NDN-MMRA: Multi-Stage Multicast Rate Adaptation in Named Data Networking WLAN

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***Abstract*—Named Data Networking (NDN) is considered as a prominent architecture towards future Wireless Local Area Networks (WLAN), and multicast plays an important role in data delivery such as media streaming, multipoint videoconferencing, etc. However, to achieve high-efficiency multicast in NDN WLAN is challenging for two significant reasons. First, without feedback mechanism in IEEE 802.11 standards, to guarantee reliability, the current multicast scheme transmits the multicast data with the basic rate (e.g., 1 Mbps for IEEE 802.11b), which inevitably increases the transmission delay for high-speed consumers. Second, as a NDN multicast group is constituted by consumers who are requesting the same content, multicast groups are easy to form and evolve rapidly, where a data rate adaptation scheme is requisite to accommodate differential multicast groups. In this paper, we propose a multi-stage multicast rate adaptation scheme for NDN WLAN, named *NDN-MMRA*, to minimize the total transmission time with reliability guarantee for multicast group members. In *NDN-MMRA*, by checking the Pending Interest Table (PIT) status information, the number of consumers in each multicast group as well as their receiving capabilities are known ahead; with the available data rates in a specific 802.11 standard, *NDN-MMRA* determines: 1) how many transmission stages are required; and 2) in each stage, which data rate should be adopted. The merit is that with multi-stage transmissions, the data rate can be adapted in descending order to accommodate high-speed consumers with delay minimized, and low-speed consumers with reliability guaranteed. We implement *NDN-MMRA* in NS-3 by adopting the ndnSIM module, and conduct extensive experiments to demonstrate its efficacy under different IEEE 802.11 standards and various underlying WLAN topologies.**

***Index Terms*—Media content delivery, named data networking, WLAN, multicast rate adaptation, dynamic multicast.**

I. Introduction

With the rapid growth of mobile devices and applications, the user demand for high-quality multimedia has increased significantly in Wireless Local Area Networks (WLAN). Cisco's Visual Network Index forecast has shown that by 2022, the mobile video will account for 82% of global mobile data traffic, and Wi-Fi traffic will take up more than 51% of total IP traffic [1]–[4]. The growing mobile video traffic poses great challenges to WLAN, which has to provide efficient wireless data transmission to guarantee the delay requirements for upper layer applications. Named Data Networking (NDN) [5]–[9] has been considered as a promising architecture towards future WLAN scenarios, as the information-centric manner intrinsically supports consumer mobility, enables multi-interface forwarding, and drives cost-effective multicast [10], [11]. For example, NDN architecture can seamlessly support the handover of mobile users without any address modification [7], which can deliver quality mobile services. In addition, NDN is a receiver-driven communications model, and NDN multicast group formation is based on consumers who are requesting the same content instead of the fixed multicast IP address, which means NDN multicast can ably match user underlying content demands. Besides, Wi-Fi's built-in broadcast mechanism can be combined with NDN features to reduce duplicated packet transmissions when the multiple consumers request for the same content. On the other hand, multicast transmission is crucial in WLAN [12]–[14] for massive data delivery such as media streaming, multipoint videoconferencing [15], etc. Therefore, it is of paramount importance to research on multicast in NDN WLAN.

However, to achieve efficient multicast transmissions in NDN WLAN, there are two inherent hurdles need to be well conquered. First, in current IEEE 802.11 standards, as there is no feedback mechanism in multicast protocol, the sender is generally required to deliver the multicast content at *the lowest data rate* (e.g., 1 Mbps in IEEE 802.11b, and 6 Mbps in IEEE 802.11a) to guarantee the transmission reliability. This scheme inevitably prolongs the transmission time for those receivers

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who have larger receiving capabilities (i.e., with better link qualities). Besides, the lower data rate results in a longer transmission time, which would increase the probability of colliding with other transmissions. Second, as NDN multicast groups are constituted by consumers who are requesting the same content instead of who are with the fixed multicast IP address. Unlike the IP multicast protocol, NDN multicast scheme can flexibly manage the multicast groups by maintaining the Pending Interest Table (PIT). In specific, the PIT records all the incoming Interest packets that a router has forwarded but not satisfied yet, and PIT can aggregate the same Interest packet when the multiple consumers request the same content. By this way, NDN multicast groups can be formed by using the PIT aggregation function. To this end, when the number of consumers increases and they request popular content, NDN multicast groups are easier to form and multicast members could be more dynamic, which has been verified by our pilot experiments in this paper. On the other hand, the receiving capabilities of consumers will change as the quality of the wireless channel varies, especially in wireless dynamic scenarios. Therefore, a fixed multicast rate is unable to efficiently accommodate differentiated and time-varying NDN multicast groups, where a lower multicast rate will lengthen the transmission time for high-speed consumers while a higher multicast rate will make the low-speed consumers fail to receive the content (i.e., degrading the reliability). Therefore, an adaptive NDN multicast rate is requisite to keep the pace of the dynamic and differentiated multicast groups in WLAN.

In the literature, there have been some multicast rate control schemes proposed for WLAN [16]–[19], most of which however are applied to end-to-end protocols (TCP/IP). These multicast protocols transmit multicast data based on IP multicast addresses to manage the multicast members and groups. There are many additional protocols (e.g., Internet Group Management Protocol (IGMP), Protocol-Independent Multicast (PIM), Pragmatic General Multicast (PGM), etc.) have been proposed to improve the multicast transmission performance, which however increase the multicast protocol complexity and result in high cost in the multicast maintenance, especially in wireless scenarios. This is also the main reason why wireless multicast is not widely used. In addition, to complement the feedback shortage, they usually collect receivers' status as the feedback information to guide the next round multicast transmission, which might loss efficiency when multicast groups vary dramatically (quite common in NDN WLAN). The limitation is that the end-to-end protocols can hardly provide efficient wireless multicast transmission, and the wireless multicast protocol is very complex with high maintenance cost, which have been indicated in many previous works [12]. On the other hand, there are few works about multicast rate control in NDN WLAN, which further motivates our research in this paper.

In this paper, we propose a novel multi-stage multicast rate adaptation scheme for NDN WLAN, named *NDN-MMRA*, which is able to adaptively adjust the multicast data rate in multiple transmission stages in accordance with the underlying multicast group condition. By implementing the NDN architecture in WLAN via NS-3, we first conduct some pilot experiments to investigate the multicast behaviors in NDN WLAN. Two major observations are achieved: 1) when consumers request the Zipf distributed contents, multicast groups can form easily and multicast transmissions can take up more than half percentages of data transmissions, indicating the capital importance role of multicast; and 2) in each multicast group, the mismatch of transmission rate and receiving capability of consumers results in quite larger average transmission time, calling for an adaptive multicast rate to well match them in real time. Then, taking the multicast transmission time, consumer receiving reliability, and consumer power consumption into account, we elaborate our *NDN-MMRA* design. In *NDN-MMRA*, to manage the multicast transmission, we build a mapping scheme from the name prefix to MAC address of consumers by checking the Pending Interest Table (PIT) status information. Relying on the mapping status and arriving PIT entries, *NDN-MMRA* is able to distinguish the unicast and multicast transmissions, and for multicast transmissions, the number of consumers together with their receiving capabilities in the multicast group are also known ahead. For a multicast group, given the available multicast rates under a specific IEEE 802.11 standard, the algorithm of *NDN-MMRA* then determines: 1) how many transmission stages are required; and 2) in each stage, which data rate should be adopted, in order to minimize the average transmission time and meanwhile guarantee the receiving reliability. With multi-stage transmissions, the high data rates can be adopted at the initial stages to reduce the transmission time for high-speed consumers and the low data rates are adopted at the last stages to guarantee the reception for those low-rate consumers. In addition, for high-speed consumers, the fast data delivery is able to reduce their power consumption during data reception, and after finishing the reception, they can switch to the sleep state during other stage transmissions by checking the PIT status.

At last, we implement *NDN-MMRA* in NS-3 by adopting the ndnSIM module and conduct extensive experiments under various IEEE 802.11 standards and WLAN topologies. Experiment results demonstrate its efficacy in terms of multicast transmission time, packet loss rate, and energy efficiency.

We highlight the contributions in this paper as follows:

1) We conduct pilot NDN multicast experiments and achieve several valuable insights, such as prevalent multicast transmissions and rate-mismatched content delivery, both of which well motivate the design of *NDN-MMRA*.
2) In order to minimize the multicast average transmission time with reliability guarantee, we propose *NDN-MMRA* to adjust the multicast rate adaptively for each multicast group, which to our best knowledge, is rarely seen in the literature. To adapt the multicast rate, we devise the multi-stage multicast rate adaptation (*MMRA*) algorithm to determine the number of transmission stages as well as the rate selection in each transmission stage, which can be applied in different IEEE 802.11 standards.
3) We implement *NDN-MMRA* in NS-3 and evaluate its efficacy under various IEEE 802.11 standards and a variety of WLAN topologies. Experiment results show that in comparison with benchmark schemes, *NDN-MMRA* can

reduce multicast transmission time by up to 38% and achieve a low packet loss rate with energy efficiency.

The remainder of this paper is organized as follows. In Section II, we introduce NDN multicast preliminaries and state motivations via pilot experiments. We present the system model and summarize our design goals in Section III. In Section IV, we elaborate the design of *NDN-MMRA*. Extensive experiments are carried out in Section V. The literature is reviewed in Section VI. We conclude the paper and direct our future work in Section VII.

II. Background and Motivation

In this section, we first introduce NDN and NDN multicast preliminaries in WLAN, and then state our motivations by carrying out some pilot experiments.

A. NDN and NDN Multicast Preliminaries

NDN Basics. NDN is a receiver-driven communication architecture, which contains two basic types of packets, i.e., Interest and Data packets [5]. In NDN, consumers send out Interest packets to request the content which returns by Data packets, and one Interest packet corresponds to one Data packet, with both carrying a unique name that identifies the requested content. To enable NDN forwarding process, each NDN node maintains the following three main components: (i) Content Store (CS), (ii) Pending Interest Table (PIT), and (iii) Forward Information Base (FIB). The CS is a temporary store to cache the Data packets, which can reduce the transmission delay when the future Interests request the same content. The PIT maintains the status information for each forwarded Interest packet (recorded as an entry), which can guide Data packet forwarding. Each PIT entry contains following information: the name associated with the entry, a list of incoming faces (from which the Interest packets with the same name have been received) together with other information such as the timestamp, and a list of outgoing faces (to which the Interest packets with the same name have been forwarded). The FIB is used to forward Interest packets toward potential nodes that can match data, which maintains name prefixes instead of IP address prefixes. For each name prefix, the FIB entry can show multiple interfaces to mach them, which can be used simultaneously by a forwarding strategy to make the Interest forwarding decision.

Particularly, as shown in Fig. 1, during the Upstream process, when a NDN node receives an Interest packet, it will check the name prefix with the CS, PIT, and FIB successively. If the content has been cached at the CS, it will be returned immediately; otherwise, the node will compare the name prefix with the PIT entry. If there is an entry with the same name, the Interest is aggregated to the entry; otherwise, a new PIT entry is created. Based on the FIB entry, the Interest packet will be then forwarded to the next hop. In contrast, during the Downstream process, when a NDN node receives a Data packet, it will check with the PIT entry to match the data, and if matched, the data will be forwarded to the matching interface (the CS could cache it if necessary), otherwise, the data will be dropped.

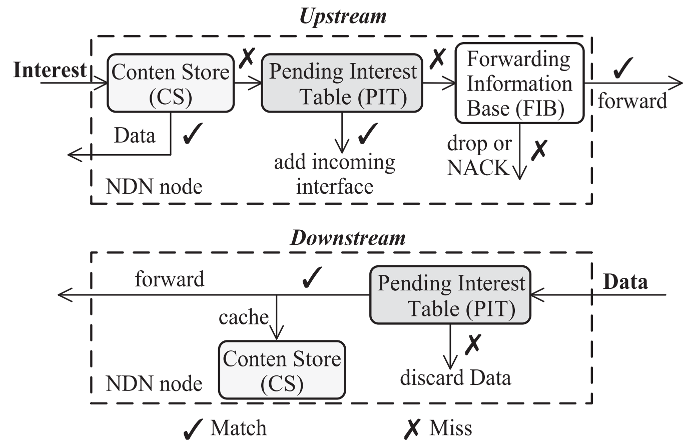


Fig. 1. NDN node forwarding process.

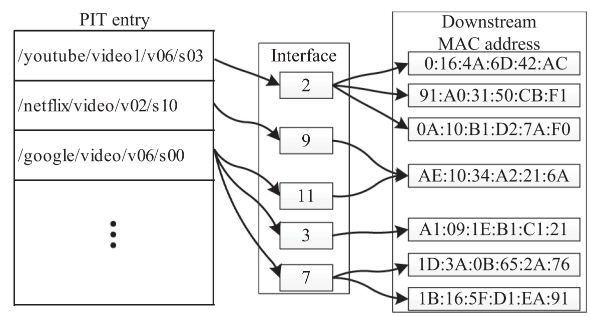
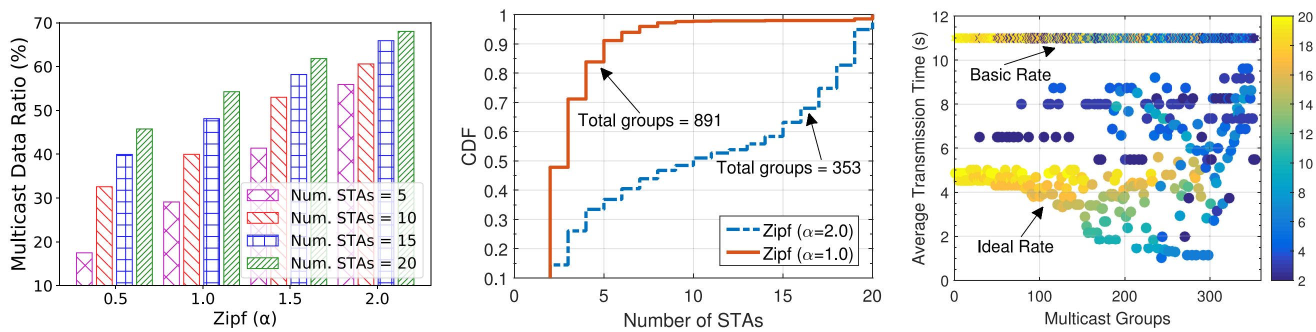


Fig. 2. PIT entry with the MAC address of STA in wireless NDN.

NDN Mulitcast in WLAN. In a wired network, the NDN architecture can naturally support multicast transmission as there are normally multiple physical interfaces and a multicast transmission happens when the data is forwarded via more than one interfaces simultaneously. However, in WLAN, each STA normally has one physical interface, and data is delivered via broadcasting. It is difficult to comment on whether the transmission is multicast or unicast. Therefore, in our previous work [20], we have proposed a scheme to distinguish between unicast and multicast data, by including the MAC address of STA to the corresponding entry in the PIT when receiving an incoming Interest packet.

In Fig. 2, the PIT table records all incoming Interest packets status information, which contains both the interfaces and corresponding MAC address in each entry. Therefore, we can check the PIT status information to map the name prefix to MAC address of STA, which is able to distinguish the multicast data. Specifically, the returned data can be classified into two categories: 1) unicast: If the PIT entry has only one interface and one MAC address corresponding to the content, the returned data is treated as an unicast stream and will be forwarded under an unicast transmission process; 2) multicast: If the PIT entry has multiple interfaces[1] or multiple MAC addresses corresponding

[1]Note that, if the AP has multiple network cards (i.e., multiple physical interfaces), the STA can access the AP via different physical interfaces. Therefore, a physical interface can correspond to one or more client MAC addresses. In this paper, we consider that each AP has only one physical interface.



(a) Multicast data formation ratio in wireless NDN (b) CDFs of number of multicast group member (c) Average multicast transmission time

Fig. 3. Motivations of multicast data rate adaptation.

to the content, the returned data is identified as a multicast stream and will be forwarded under a multicast transmission process.

B. Motivation

After identifying multicast data packets, we are interested in multicast performance in NDN WLAN. In this subsection, based on our implemented NDN WLAN platform in NS-3 (detailed implementation and experiment setup can be found in performance evaluation section), we conduct some pilot experiments to characterize the multicast performance.

Multicast Data Prevalence in NDN WLAN. A NDN multicast group forms when multiple consumers request the same content. Generally, when there are multiple consumers to request some popular contents, multicast transmission may forms frequently. Specifically, we plot the multicast data ratio in Fig. 3 (a) where multiple consumers send Interest packets (the request rate is 1 Interest/s and the total number of Interest packets is 200) to request for twenty contents, and the request follows a Zipf distribution which is widely used to mimic the user request distribution in the literature [10]. For the Zipf distribution, there is a coefficient α, which means the skewness of popularity distribution, and a larger α indicates more concentrated content requests. We can easily observe that multicast transmission is rather common in NDN WLAN as the multicast data takes up a significant ratio. For instance, given a normal case when there are 10 consumers and Zipf ($\alpha = 1.0$), the multicast data ratio can reach up to 40%. In addition, with increasing the number of STAs and the value of α, the multicast data ratio can further increase dramatically. Therefore, we can conclude that multicast transmission prevails in NDN WLAN data transmission, and we should carefully guarantee multicast performance.

Dynamics of Multicast Group Members. After disclosing the multicast prevalence phenomenon, we then investigate the number of multicast group members, which is important to design an efficient multicast transmission scheme. To this end, during the experiments, for each identified multicast transmission, we extract the number of multicast group members and plot their cumulative distribution functions (CDFs) in Fig. 3 (b) when α is set to be 1.0 and 2.0, respectively. We have two major observations. First, multicast groups are easy to form and the number of multicast group members vary dynamically. For instance, when Zipf ($\alpha = 2.0$), there are total 353 multicast groups, and the proportion of member number evenly distributes within the range from 2 to 20. With a dynamic number of multicast group members, the multicast transmission scheme has to be robust enough as the members may have quite distinct receiving capabilities, calling for a versatile data rate to minimize the delivery delay with reliability guarantee. Second, when the requested contents are more concentrated, e.g., increasing α from 1.0 to 2.0, the number of multicast groups may decrease but the number of members in each multicast group will increase significantly. Particularly, when Zipf ($\alpha = 1.0$), the number of multicast groups increases to 891. In addition, the median (with the CDF value of 50%) number of members decrease from 10 (with $\alpha = 2.0$) to 3 (with $\alpha = 1.0$). It is reasonable as the requested contents are more concentrated, more users are likely to request the same popular contents, enlarging the size of multicast groups for popular contents while decreasing the number of small-size multicast groups for unpopular contents.

Multicast Performance Improvement Space. To guarantee the reliability of multicast data transmission in WLAN, the current IEEE 802.11 standards require the multicast scheme to adopt the basic data rate to transmit the multicast data. It will inevitably increase the transmission time for STAs with higher receiving capabilities. This limitation may significantly deteriorate the multicast performance, as we have disclosed that the multicast transmission prevails and the number of multicast group members can be large. To this end, we then investigate the multicast performance improvement space. Specifically, for each multicast group in the above experiment (with $\alpha = 2.0$), we adopt a basic rate (e.g., 1 Mbps in IEEE 802.11b) and an ideal rate[2] to calculate the STA average transmission time, the results of which are shown in Fig. 3 (c), where the color represents the number of members in the multicast group. Two major observations can be achieved. First, the average transmission time of basic rate scheme is significantly higher than the ideal rate scheme. For instance, for the basic rate scheme, the average

[2]Considering the receiving capability of an STA, the ideal rate is an upper-bound rate, i.e., the maximum data rate at which the STA can successfully receive the multicast data.

transmission time keeps around 11 s (the size of content is 11 M), while most transmission times in ideal rate scheme fluctuate between 2 to 8 s. Second, when the number of members in the multicast group is large, the ideal rate scheme can achieve a higher benefit as we can see that bright dots generally have smaller transmission times. The reason is that with more multicast group members, more users can be served by high data rates.

Summary. Our pilot experiments reveal that: 1): multicast transmission is prevalent in NDN WLAN; 2) the multicast group formation is dynamic; and 3) considerable multicast performance improvement space exists in accordance with the underlying multicast group formation condition. These observations motivate our design for multicast data rate adaptation, which is elaborated in what follows.

III. System Model and Design Goals

A. System Model

There are two major entities in the considered system as follows:

1) An AP: We consider a typical WLAN scenario, where an AP provides data access services for STAs that are in association with the AP. In particular, the AP connects to the data producer via a router.
2) STAs: There are multiple STAs in association with the AP, and they will send out Interest packets to request for Data packets.
3) NDN Communication Architecture: In the WLAN, the AP and all associated STAs exchange data under a NDN communication architecture, the basic procedure of which has been introduced in the preceding section.

It should be noted that we mainly consider multicast performance in this paper. Therefore, the AP has to detect the multicast group formation under the NDN architecture. If there is a multicast group, the AP will execute the algorithm of *NDN-MMRA* to adapt the multicast data rates at multiple stages to accommodate STAs in the multicast group, which will be detailed in the following section.

B. Optimization Directions

There are three optimization directions to motivate our design of *NDN-MMRA*.

1) Average Transmission Time. During multi-stage transmissions, to minimize the average transmission time of multicast group members is essential, where the transmission time of a member refers to the interval of time elapsed between the member sending the Interest packet and successfully receiving the Data packet.
2) Reliability. Each member in the multcast group should be guaranteed to receive the multicast data successfully.
3) Power Consumption. Power consumption of multicast transmission is critical for power-constrained STAs. During the transmission, it is necessary to reduce the time of channel listening and data receiving for power saving.

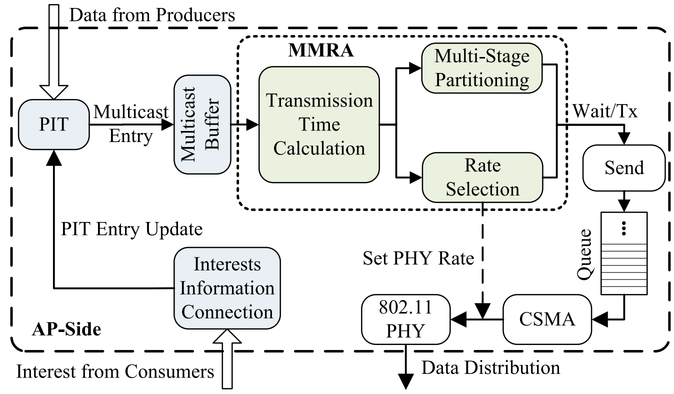


Fig. 4. Overview of *NDN-MMRA* scheme for WLAN.

IV. Design of *NDN-MMRA*

In this section, we present the designed *NDN-MMRA* scheme, which is shown in Fig. 4. As a prerequisite for *NDN-MMRA*, we first introduce the PIT update process that deals with the dynamics of NDN multicast. When an AP receives an Interest packet, it updates the PIT information, and waits for the pending data feedback. Upon the pending data arrival, the AP will find the corresponding multicast entry in the multicast buffer based on the PIT status information. The devised *MMRA* algorithm consists of three steps: transmission time calculation, multi-stage partitioning, and rate selection. Based on the entry information, the multicast transmission time of the downstream consumers will be calculated. To minimize the NDN multicast transmission time, the *MMRA* algorithm adaptively adjusts the number of transmission stages and the corresponding transmission data rate for each multicast entry. We also integrate the caching mechanism in *NDN-MMRA* to further enhance its performance. At last, we give an example for showing how *NDN-MMRA* works in practice. Note that, the *NDN-MMRA* scheme is implemented on the AP side, without requiring any modification on the STA side.

A. PIT Update for Dynamic of NDN Multicast

IP-based multicast schemes use destination IP and MAC addresses for data packets dissemination. Additional management protocols, e.g., IGMP [12], are designed to enable the dynamic joining and leaving of a multicast group. Meanwhile, IP multicast requires additional routing protocols and dedicated IP multicast address to build a multicast distribution tree that associates all the multicast group members. In addition, IP multicast communication has to rely on the IP multicast addresses, which reduces the flexibility and compatibility. Compared with IP multicast, NDN multicast is established based on multiple consumers who are requesting the same content, without any additional management protocols. As the number of consumers increases and the requested content change, which significantly increases the dynamics in NDN multicast member and group. As a result, the PIT table update is important to NDN multicast, as it can be exploited to maintain multicast group information, without requiring additional supporting protocols.

When AP receives an Interest packet, it will try to find the name prefix in the PIT. If there is no matching entry in PIT, the AP will add the incoming interface of the Interest packet and the corresponding STA MAC address as a new entry in the PIT and forward the Interest packet to the next hop based on its FIB information. If a matching entry exists in the PIT, the Interest packet will not be forwarded to the next hop. Instead, only the lifetime of the corresponding entry is updated. To update the information of a PIT entry, the following two cases are considered: the same consumer requests the same content and multiple different consumers request the same content. For the former case, the Interest packet will not be forwarded and the corresponding entry lifetime will be overwritten. Hence, the members of the multicast group remain unchanged. In addition, the same Interest packets will be aggregated in PIT when the Interest packets come from the consumer during the entry lifetime (the default value is 2 seconds). For the latter case, the Interest packet also will not be forwarded to the next hop. The AP will add the incoming interface, and update the corresponding entry lifetime in PIT, which means that a new member is added in the multicast group.

*B. Multi-Stage Multicast Rate Adaptation (*MMRA*) Algorithm*

NDN multicast formation is based on the PIT status information, which records the dynamic of NDN multicast (e.g., multicast groups and members). As mentioned in subsection II-B, current 802.11 multicast rate control schemes are not suitable to solve the high dynamic multicast transmission problem, especially for wireless NDN scenarios. To address this issue, we devise the *MMRA* algorithm to dynamically select a high data rate for each transmission stage, which takes into account the number of STAs and the receivable data rate from the corresponding PIT entry. The key idea of *MMRA* algorithm is selecting the data rate that minimizes the total transmission time for each transmission stage. This is achieved by repeatedly transmitting the same data using different data rates in different stages.

Denote by T_{total} the NDN multicast transmission time, and our objective is to minimize T_{total} via multi-stage transmissions at different rates. Formally, the optimization problem can be formulated as follows.

$$\min_{r} t(r) * N(r), \tag{1}$$

where $t(r) = t_{rx}(r) + t_{wait}(r)$, and r is a data rate of STA, $t_{rx}(r)$ indicates the time that STA receives the multicast data at rate r, and t_{wait} shows the time that STA is waiting for receiving the multicast data in the air. In additio, N is the total number of STAs (multicast members), and $N(r)$ represents the total number of STAs that are receiving data at rate r. $N(r) = \sum_{i=1}^{R^{\upsilon}} n(i, r)$, where $n(i, r)$ is the number of STAs that are receiving data at rate r and an AP sends the data at rate $i \leqslant r$. υ is one of IEEE 802.11 protocols, such as 802.11b and 802.11a, and R^{υ} indicates the total number of data rates supported by STA in protocol υ (e.g., R^{υ} is 4, and $i \in [1, 2, 5.5, 11]$ Mbps, and R^{υ} is 8, and $i \in [6, 9, 12, 18, 24, 36, 48, 54]$ Mbps in IEEE 802.11b, and 802.11a, respectively), and i is a data rate in the 802.11 protocol. When a STA receives data at rate r, and an AP sends the data at rate $i \leqslant r$, it means that the STA can receive the data at rate i. Otherwise, the STA cannot receive the data at rate r when the AP sends the data at rate $i > r$.

Algorithm 1: Multi-Stage Multicast Rate Adaptation.

Input: Multicast PIT entry set $\mathcal{M} = \{M_1, \cdots, M_n\}$
Output: Number of transmission stages ($\mathcal{MR}$) and rate list ($\mathcal{RL}$), $\{(\mathcal{MR}_1, \mathcal{RL}_1), \cdots, (\mathcal{MR}_n, \mathcal{RL}_n)\}$
Initialize the multicast group in $\mathcal{M}$
Initialize $N, n(r) \leftarrow M_i$
Initialize memory $\mathcal{D}$
for each group $\mathcal{M}$ **do**
  Calculate R^{υ};
  Calculate $n(r)$ in each R^{υ}_r;
end for
function Recursion R^{υ}_r, N
  if $R^{\upsilon}_r == 1$ **then**
    Add rate r in $\mathcal{RL}$ and $\mathcal{MR}_r = 1$ in $\mathcal{MR}$
    return $\mathcal{MR}$, $\mathcal{RL}$
  else
    for $i = 1$ **to** R^{υ}_r
      Calculate $T_{total}\{r(i)\} \leftarrow \sum_{i=1}^{R^{\upsilon}_r} t_i * n(i)$;
      Calculate $\mathcal{MR}_{r(i)}$;
      Record $T_{total}\{r(i)\}$, $\mathcal{MR}_{r(i)}$ and $r(i)$ in $\mathcal{D}$;
    end for
    return *Recursion*$(R^{\upsilon}_{r+1}, N - n(r))$;
  end for
end function
Select $T(r) = min(T_{total})$ in $\mathcal{D}$
if $T(r)$ is **Ture** && $\mathcal{MR}_r$ is the minimum **then**
  Add $\mathcal{MR}_r$ in $\mathcal{MR}$, $\mathcal{RL}_r$ in $\mathcal{RL}$.
else
  return $\mathcal{MR}$, $\mathcal{RL}$
end for
return $\{(\mathcal{MR}_1, \mathcal{RL}_1), \cdots, (\mathcal{MR}_n, \mathcal{RL}_n)\}$

Different WLAN protocols support different levels of data rates. For instance, 802.11b supports four data rates (i.e., 1, 2, 5.5, and 11 Mbps), while 802.11a supports eight data rates (i.e., 6, 9, 12, 18, 24, 36, 48, and 54 Mbps). When multiple STAs have different data rates, for each NDN multicast group, the corresponding multicast data rate selection can be formulated as a combinatorial optimization problem. To solve this problem, we design a greedy algorithm to minimize the multicast transmission time for each group by selecting a rate list for different transmission stages. If all STAs have the same data rate, the AP only needs to transmit the multicast data once at that data rate. Otherwise, the AP will use the greedy algorithm to minimize the multicast transmission time by reducing the number of transmission stages. Algorithm 1 shows the detailed process of multicast data rate selection.

Take the IEEE 802.11b as an example, it supports four levels of data ratesand and a NDN multicast can be divided into at most four transmission stages. *MMRA* algorithm selects the minimum data rate for the last multicast transmission stage, which

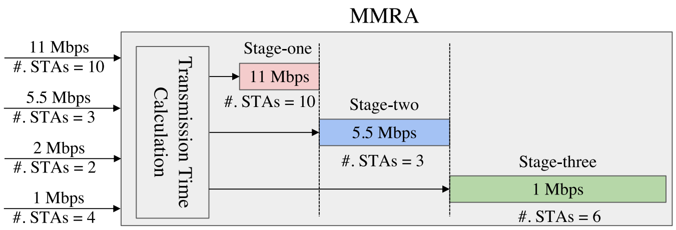


Fig. 5. Rate adaptation process in MMRA algorithm.

will mitigate the multicast packet error rate and retransmission times if data loss at a high data rate transmission stage. Note that multicast data transmission at larger data rate should have higher priority in *NDN-MMRA*. According to the number of transmission stages, the NDN multicast can be categorized into the following cases.

1) **One-Stage**. All STAs have the same data rate in a NDN multicast group. Data will be delivered with the same rate only once.
2) **Two-Stage**. There are two data rates in the multicast group, and the multicast data transmission is divided into two stages. The maximum number of rate combinations is $C_4^2 = 6$.
3) **Three-Stage**. There are three data rates in the multicast group, and the multicast data transmission can be divided into three stages. The maximum number of rate combinations is $C_4^3 = 4$.
4) **Four-Stage**. There are four data rates in the multicast group, and the multicast data transmission can be partitioned into four stages. There is only one possible rate combination.

We detail the three-stage transmission process as an example. Suppose the data rate of three stages are R_1, R_2, and R_3 respectively. Accordingly, the transmission time in three stages is T_1, T_2, and T_3, respectively, we have

$$T_{total} = T_1 * N(R_1) + (T_1 + T_2) * N(R_2) + (T_1 + T_2 + T_3) * N(R_3). \quad (2)$$

where $N = N(R_1) + N(R_2) + N(R_3)$.

Fig. 5 shows the rate adaptation process in our proposed MMRA algorithm. When the multiple STAs request the same content, the AP will find the corresponding multicast entry in the multicast buffer based on the PIT status information. After that, the devised MMRA algorithm works with three steps: transmission time calculation, multi-stage partitioning, and rate selection. For example, we suppose that the number of STAs who are with the data rate of 11 Mbps, 5.5 Mbps, 2 Mbps, and 1 Mbps, is 10, 3, 2, and 4, respectively. According to the Eq. (1) and (2), we can calculate the transmission time of multiple transmission stages, and select a data rate for each stage. As shown in Fig. 5, the multicast transmission process is divided into three-stage transmissions. In the Stage-one, AP sends the multicast data at 11 Mbps, and the 10 STAs can receive the multicast data. In the Stage-two, AP sends the multicast data at 5.5 Mbps, and the 3 STAs can receive the multicast data. In the Stage-three, AP sends the multicast data at 1 Mbps, an the 6 STAs can receive the same multicast data, including the 2 STAs with 2 Mbps and 4 STAs with 1 Mbps.

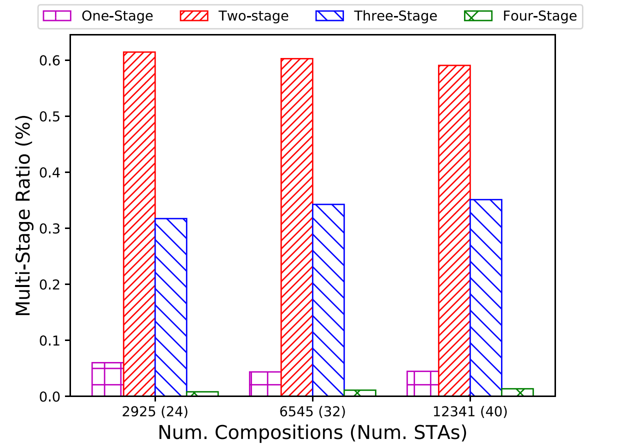


Fig. 6. Multi-stage ratio in the different numbers of fixed STAs.

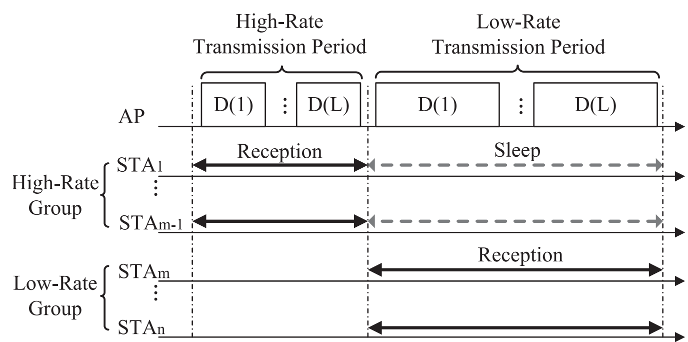


Fig. 7. Multi-rate transmission in a NDN multicast group.

Considering the number of STAs and the distribution of transmission stages, the NDN multicast has several potential compositions, which leads to dynamic multicast rate selection and varying multicast completion time. With the increase of number of STAs, the number of multi-stage combinations will significantly increase when multiple STAs support different data rates. We list all the possible combinations and the multi-stage ratio of the multicast when the number of multicast member is given by 802.11b protocol. For instance, the number of combinations increases from 2925 to 12341 when the number of STAs increases from 24 to 40, as shown in Fig. 6. In addition, we find that the two-stage ratio of the multicast is significantly higher than the others, and the ratio stays at approximately 61% even when the number of STAs increases from 24 to 40. The reason is that the IEEE 802.11b protocol supports only four data rates, and the minimum rate is selected in each multicast group. Moreover, the number of rate combination is maximum in two-stage transmission process.

C. Multi-Rate Transmission in WLAN

To improve the NDN multicast transmission efficiency and reliability, we propose a multi-rate transmission scheme for NDN multicasting, as shown in Fig. 7. There are two transmission periods: high-rate transmission period (TX_HR) and low-rate transmission period (TX_LR). During the high-rate transmission period, there may be multiple transmission stages, determined the supportable different data rates in the IEEE 802.11b protocol. In low-rate transmission period, AP uses the lowest rate to transmit the multicast data. For different transmission stages, the AP first sends the multicast data at the high rate which is decided by the multi-stage multicast rate adaptation algorithm (Algorithm 1) in the high-rate transmission period. If the STAs successfully receive the multicast data, it goes to sleep state to reduce energy consumption. Then, the AP sends the same multicast data at the low data rate which is configured as the minimum data rate supported by all the STAs running IEEE 802.11 protocols. Note that TX_HR is set to lower rate in initialization, TX_LR is set to a high data rate as a minimum rate in a multicast group. Detailed transmission process is given in Algorithm 2.

D. Integrating Caching Mechanism

Caching is one of the significant characteristics in NDN architecture, which can further improve network performance [21]–[23]. In-network caching stores data at intermediate nodes and then use it for future transmission. Compared with TCP/IP protocol, NDN naturally supports multicast and retransmission from intermediate caching nodes. In wireless NDN, in-network caching can benefit NDN multicast in both multicast formation and multicast data retransmission.

During multicast formation, NDN multicast is formed based on the same content requested by multiple consumers. In wireless scenario, caching can reduce the data delay and increase the probability of multicast formation when an AP waits for the pending data. When a multicast data loss or error occurs during the transmission process, the consumers can retrieve the data from the nearest cache node, which is much faster than that from the producer. In addition, the caching mechanism can further increase the probability of multicast formation because the cache can provide a faster response to subsequent requests, especially when the number of consumers is large. In multicast data retransmission, reliable data delivery is challenging in wireless NDN because there is no ACK or feedback mechanism. Relying on caching, retransmission can be readily instantiated via unicast or rebuilt multicast. It significantly reduces network data dissemination latency and retransmission frequency. In this way, the caching mechanism can further improve the reliability of NDN multicast data transmission even when there is no ACK or feedback mechanism.

E. An Example to NDN-MMRA

As shown in Fig. 8, we consider a case in which there are two multicast groups. Assume that the STAs have different data rates in a multicast group, and the MinRate scheme is used to transmit the multicast data for Group1, and the AP uses the *NDN-MMRA* scheme to transmit the multicast data for Group2. The STAs will use the lowest data rate to receive the multicast data when the AP sends the Delivery Traffic Indication Message (DTIM) beacon to notify the members of Group1. The default multicast data rate is the basic rate (e.g., 1 Mbps for IEEE 802.11b, 6 Mbps for IEEE 802.11a), which significantly increases the multicast

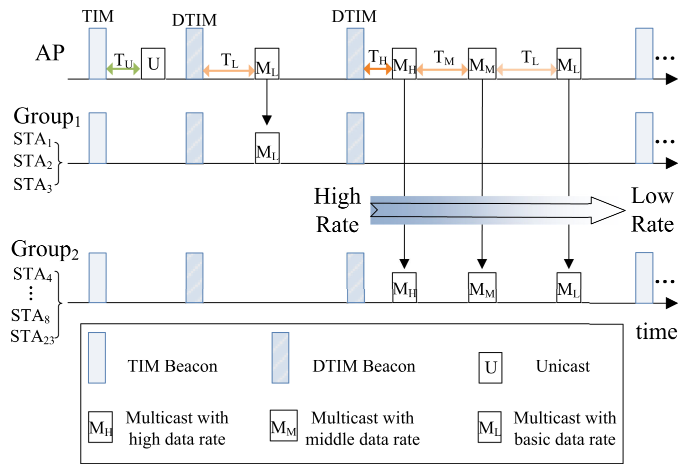


Fig. 8. An example to transmit the multicast data under *MinRate* (for Group1) and *NDN-MMRA* (for Group2) in wireless NDN.

Algorithm 2: Multicast Transmission Process.

Input: $\mathcal{MR}$, $\mathcal{RL}$
Output: TX_HR, TX_LR
Initialize TX_HR is the lowest rate and TX_LR is the highest data rate in $\mathcal{RL}$
for each stage in $\mathcal{MR}$ **do**
  $\Gamma \leftarrow Sort(\mathcal{RL})$
  if $size(\Gamma) == 1$ **then**
    Select Γ to update the TX_LR;
  else if $size(\Gamma) > 1$ **then**
    Select $r = min(\Gamma)$ to update the TX_LR;
    Remove r in Γ;
    TX_HR $\leftarrow Sort(\Gamma)$;
  end for
end for
return TX_HR, TX_LR.

transmission time and bandwidth wastage. In the *NDN-MMRA* scheme, if AP sends the multicast data to Group2 by DTIM beacon notification, *NDN-MMRA* first uses Algorithm 1 to calculate the number of stages and the corresponding rate lists. Then, *NDN-MMRA* uses Algorithm 2 to transmit the same multicast data at different rates based on the stage and rate list information. For example, there are twenty STAs (STA4 to STA23) in Group2 and all STAs use IEEE 802.11b protocol. In this case, we assume that the data rate of 10 STAs is 11 Mbps, the data rate of 5 STAs is 5 Mbps, and the data rate of the remaining STAs is 1 Mbps. In order to reduce mulitcast transmission time, *NDN-MMRA* uses the number of mulitcast members and it's data rate to calculate transmission stage and corresponding data rate. Fig. 8 shows that multicast data is transmitted in three stages, and the same multicast data is transmitted at different rates in different stages. Moreover, *NDN-MMRA* first sends the multicast data at a higher data rate, and then sends the same multicast data at a lower data rate. Hence, the multicast data rate of the three stages are 11 Mbps, 5 Mbps, and 1 Mbps, respectively. Therefore, the *NDN-MMRA* scheme can significantly reduce the NDN

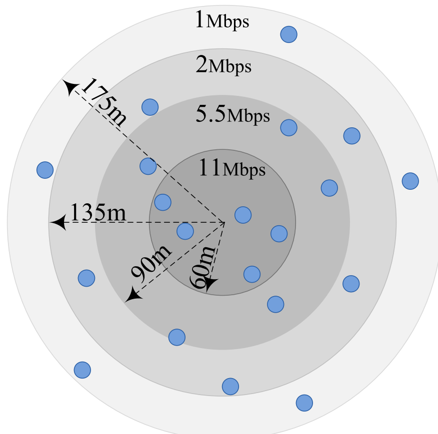


Fig. 9. Link capacity vs. communication distance under IEEE 802.11b, where blue nodes are STAs, and the central node is AP.

multicast transmission time especially when the number of multicast members is large and the corresponding data rate changes greatly.

V. Performance Evaluation

In this section, we evaluate the performance of proposed *NDN-MMRA* by adopting the ndnSIM [24] module in NS-3. Particularly, we first present the evaluation methodology including experiment setup, and benchmark scheme and performance metric design. Then, performance comparisons under different experiment settings are carried out to demonstrate the efficacy of *NDN-MMRA*.

A. Evaluation Methodology

1) Experiment Setup: Fig. 9 shows the available link capacities under IEEE 802.11b which depend on the distance between the STA and AP (the variation can be different under other IEEE 802.11 standards). We assume that all STAs are randomly situated around the AP in accordance with a 2-dimensional mobility model [24]. We consider a typical WLAN scenario, where STAs download their interested traffic via the AP under corresponding data rates, and the AP connects to the data producer via a router with the 10 ms AP-router and 100 ms router-producer P2P links. Three different data rate distribution scenarios are considered, i.e., *High data rate scenario (HS)*, *Moderate data rate scenario (MS)*, and *Low data rate scenario (LS)*. In HS, the data rates of more than 80% STAs are set to be 11 Mbps, and the data rates of other STAs range among 1 Mpbs, 2 Mbps, and 5.5 Mbps. In MS, the data rates of 80% STAs are set to be 2 Mbps and 5.5 Mbps, and the data rates of other STAs are randomly set as 11 Mbps or 1 Mbps. In LS, the data rates of 80% STAs are set to be 1 Mbps, and the data rates of other STAs are randomly set to be 11 Mbps, 5.5 Mbps, or 2 Mbps. In all scenarios, the number of STAs ranges from 8 to 60, and the number of total contents ranges from 50 to 10000. Each STA has a request rate, ranging from 1 to 10 Interest packets per second. In addition, the request of STA Interest packet follows the Zipf distribution with a parameter α, which indicates the skewness of request contents and is empirically set to be 2.0 [25]. Detailed experiment parameters are listed in Table I.

TABLE I
Experiments Parameters

Parameters	Value
Data payload	$1024\ bytes$
CS size	10000
Packet retransmission limit	4
P2P link delay (router to producer / router to AP)	$100/10\ ms$
Number of contents	$50 - 10000$
Cache size (packets)	10
IEEE 802.11 standards	802.11a/b
Data rate scenario	LS/MS/HS
Number of STAs	$8 - 60$
Request rate (Interest packets/s)	$1 - 10$
Wi-Fi Channel	$LogDistance$
Simulation time	$1000\ s$

2) Benchmark Schemes: To verify the effectiveness of proposed *NDN-MMRA*, we consider the following benchmark schemes.

1) *BasicRate*: The current IEEE 802.11 standards adopt this scheme, in which the AP selects the lowest (basic) data rate from the available data rate set under the standard to deliver contents.
2) *MinRate*: The *BasicRate* scheme is updated to implement this scheme, in which for an established multicast group, the minimum data rate of group members is selected to deliver the multicast content.

3) Performance Metrics: We design the following metrics for performance comparison.

1) Transmission Time: Given a multicast group, the transmission time refers to the interval of time elapsed when all group members receive the multicast data.
2) Delay: For a sent Interest packet, the delay refers to the interval of time elapsed when the data packet is received (including the retransmission time).
3) Packet Loss Rate: It refers to the ratio of dropped packets to the total number of transmitted packets.
4) Energy Consumption: For a STA, the energy consumption refers to the sum energy consumption of all states including idle listening (IL), transmitting (TX), receiving (RX), and sleep states [26].

B. Impact of Experiment Parameters

We evaluate the impact of experiment parameters including the number of contents and STA request rates, where the number of STAs is set to be 20. Fig. 10 shows the average transmission time (calculated by the sum transmission time of all multicast groups to the total number of multicast groups) under different data rate distribution scenarios when varying the number of contents. We can see that the number of contents has light impact on the performance as the results of three bars are very close to each other. It is reasonable as the request contents follow a Zipf distribution, which means that consumers would frequently request for a small number of "popular" contents to form multicast groups. Compared with the impact of number of contents, the data rate distribution scenario has more significant impact on the

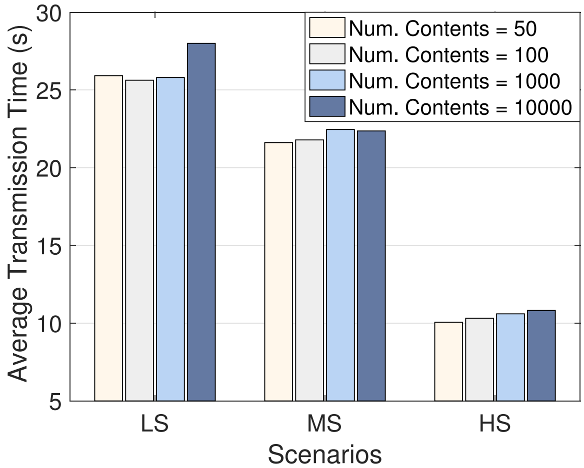


Fig. 10. Impact of content number.

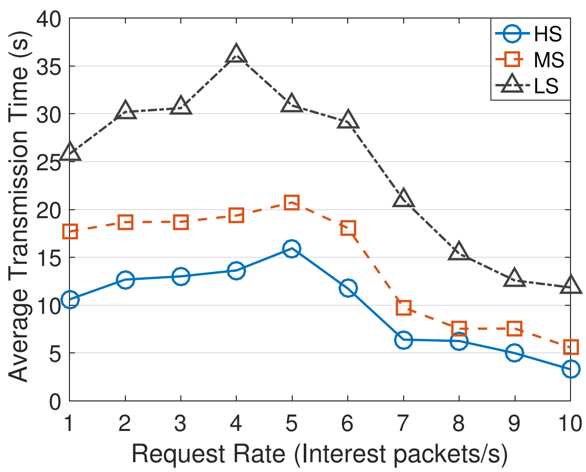


Fig. 11. Impact of the request rate.

performance as the performance gap under different scenarios are obvious. As the impact of number of contents is light, we fix it to be 1000 and then investigate the impact of request rate.

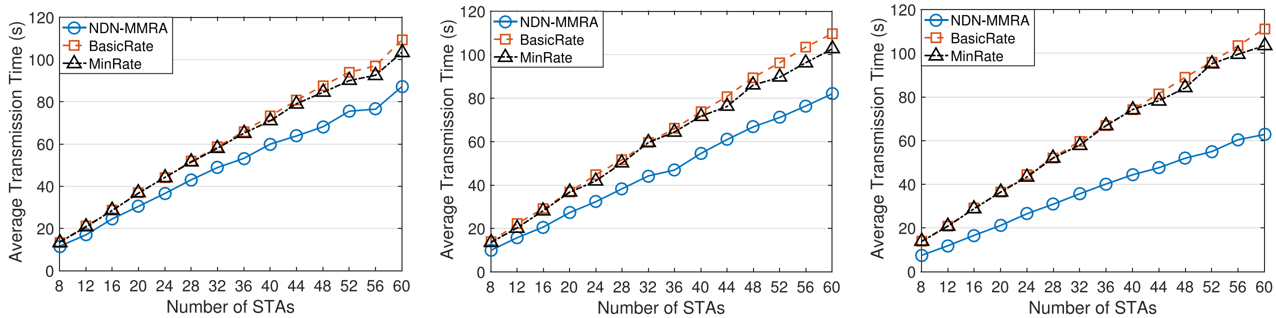
Fig. 11 shows the average transmission time under different scenarios when varying the request rate from 1 to 10 Interest packets per second. We can see that in all scenarios, as the request rate increases, the average transmission time increases first and then degrades dramatically. For the increase part, it happens since consumers request more packets, resulting in larger multicast groups (with more STAs) that take longer time to finish the data delivery for all consumers. For the decrease part, it happens since excessive requests lead to frequent channel congestion, which may block the multicast group formation, and result in smaller multicast groups and shorter time for data delivery. Generally, when increasing the rate, the STAs would request more contents, which can result in larger multicast groups. To complete the transmission for the larger groups, longer transmission time is required, which can well explain why the average transmission time increases first with the Interest packet rate. However, when the Interest packet rate becomes relatively large, e.g., larger than 5 packets/s, the excessive load would congest the channel and the Interest packets may drop significantly, which can block the multicast group formation and result in smaller multicast groups. The main reason is that those multicast members who fail to receive the data within a normal threshold (even after several retransmissions), their transmission time are not counted since there is no value for them. Therefore, the average transmission time decreases along with the Interest packet rate when the rate becomes relatively large. Congestion control is important for efficient transmission, which however is out of the scope of this paper [27]. To avoid the channel congestion impact, in following experiments, the request rate is set to be 2 (Interest packets/s).

C. Performance Comparison

In this subsection, we compare *NDN-MMRA* with other benchmark schemes in terms of multicast transmission time, packet delay, packet loss rate, and energy consumption.

1) Multicast Transmission Time: Fig. 12 shows the average transmission time achieved by different schemes under LS, MS, and HS scenarios. We can have three major observations. First, as the number of STAs increases, the average transmission time achieved by all schemes increases accordingly, which is reasonable as more STAs can form larger multicast groups, resulting in longer transmission times. Second, under all scenarios, *NDN-MMRA* achieves the lowest average transmission time in comparison with other benchmark schemes. For instance, when setting 40 STAs under the LS scenario, the average transmission time achieved by *NDN-MMRA*, *MinRate*, and *BasicRate* is about 60, 70, and 72 seconds, respectively. Third, when consumers have larger potential receiving data rates, e.g., under the HS scenario, *NDN-MMRA* can achieve better performance. Particularly, for the scenarios of LS, MS, and HS, the performance gap between *NDN-MMRA* and other two benchmark schemes becomes more significant. For instance, when setting 40 STAs under the LS scenario, compared with *MinRate* and *BasicRate*, *NDN-MMRA* can improve the performance by 14.3% and 16.7%, respectively, while when setting 40 STAs under the HS scenario, *NDN-MMRA* can improve the performance by 38.9% and 39.7%, respectively.

2) Packet Delay: Fig. 13 shows the average packet delay (including both unicast and multicast packets) achieved by different strategies under the MS scenario. We can see that in all schemes, the average packet delay increases as the number of STAs increases, which is reasonable as more consumers contend for the channel. In addition, it can be seen that *MinRate* achieves the largest average delay, which happens due to more retransmissions in the scheme as it adopts the minimum data rate of multicast group members rather than the lowest data rate in the 802.11 standard like the schemes of *BasicRate* and *NDN-MMRA*. As there are multi-stage transmissions in *NDN-MMRA*, *NDN-MMRA* benefits high-speed consumers while may delay low-speed consumers. Therefore, the averaged packet delay in *NDN-MMRA* can sometimes outperform *BasicRate* and sometimes perform worse than it, which depends on the underlying multicast formation conditions. For instance, when the number of STAs is 60, more multicast transmissions can be triggered, where the potential of *NDN-MMRA* can be



(a) Low data rate scenario (LS) (b) Moderate data rate scenario (MS) (c) High data rate scenario (HS)

Fig. 12. Multicast transmission time comparison.

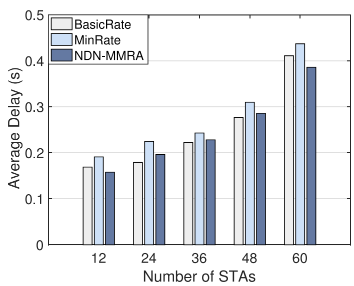


Fig. 13. Packet delay comparison under MS.

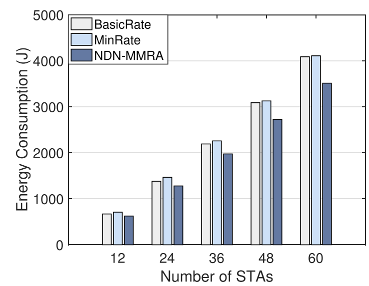


Fig. 15. Energy efficiency comparison under MS.

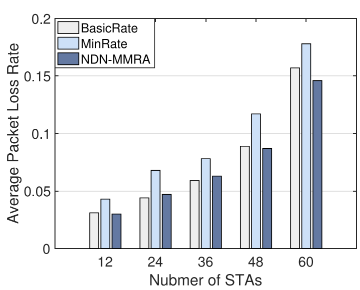


Fig. 14. Packet loss rate comparison under MS.

well unleashed, resulting in a significant performance gap in comparison with *BasicRate*.

3) Packet Loss Rate: Fig. 14 shows the average packet loss rate achieved by different strategies under the MS scenario. Likewise, we can see that *MinRate* has the worst performance in terms of the packet loss rate since it adopts the minimum data rate of multicast group members rather than the lowest data rate in the standard, but *BasicRate* and *NDN-MMRA* adopt the lowest data rate in the standard, which can enhance the packet reliability. In addition, when the multicast group is large and group members have diverse receiving capabilities, *NDN-MMRA* triggers multiple transmissions at different data rates, which can further enhance the packet reliability. Therefore, *NDN-MMRA* is able to achieve the superior performance especially when the number of STA is large, e.g., 48 or 60, leading to more NDN multicast transmissions.

4) Energy Efficiency: Energy efficiency is quite important for power-constrained mobile devices. We evaluate power consumption under different schemes. Particularly, we extract the duration of power states (including IL, RX, TX, sleep) of each STA and calculate the according power consumption in accordance with the empirical power consumption model for each power state [20]. Fig. 15 shows the average power consumption achieved by different schemes under the MS scenario. We can see that *NDN-MMRA* can achieve the supreme energy efficiency under all settings. For instance, when the number of STAs is 60, the average consumption in *BasicRate* and *MinRate* is about 4088 and 4109J, while the value is about 3513J in *NDN-MMRA*, with respective 14.1% and 14.5% energy efficiency improvement. This happens since *NDN-MMRA* facilitates the receiving process for high-speed consumers, which can significantly reduce energy consumption during RX states. However, in other benchmark schemes, all consumers have to stay in RX states for a long time in order to receive the data, resulting in much energy consumption.

D. Performance Enhancement by Caching

As caching is an important component in NDN, in this subsection, we evaluate the performance enhancement by caching. Specifically, the caching functions are enabled at the router node, with a cache size of 10 packets. In addition, two widely used content update strategies, i.e., least recently used (LRU) and feast frequently used (LFU) [28], are adopted to conduct caching. Fig. 16 shows the average multicast transmission time achieved by different schemes without/without caching under the MS scenario. It can be seen that *NDN-MMRA* outperforms other benchmark schemes significantly under all settings. In addition, with caching, the performance of *NDN-MMRA* can be further significantly enhanced. For instance, without caching, the average

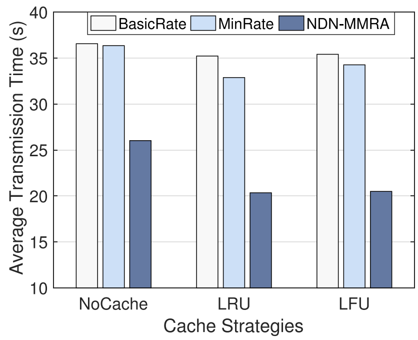


Fig. 16. Performance enhancement by caching.

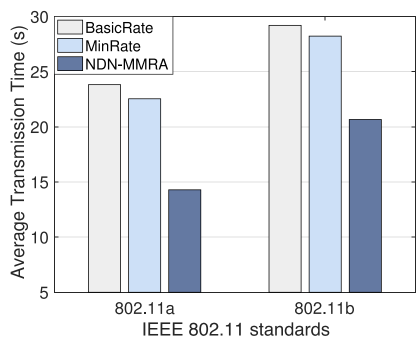


Fig. 17. Performance under different IEEE 802.11 standards.

transmission time is about 36.6, 36.4, and 26 seconds in *BasicRate*, *MinRate*, and *NDN-MMRA*, respectively, while with LRU caching, the average transmission time decreases to 35.2, 32.9, and 20.5 in three schemes, reduced by 3.8%, 9.6%, and 21.2%, respectively.

E. Robustness Performance Under Different 802.11 Standards

We evaluate the robustness of *NDN-MMRA* by implementing it under different IEEE 802.11 standards, i.e., 802.11a and 802.11b. Unlike 802.11b which has the available data set of $[1, 2, 5.5, 11]$ Mbps, 802.11a has the available data set of $[6, 9, 12, 18, 24, 36, 48, 54]$ Mbps, which is quite different. Fig. 17 shows the average transmission time achieved under different 802.11 standards. We can conclude that *NDN-MMRA* is quite robust as it outperforms other benchmark schemes significantly under both 802.11 standards. It means that *NDN-MMRA* can efficiently work under different 802.11 standards. In addition, as the available data rates in 802.11a are more diversified, the performance gap between *NDN-MMRA* and benchmark schemes can be more significant under 802.11a. For instance, in 802.11b, compared with *MinRate*, *NDN-MMRA* can improve the performance by 26.9%, while in 802.11a, the performance can be improved by 36.9%.

VI. Related Work

The rate control schemes have been deeply investigated in WLAN [29]–[33]. In this section, we first review some related works regarding to rate adaptation schemes (unicast) in IEEE 802.11 standards. Then, we review the rate adaptation schemes designed especially for WLAN multicast.

Rate Adaptation for Unicast in WLAN. In IEEE 802.11 standards, some rate adaptation schemes have been proposed for unicast in WLAN, such as auto rate fallback (ARF), receiver-based auto rate (RBAR), robust rate adaptation algorithm (RRAA), collision-aware rate adaptation (CARA), and other enhanced rate adaptation schemes [34]–[36]. The rate adaptation scheme is divided into two categories based on whether the receiver participates in the rate selection process: (i) based on the information statistics method, and (ii) based on the receiver feedback approach. Classification by the layer, the rate adaptation scheme is divided into three categories: (i) MAC layer, (ii) PHY layer, and (iii) hybrid approach combines the MAC and PHY layer. Although the proposed rate adaptation schemes can effectively improve transmission performance, it cannot work well for wireless multicast communication.

Rate Adaptation for Multicast in WLAN. The unicast reliable transmission has been deeply investigated by using the ACK feedback, RTS/CTS, and ARQ recovery scheme in wireless communications. However, there is no reliable approach to provide guaranteed reliability for multicast communication, which the current multicast protocol uses the basic data rate to transmit multicast data without any feedback from multicast receivers in WLAN. In addition, there is no feedback scheme from receiver and retransmission scheme from loss or error to support multicast communication in WLAN. The basic reason is that the multicast sender does not know whether the multicast data is received successfully or an error occurs from receiver. To overcome these problems, several solutions have been proposed [37]–[40]. The study in [41] has proposed the DirCast system for multicast transmission on Wi-Fi networks, which pseudo-broadcast, and augments it with destination control, association control and proactive FEC to improve multicast performance without changing the MAC layer. In [42], the authors have proposed JuCast to improve the performance of video multicast streaming over multiple APs, which design a joint user and rate allocation scheme. The authors [43] report two causes of packet loss: selection of PHY/FEC rates, PSSI and CRC error notifications in the proposed InFRA. InFRA can efficient use the interference-aware PHY/FEC rate decision enables to support the multicast service with minimal cost. In [11], the authors have proposed a multicast scheduling scheme to optimize the average delay, power, and fetching costs for wireless CCN. In [17], to improve the high multicast throughput with performance guarantees in large scale Wi-Fi multicast scenario, the authors design a multicast dynamic rate adaptation (MuDRA) algorithm by using a light-weight feedback scheme to adjust the rate adaptation response time. In [40], the authors have proposed a reliable and energy-efficient hybrid screen mirroring multicast protocol for multimedia serive in Wi-Fi networks, which designs an overhearing-based multicast transmission protocol to overcome the multicast problem (e.g., low transmission rate and high packet loss).

To summarize, as most of the current multicast data adaptation schemes are proposed for end-to-end TCP/IP protocols, they transmit data packets based on IP multicast addresses, under which the multicast groups and members are maintained.

They cannot be adopted directly under NDN architecture since the NDN multicast groups are maintained by the PIT instead of the fixed multicast IP address. On the other hand, as the current multicast scheme usually adopts the basic data rate to guarantee the receiving reliability, it cannot achieve the satisfying performance in terms of transmission time when there are dynamic multicast groups in NDN WLAN.

VII. Conclusion and Future Work

In this paper, we have proposed a multi-stage multicast rate adaptation scheme in NDN WLAN, named *NDN-MMRA*, to adapt data rate for multicast transmissions, which is crucial for future high-volume media streaming and multipoint videoconferencing. Particularly, to distinguish the NDN multicast, we have designed a mapping scheme between the entry and STA MAC address in PIT. Given a multicast group, we have devised the *MMRA* algorithm to determine the number of transmission stages and select the suitable data rate in each stage, in order to minimize the average multicast transmission time while guaranteeing the reliability. In addition, we have integrated the caching mechanism in *NDN-MMRA* to further enhance the multicast transmission performance. At last, we have implemented *NDN-MMRA* in NS-3 and carried out extensive experiments to corroborate the efficacy of *NDN-MMRA* under various IEEE 802.11 standards and WLAN topologies. For our future work, we will investigate the congestion control in multicast transmission and integrate it in *NDN-MMRA* to enhance the robustness of *NDN-MMRA*.

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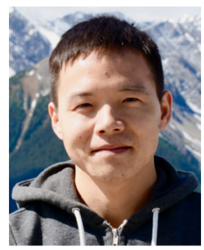

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