lceil\frac{R}{\check{R}}\rceil$ channels are required to avoid interference between PLT nodes on the path. Adding the $\min\{m, 3\}$ orthogonal channels used by regular nodes to remove intra-path interference, a total number of $3\lceil\frac{R}{\check{R}}\rceil + \min\{m, 3\}$ orthogonal channels are required. We have

$$[3\lceil\frac{R}{\check{R}}\rceil + \min\{m,3\}] - [\lceil\frac{R}{\check{R}}\rceil + \min\{\lceil\frac{\check{d}}{d}\rceil, 3\}] > 0.^7 \tag{2}$$

Namely, this non-ART transmission needs more orthogonal channels to avoid intra-path interference than the ART transmissions. For external interference, the non-ART transmission with $m < \lceil\frac{\check{d}}{d}\rceil$ surely needs more orthogonal channels to be interference-free as it uses PLT transmissions (having larger coverage) more frequently than the ART transmission does.

Altogether, the use of $\check{R}$ at the $j(\lceil\frac{\check{d}}{d}\rceil+1)$th hops is more efficient in controlling the usage of orthogonal channels while improving the high-throughput transmission coverage. Q.E.D

We use an example in Fig. 5 to illustrate the role assignment for ART nodes. Suppose $\frac{R}{\check{R}} = 1.6$ and $\frac{\check{d}}{d} = 1.5$. Nodes at the $j(\lceil\frac{\check{d}}{d}\rceil+1)$th hops are nodes 2 and 5. ART assigns them to be PLT nodes. These PLT nodes employ $\lceil\frac{R}{\check{R}}\rceil = 2$ channels in parallel to transmit at $\check{R}$. All other nodes 0, 1, 3, and 4 are regular nodes that transmit at R.

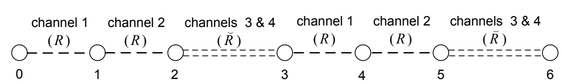


Fig. 5. An example of the alternate rate transmission in a line topology.

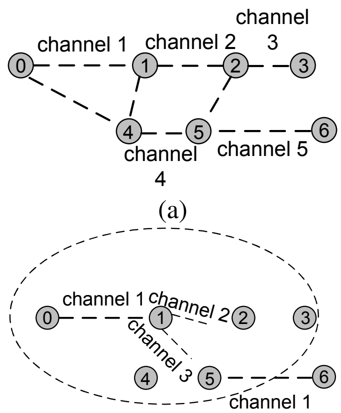
The ART transmission in Fig. 5 is interference-free if 4 orthogonal channels are available. The effectiveness of ART in saving channels may be called into question because 4 orthogonal channels are needed to avoid interference, rather than 3 that would be necessary in such a line topology. However, in practice, wireless networks are much more complicated than a line topology. For the transmission in Fig. 6, node 0 is the sender and nodes $1 \sim 6$ are receivers. Fig. 6 (a) shows that 5 orthogonal channels are

[5] Theorem 3 presents the equations for achieving $\check{R}$.

[6] The two closest PLT nodes do not interfere with each other as they are not in each other's interference coverage.

[7] Note that $m < \lceil\frac{\check{d}}{d}\rceil$. Then, if $\lceil\frac{\check{d}}{d}\rceil < 3$, expression (2) can be simplifed as $2\lceil\frac{R}{\check{R}}\rceil + m - \lceil\frac{\check{d}}{d}\rceil$. Since both m and $\lceil\frac{\check{d}}{d}\rceil$ are less than 3, it infers that $m - \lceil\frac{\check{d}}{d}\rceil < -1$ and hence $2\lceil\frac{R}{\check{R}}\rceil + m - \lceil\frac{\check{d}}{d}\rceil > 0$. By the similar way, expression (3) can be proved for the cases $m < 3 < \lceil\frac{\check{d}}{d}\rceil$ and $m > 3$.

required for avoiding interference if only using the benchmark rate to transmit packets. In Fig. 6 (b), node 1 employs PLT that uses 2 low-rate channels to cover nodes $2 \sim 5$. Note that, with ART, node 4 receivers on channels 2 and 3 instead of channel 1 (Fig. 6 (a)). Also, node 5 reuses channel 1 to transmit to node 6 without interfering other coexisting transmissions. ART saves 2 orthogonal channels in this example.



(b)

Fig. 6. An example of ART in a multicast communication.

C. PLT Transmission Rate

Theorem 3 *In order to achieve the best channel utilization to gain the largest throughput-guaranteed transmission coverage, the PLT rate $\check{R}$ should have a transmission coverage satisfying*

$$max\{\frac{\lceil \frac{d_i}{d} \rceil \times d + d_i}{min\{3, \lceil \frac{d_i}{d} \rceil\} + \lceil \frac{R}{r_i} \rceil + \psi}, i \in [0, n-1]\},$$

where $\psi = \lceil \lambda d_i \rceil + (\lceil \lambda d \rceil - 3)\lceil \frac{d_i}{d} \rceil + 1$, d_i and d are the radiuses of transmission coverage of channels using rates r_i and R (the benchmark rate of regular nodes) respectively, and λ is the average node density in the system.

Proof. Suppose PLT employs the ith available rate, i.e., r_i. Based on the proof of Theorem 2, to avoid intra-path interference, $min\{3, \lceil \frac{d_i}{d} \rceil\} + \lceil \frac{R}{r_i} \rceil$ orthogonal channels are required by ART.

Denote the average node density in the system as λ. To avoid external interference, we calculate the number of required orthogonal channels between two PLT nodes as these channels can be reused by nodes between other pairs of PLT nodes. A PLT node has $(\lceil \lambda d_i \rceil - \lceil \frac{d_i}{d} \rceil)$ neighboring nodes that are not on the path; the next-hop regular node of the PLT node has $(\lceil \lambda d \rceil - 1)$ neighboring nodes that are not on the path; each of the other $(\lceil \frac{d_i}{d} \rceil - 1)$ regular nodes between two PLT nodes covers 2 regular nodes on the path and hence needs a set of $(\lceil \lambda d \rceil - 2)$ orthogonal channels to avoid external interference. Therefore, a total number of $\psi = \lceil \lambda d_i \rceil + (\lceil \lambda d \rceil - 3)\lceil \frac{d_i}{d} \rceil + 1$ orthogonal channels is needed to remove external interference.

For the coverage of ART, it is not hard to obtain $\lceil \frac{d_i}{d} \rceil \times d + d_i$. Then, the per channel coverage achieved by ART using R and r_i is $\frac{\lceil \frac{d_i}{d} \rceil \times d + d_i}{min\{3, \lceil \frac{d_i}{d} \rceil\} + \lceil \frac{R}{r_i} \rceil + \psi}, i \in [0, n-1]$. Hence, to achieve the best channel utilization in terms of increasing transmission coverage, the transmission coverage of PLT transmissions should meet

$$max\{\frac{\lceil \frac{d_i}{d} \rceil \times d + d_i}{min\{3, \lceil \frac{d_i}{d} \rceil\} + \lceil \frac{R}{r_i} \rceil + \psi}, i \in [0, n-1]\}.$$

Q.E.D

V. Link-controlled Multi-rate Multi-channel Multicasting Tree (LC-MRMC)

The construction of an LC-MRMC tree is initiated by the registration procedure of receivers. Each multicast receiver broadcasts a REGISTRATION packet to the multicast sender s, including the fields of Group_ID identifying the multicast group, Hop_Count recording the hop number between a mesh node and s, and Forwarder_list recording the IP address and the reliability of a REGISTRATION forwarder. Hop_Count is initially set as 0 by a receiver but increased by 1 at each intermediate node that forwards this REGISTRATION. Meanwhile, each node updates the Forwarder_List by adding its IP address and reliability (the inverse of the loss rate at this node) into this field. A REGISTRATION message is transmitted with the benchmark rate R. Receivers learn the group ID and R by contacting a group manager (GM), a special node maintaining information regarding system topologies and implementing ART analysis based on our theorems[8]. For robust communications, a multicast may have more than one GM.

To set up ART paths, the sender s replies with an ACK message to each receiver via broadcast. Each ACK is forwarded with rate $\check{R}$ at the $j(\lceil \frac{\check{d}}{d} \rceil + 1)$th hops ($j \in N$) but with rate R at all other hops[9]. An ACK packet records the IP address and the hop distance (to s) of each forwarder. The information is returned to s by each receiver when it replies with a TOPOLOGY message via unicast. Once s receives TOPOLOGYs from all receivers, it starts constructing a multicast tree by refining our previous LCRT [14] algorithm for the use of ART transmissions. More specifically, s assigns multicast nodes on ART paths into different levels based on their shortest numbers of hops to s. For example, in Fig. 7, nodes 7∼9 need at least 3 ART hops to reach the sender node 0 and hence they are level-3 nodes.

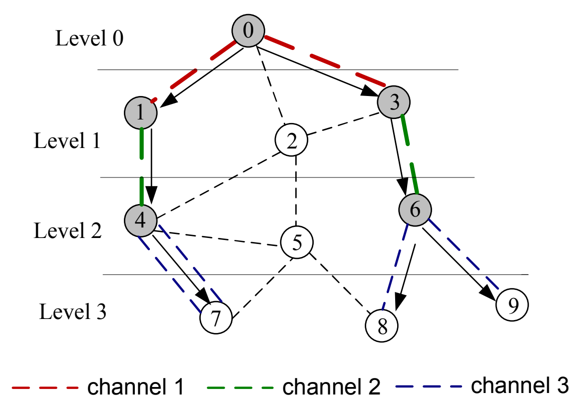


Fig. 7. An example of the LC-MRMC multicasting tree.

[8]There are plenty of studies (e.g., RRAS multicast group manager) providing solutions to develop a GM. Due to the limited space, we do not develop further details about GMs in this paper.

[9]Like receivers, s learns R, $\check{R}$ and the group ID from the GM.

s then selects LC-MRMC forwarders to construct a multicast tree. In order to achieve reliable and interference-controlled multicast connections, the LC-MRMC weight

$$\omega = \chi_{\times}\frac{1}{\upsilon} \times \frac{1}{\kappa} \times \frac{1}{l} \qquad (3)$$

is proposed, where χ and υ are a node's number of on-tree neighbors that have or haven't found their upstream forwarders respectively, κ is a node's number of neighboring forwarders at the same level, and l is a node's loss rate. Nodes with greater weights have the priority to be LC-MRMC forwarders. The employment of $\chi \times \frac{1}{\upsilon} \times \frac{1}{\kappa}$ controls interference by allowing a node having more downstream children but fewer other neighbors to to become an LC-MRMC forwarder with priority. Hereafter, s constructs a LC-MRMC tree by following Steps 4-16 in Algorithm 1.

Algorithm 1 The Link-Controlled Multi-rate Multi-channel Multicasting Tree

Input: Multicast source s; multicast receivers;
Output: The constructed LC-MRMC tree;

1. Each group receiver sends a REGISTRATION packet to s by broadcasting, with the field HOP_COUNT set as 0;
2. Each intermediate node forwards a REGISTRATION from the same receiver once, after updating HOP_COUNT and FORWARDER_LIST;
3. Once receiving REGISTRATION packets from all receivers, s assigns all involved nodes into different levels;
4. $j = H - 1$; // H is the maximum number of hops from s to all receivers
5. **While** $j > 0$
6. s selects a non-forwarder node at level j that has the largest weight (based on (3)) as an LC-MRMC forwarder at this level;
7. **If** the selected forwarders at level j cover all LC-MRMC forwarders or receivers at level $(j + 1)$
8. $j = j - 1$;
9. **Otherwise**, goes to step 6 to continue selecting on-tree forwarders at level j;
10. s arranges orthogonal or low-overlapping channels in a channel set with orthogonal channels listed before low-overlapping channels;
11. $j = 0$;
12. **While** $j < (H - 2)$
13. **If** forwarders at level j are regular forwarders,
14. s assigns the cth channel in the channel set to forwarders at level j; // c is the remainder of the expression $j \div L$, L is the total number of channels in the channel set
15. **Otherwise**, // forwarders at level j are PLT forwarders
16. s assigns the cth channel to the $(c + \lceil \frac{R}{\check{R}} \rceil)$th channel to forwarders at level j;

To illustrate the algorithm, in Fig. 7, suppose nodes 7, 8, and 9 are group receivers and node 0 is the multicast source. Based on their shortest hop distances, all involved nodes are assigned into different levels as shown in the figure. Starting from level 2, node 0 selects LC-MRMC forwarders that can reliably cover the most number of uncovered group receivers at level 3. Suppose nodes 4 & 5 & 6 have the same loss rates. Initially, both nodes 5 & 6 connect to two uncovered children: node 5 covers nodes 7 & 8 and node 6 covers node 8 & 9, i.e., $\chi_5 = \chi_6 = 2$. To select the first forwarder between them, the values of κ of the two nodes are checked. Since node 6 has no neighbors at level 2, node 6 is firstly selected as a forwarder. Now, at level 3, only node 7 has not found its forwarder. Both nodes 4 & 5 can connect to node 7. Also, $\chi_4 = \chi_5 = 1$ and $\kappa_4 = \kappa_5 = 1$. To choose the second forwarder, the values of υ is checked. Node 4 becomes the second forwarder at level 2 as $\upsilon_4 = 0 < \upsilon_5 = 1$. By the similar way, forwarders at level 1 are selected. The constructed LC-MRMC tree and its channel plan are illustrated by the colored arrow lines in Fig. 7.

VI. Simulation Evaluation

In this section, we use NS2 simulations to evaluate the performance of the proposed ART and LC-MRMC. The simulations use the parameters listed in Table I. Based on the MPEG-4 file *StarWarsIV.dat*, simulated video flows are generated with the transmission rates in the range $[100Kbps, 2Mbps]$. There are 4 orthogonal channels used in our simulations. Each simulation lasts 500s. Performance curves in our figures are plotted based on the average values of 20 simulation runs.

A. ART Evaluation

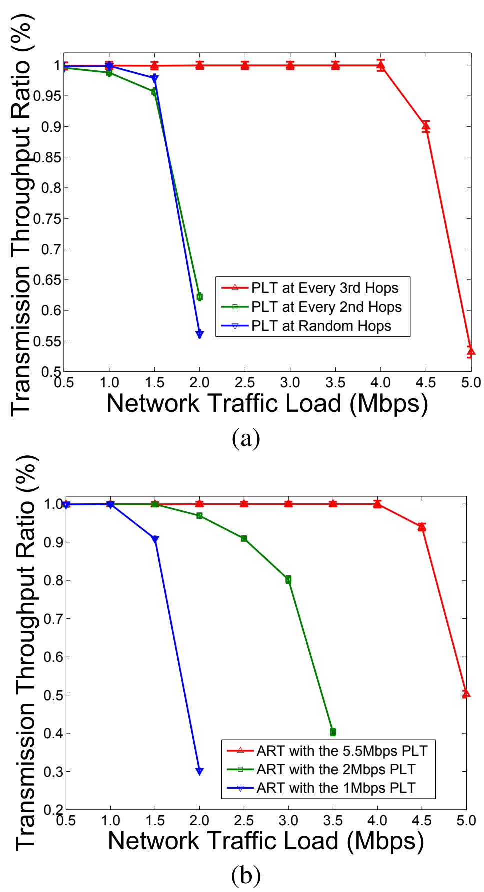


Fig. 8. Comparison of throughput ratios achieved on the 10-hop path: (a) the PLT adopted at different hops; (b) the PLT with different transmission rates.

In order to evaluate whether Theorems 2 & 3 generate an ART transmission that provides the best balance between throughput and coverage among all plans for allocating regular and PLT transmissions, we observe the transmission throughput ratios when a) allocating PLT transmissions at different hops and b) assigning different rates for PLT transmissions. The simulation observation focuses on a 10-hop path with 3 hops each adjacent to a distinct nearby path. In the first simulation, the benchmark rate is 11Mbps and the PLT rate is 5.5Mbps. Based on Theorem 2, ART employs PLT transmissions at every 3rd hops. Fig. 8 (a) plots the curves of transmission throughput ratios, i.e., the ration of the amount of successfully received data to the total transmitted data, for the three PLT usage schemes. The two schemes that employ PLT randomly or at every 2nd hop present similar throughput performance - much lower than the throughput achieved by ART. This is because interference on the same path is greatly avoided by using PLT transmissions at specific hops.

We then evaluate ART when PLT uses different transmission rates. Three pairs of benchmark rates and PLT rates are compared: (11Mbps, 5.5Mbps), (11Mbps, 2Mbps), and (11Mbps, 1Mbps). The 11Mbps benchmark rate is decided based on (2). In detail, when transmitting the same video flows, based on (2), the benchmark rate is decided by $d_i r_i \beta_i$, where d_i and $r_i \beta_i$ are the transmission coverage and the effective throughput of rate r_i. Recall that Fig. 2 (a) gives the effective throughput $r_i \beta_i$ for each rate r_i. Hence, by combining the coverage of each transmission rate, the 11Mbps benchmark rate is achieved. The simulation results in Fig. 8 (b) show that the rate pair (11Mbps, 5.5Mbps) achieves the best throughput performance across the observed path. This result matches our analysis in Theorem 3 in which the rate having the maximum value for $\frac{\lceil \frac{d_i}{d} \rceil \times d + d_i}{min\{3, \lceil \frac{d_i}{d} \rceil\} + \lceil \frac{R}{r_i} \rceil + \psi}$ should be used by PLT. The three pairs of simulated rates have the values of 82.91, 61.23, and 48.54 for the expression $\frac{\lceil \frac{d_i}{d} \rceil \times d + d_i}{min\{3, \lceil \frac{d_i}{d} \rceil\} + \lceil \frac{R}{r_i} \rceil}$. Hence, Theorem 3 agrees that (11Mbps, 5.5Mbps) should be used by the ART.

B. Performance Evaluation in a Random WMN

For evaluating LC-MRMC, we compare the average multicast throughput, the average multicast delay and the multicast coverage of five different wireless multicast schemes in a wireless network with 100 mesh nodes: DF [11], MCM which uses Breadth First Search to find the minimum number of relay nodes [18], MCM-MC which is a MCM tree with channel allocation [18], LC-MR which is our multicast tree without channel allocation, and our LC-MRMC. The locations (i.e., coordinates) of mesh nodes are randomly set by the simulations so as to achieve a distribution density such that there is on average 3.82 nodes within the range of 11Mbps transmissions. Among the 100 mesh nodes, 15 nodes are selected as group receivers. All other simulation settings are the same as the ones used for previous simulations.

Fig. 9 (a) shows the average multicast throughput ratios achieved by different multicast schemes. DF generates the worst throughput performance because its wireless multicast architecture uses resources inefficiently by transmitting the same multimedia traffic more than one time. Also, when using different transmission rates, nodes generate different transmission coverage causing complicated interference topology. For MCM and LC-MR that

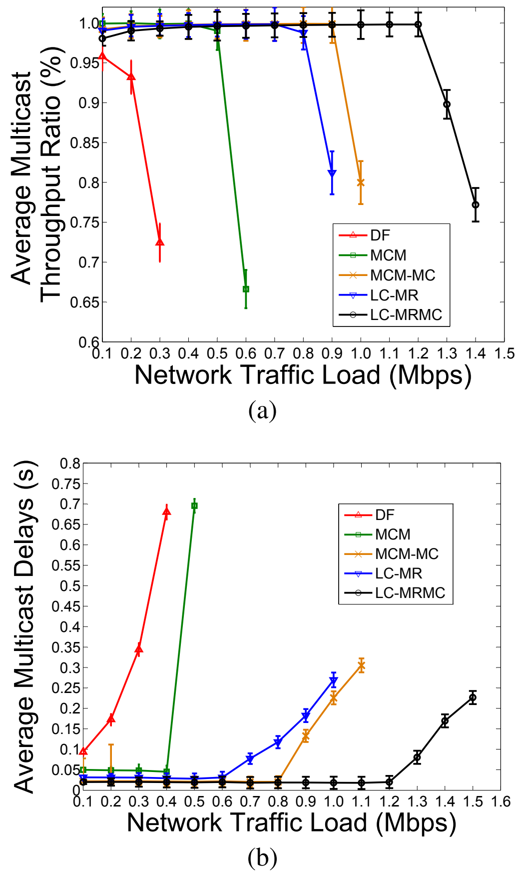
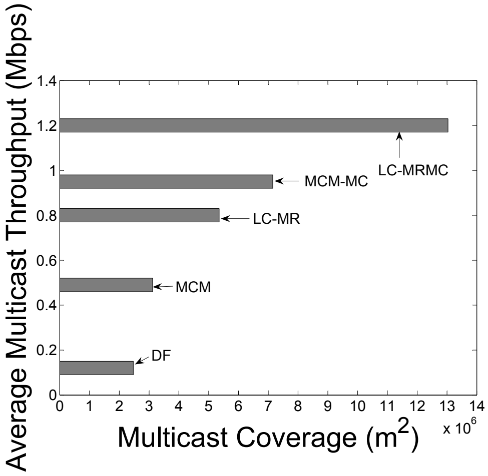


Fig. 9. Comparison of the average throughput ratios (a) and the average delays (b) achieved in the random WMN.

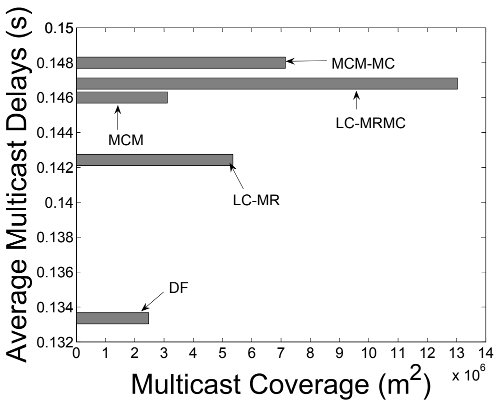
do not employ multiple channels, LC-MR achieves a higher average multicast throughput because it avoids more interference and employs more stable wireless nodes to multicast. MCM-MC and LC-MRMC are the multi-channel versions of MCM and LC-MR respectively. The reason for LC-MRMC to be able to carry a larger multicast traffic load (around 35% improvement) than MCM-MC does is because LC-MRMC uses PLT at appropriate hops to increase the coverage which not only results in the reduced number of multicast forwarders but also increases the distances between some hops.

Fig. 9 (b) shows the average multicast delays. Each delay is the average value of the average delays of 6 receivers. DF generates the longest delay even when the traffic load is low because the intensive interference causes longer queueing delays. LC-MR achieves better delay performance than MCM does. It is because PLT in LC-MR connects a part of nodes by only one hop instead of multiple hops in MCM, apart from the reasons for its higher throughput performance Fig. 9 (a). Similarly, the average multicast delays of LC-MRMC are much shorter than the ones of MCM-MC. Combining both throughput and delay performance, LC-MRMC can admit at least 35% extra video traffic with guaranteed delays and throughput as compared to other multicast schemes.

We also evaluate the performance-guaranteed multicast coverage that can be achieved by these multicast schemes. Fig. 10 (a) shows the effective multicast throughput of the five schemes and their largest coverage within which their effective multicast



(a)



(b)

Fig. 10. Comparison of multicast coverage (a) with acceptable average multicast throughput and (b) with acceptable average multicast delays.

throughput can be guaranteed. Fig. 10 (b) reports the maximum multicast coverage of different schemes when guaranteeing the acceptable multicast delays. Via multiple hops, LC-MRMC can multicast 1.2Mbps video traffic to an area of of $13km^2$ with guaranteed delay performance $146.5ms$. This shows that, in our simulations, LC-MRMC increases multicast coverage by more than than 85.7% under higher traffic loads.

VII. Conclusion

In this paper, we investigated the transmission opportunity afforded by multiple transmission rates and multiple channels for wireless multicast in mesh networks. Our development was based on several interesting findings derived from observations of our simulation of the behaviour of MRMC transmissions in multi-hop WMNs. Parallel low-rate transmission was proposed to improve high-throughput coverage by simple processes with light overheads. In order to address the challenge to PLT posed by limited channel resources, the alternative rate transmission scheme was designed to alternatively run regular and PLT transmissions in order to extend interference-free coverage with high throughput. We then presented the new LC-MRMC algorithm that employs the minimum number of reliable on-tree forwarders to form ART paths to extend high-throughput coverage in a multicast environment. Our NS2 simulation results proved that LC-MRMC delivers multimedia flows with higher performance to a coverage area which is at least 85% larger than existing multi-rate multi-channel schemes.

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