Throughput Optimization for Multirate Multicasting Through Association Control in IEEE 802.11 WLAN

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Abstract. Multicasting in wireless local area network is an efficient way to deliver message from a source user to a specified group of destination users simultaneously. In unirate multicasting, all users belonging to a particular group receive their services at the same basic rate. This may underutilize network resources as users requirements are generally heterogeneous in nature. To resolve this limitation, multirate multicasting is introduced, where different users belonging to a particular group may receive their services at different rates. Often dense deployment of access points (APs) is required for coverage and capacity improvement. Thus an station (STA) may come under the coverage range of several APs and hence there may exists many possible associations between the STAs and the APs. Hence finding an efficient association is very important as individual throughput of the STAs as well as the overall system throughput depend on it. We have developed an efficient algorithm to find an appropriate association for multirate multicasting. The objective is to maximize overall system throughput while respecting the user fairness. Through simulations, we have evaluated and compared the performance of our proposed algorithm with other well-known metrics such as received signal strength indicator, minimum hop-distance, in-range STA number and normalized cost. Results show that the proposed algorithm significantly improves the overall system throughput in comparison to these metrics.

Keywords: IEEE 802.11 WLAN · Multirate multicast · Multicast association · Association control · Throughput maximization · User fairness

1 Introduction

Multicasting is a technique in which a message or information can be delivered from a source user to a group of destination users simultaneously. Recently multicasting for multimedia applications like live lectures, online examinations, and video conferences are increasingly being used in several sectors. The IEEE 802.11

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wireless local area network (WLAN) has become the most popular and widely used wireless Internet access technology because of its low-cost and high-speed connectivity to the users. In an infrastructure based WLAN a set of access points (APs) is directly or via multi-hop connected to the Internet through a wired backbone network. A set of stations (STAs) access this network through these APs. An AP establishes a cell and coordinates all the communications that take place within that cell's area. Typically a dense deployment of the APs is required for coverage and capacity improvement in WLAN. Since many APs are deployed in a region, it is possible that an STA may be in the range of several APs, though it should be associated with only one AP at a time. In such situation, a well-known problem is which AP an STA selects to associate with [5,14]. An STA can receive data frames from an AP only when it is associated with that AP. This requires an STA to AP *association*. An STA may request different kind of services from the service provider such as *unicast services* and *multicast services*. When an STA maintains an association with an AP to get its unicast services then that kind of association is known as *unicast association*. Similarly, an association that is maintained by an STA with an AP to get its multicast services is known as *multicast association*. In this paper we deal with the multicast association problem and hence, in the rest of the paper, by association we mean to say multicast association.

There are two types of multicasting namely *unirate multicasting* and *multirate multicasting*. In an unirate multicasting, all the users belonging to a particular multicast group receive their services at the *same data rate* known as multicast session rate. This rate is determined according to the *worst channel condition* observed among all the users in a multicast group. Multicasting at this lower rate will occupy the transmission channel for a longer time and hence may *underutilize* the network resources [25]. In addition, it is not possible to meet the *heterogeneity* in user requirements by unirate multicasting. Hence it is desirable to use the multirate transmission to meet the heterogeneity in user requirements as well as efficient utilization of the network resources. In multirate multicasting, different users belonging to a particular group may receive their multicast services at different rates [12,13,21,22]. This does not imply separate rate for each user as multicasting is not a mere combination of several unicasting sessions. An AP must transmit its multicast packets to its associated STAs at the same rate. But different APs may transmit at different rates. The rate at which an AP will transmit multicast packets must be determined by taking into account the worst channel condition observed between the concerned AP and its associated STAs [3]. Thus unlike unirate multicasting there is no unique multicast session rate in multirate multicasting.

Time is divided into cycles, where a cycle duration is shared by both the unicast and multicast sessions. At the beginning of a multicast session, the APs and the STAs need to switch from their unicast to multicast mode within a fixed time interval. Such time-synchronization with respect to both APs and STAs can be achieved by network time protocol (NTP) [16,18]. Since multicast transmission at lower rate always results in the longer transmission time, designing a multicast algorithm that can reduce the channel occupancy time by increasing the transmission rate is desirable. This higher transmission rate will increase the overall system throughput by reducing the required number of time slots for completing the ongoing multicast session. This in effect helps to increase the unicast session duration as well.

In this paper, our main objective is to find an optimal association between the STAs and the APs such that the overall system throughput is maximized while taking care of the fairness of individual throughput obtained by the STAs. It is important to note that the problem of finding optimally fair utility allocation vector for multirate multicasting is NP-hard [21,23]. Therefore, we have developed a greedy algorithm for finding such optimal association which works as follows. If we associate an STA with an AP it may *pull-up* or *pull-down* the overall system throughput depending on the position of the concerned STA with respect to the positions of other STAs already associated with the concerned AP. An STA is associated with an AP based on the amount of throughput it pulls up or pulls down. The strategy is fair as an STA makes its association decision by considering not only its own throughput but also the throughput obtained by other STAs. We have compared the performance of the proposed algorithm with other well-known metrics like received signal strength indicator (RSSI) [4,5,7,8,14–16], minimum hop-distance [7,8,15,16], in-range STA number [7,8,15,16] and normalized cost [7,8,15]. Simulation results show that the proposed algorithm achieves much improved overall system throughput in comparison to these metrics.

The rest of the paper is organized as follows: Sect. 2 summarizes the related works. The system model is described in Sect. 3. Section 4 presents the problem statement and its mathematical formulation. The key idea of the solution approach is demonstrated through some motivational examples in Sect. 5. The proposed greedy algorithm is presented in Sect. 6. The time complexity of the proposed greedy algorithm is also presented in this section. The simulation results are presented in Sect. 7. Finally, Sect. 8 concludes the paper.

2 Related Works

The multicast association control in WLAN have been studied by several researchers. In [6], the authors have proposed an association strategy for supporting real-time multicast services in WLAN. In [15,16], the authors have proposed an association control mechanism for WLAN which optimizes the overall network load. An association strategy is proposed in [7,8] which maximizes the system throughput by controlling the multicast session data rate. All these studies are, however, based on the unirate multicasting.

Several authors have studied different aspects of multirate multicasting in WLAN. In [10], the authors have considered multirate transmissions to reduce the multicast/broadcast latency. An utility based multirate transmission is proposed in [12] which takes into account the heterogeneity in user requirement as well as the user fairness. A routing metric for reliable multicast in multirate WLAN environment have been studied in [20,25]. In [20], a routing and congestion control mechanism is proposed for multirate multicasting. A fair distributed congestion control mechanism for multirate multicast is presented in [22]. The problem of congestion control in networks which support the multirate multicasting have been studied in [11]. A low-overhead rate control and fair allocation of utilities for multirate multicasting is studied in [13,21]. Authors in [21,23] have shown that the problem of finding lexicographically optimal utility allocation vector for multirate multicasting is NP-hard. In [1,9,24] authors have considered the resource allocation problem for multicast services in WLAN. In [19], authors have shown that though the multirate multicasting improves the user quality of service (QoS), it also complicates the network optimization. They introduced a control scheme which dynamically optimizes the multirate multicast transmissions. A multirate multicasting method over wireless networks with time varying channel conditions and limited bandwidth have been proposed in [2], which dynamically adapts the transmission rate and forward error correction (FEC) for multicasting video traffic. In [17], a joint dynamic rate allocation and transmission scheduling optimization scheme based on opportunistic routing and network coding is proposed for scalable video multirate multicasting.

Though different aspects of multirate multicasting have been considered by several researchers, the multicast association problem in combination with the maximization of overall system throughput while respecting the user fairness has not been adequately studied. In this paper, we have developed an efficient greedy algorithm for finding an optimal association between the subscribed STAs and the available APs for multirate multicasting in WLAN which maximizes the overall system throughput while respecting the fairness of the individual throughput obtained by the users.

3 Network Model

The network model used in our study is described as follows. We have considered an infrastructure based WLAN where n number of APs are directly or via multi-hop connected through a wired backbone network to the main access point (MAP). The MAP is nothing but a special AP which has the backbone Internet connection. There are m number of subscribed STAs, which access this network through these APs. An AP establishes a cell and coordinates all the communications that take place within that cell's area. Typically an area is covered by multiple APs. Thus an STA may be in the coverage range of several APs. An STA can be associated with at most one AP at a time but an AP may serve multiple STAs simultaneously. We assume that an AP can serve at most 32 STAs simultaneously [15,16,29]. An STA can send/receive data packets via an AP only when it is associated to that AP. Network time is divided into cycles, where a cycle duration is shared by both the unicast and multicast sessions. The cycle duration as well as the unicast and multicast session intervals are configured by the network provider. The network service provider advertises these system information by means of beacon signals. At the beginning of a multicast session, the APs and the STAs need to switch from their unicast mode to the multicast mode at a fixed time interval. Such time-synchronization with respect to both APs and STAs may be achieved by network time protocol (NTP) [18].

Though according to the current IEEE 802.11 standard [26], multicast packets are transmitted to all the subscribed STAs at the same *basic data rate*, the feasibility of transmitting multicast packets at a rate higher than the basic rate have been established and studied by several authors [10,12,16]. According to IEEE 802.11 standard, IEEE 802.11b WLAN supports 1.0, 2.0, 5.5 and 11.0 Mbps data rates [26]. It uses dynamic rate shifting which allows the data rates to be automatically adjusted with the changing nature of the radio channel condition. For each rate, there is an optimal range for the successful operation at that rate. Most IEEE 802.11b vendors provide the optimal range for each data rate [27,28,30–32] in accordance with their supplied devices. Note that the optimal ranges vary with different vendors [27,28,30–32] and also with different models of the same vendor [31,32]. In our model, given the positions of the APs and the STAs, the physical rate at which an STA can be associated to an AP is determined based on these optimal ranges. The rate at which an AP transmits its multicast packets to its associated STAs and the overall system throughput obtained by an association are then computed based on these physical data rates. It is important to note that in our study we have considered the legacy of IEEE 802.11b standard for simplicity. However, our approach can be extended to any other standards (e.g., IEEE 802.11 a, g, n) as long as the operating rates and their respective optimal ranges are known.

4 Problem Statement and Its Mathematical Formulation

In order to get the multicast services, an STA must be associated with an AP at a certain physical rate. Let r_{ij} be this physical rate at which STA i can be associated with AP j. The value of r_{ij} can be computed based on the optimal ranges for different rates as stated earlier. We assume that STA i can be associated to AP j only if $r_{ij} \geq \tau$, where τ is a predefined threshold data rate. This threshold is determined based on the minimum rate required by an STA for decoding its multicast packets at the handset. This implies that an STA i will be considered as outside the coverage range of the network and can not be associated to any AP if $r_{ij} < \tau \ \forall \ j \in S_{AP}$, where S_{AP} is the set of available APs in the network.

In multirate multicasting, the rate at which an AP transmits its multicast packets is determined based on the worst channel condition observed between the AP and its associated STAs. All the associated STAs of an AP receive their multicast packets at this rate. Let r_j^{min} be this rate at which AP j transmits its multicast packets to its associated STAs. Hence to ensure the full coverage, the r_j^{min} of AP j must be set to the lowest of the data rates obtained by the STAs associated with AP j. That is $r_j^{min} = \min_i\{r_{ij}$: STA i is associated to AP $j\}$. The throughput provided by AP j to its associated STAs can be represented as $\sigma_j = (r_j^{min} \times m_j)$, where m_j is the number of STAs associated with AP j. Here σ_j implies the total amount of data received by all the STAs associated with AP j per unit time. The overall system throughput is then defined as $\sigma = \sum_{j=1}^{n} \sigma_j$, where n is the total number of APs. Here σ represents the total amount of data received by all the STAs per unit time.

Now, from the network service provider prospectives, it is very important to increase the overall system throughput as their gross revenue is directly depending on it. Let C be the cost per unit data usage. Then the gross revenue earned or generated by the Internet service provider from the current multicast session is $G_{revenue} = C \times \sum_{j=1}^{n} \sigma_j$. It is evident from the said equation that the gross revenue earned by the network service provider is directly proportional with the overall system throughput. It is clear that if we are able to achieve higher value of overall system throughput for ongoing multicast session which in tern generate more amount of gross revenue for the network service provider. So, in this paper our main objective is to find an association between the APs and the STAs such that the overall system throughput is maximized.

Let S_{AP} be the set of APs and S_{STA} be the set of STAs which receive at least τ data rate from at least one AP in S_{AP}. Let $\mathscr{C}$ be the set of available data rates. It is important to note that r_j^{min} $(j \in S_{AP})$ is a real variable belongs to $\mathscr{C}$, where $\mathscr{C} = \{1.0, 2.0, 5.5, 11.0\}$. For all $i \in S_{STA}$ and $j \in S_{AP}$, we define the following binary variables.

$$x_{ij} = \begin{cases} 1 & \text{if } \texttt{STA}\, i \text{ is associated with } \texttt{AP}\, j \\ 0 & \text{otherwise.} \end{cases}$$

$$a_j = \begin{cases} 1 & \text{if } \texttt{AP}\, j \text{ is selected to transmit at } 1.0\,\texttt{Mbps} \text{ rate} \\ 0 & \text{otherwise.} \end{cases}$$

$$b_j = \begin{cases} 1 & \text{if } \texttt{AP}\, j \text{ is selected to transmit at } 2.0\,\texttt{Mbps} \text{ rate} \\ 0 & \text{otherwise.} \end{cases}$$

$$c_j = \begin{cases} 1 & \text{if } \texttt{AP}\, j \text{ is selected to transmit at } 5.5\,\texttt{Mbps} \text{ rate} \\ 0 & \text{otherwise.} \end{cases}$$

$$d_j = \begin{cases} 1 & \text{if } \texttt{AP}\, j \text{ is selected to transmit at } 11.0\,\texttt{Mbps} \text{ rate} \\ 0 & \text{otherwise.} \end{cases}$$

It is important to note that r_{ij} is a pre-computed value and therefore, not an optimization variable. Also τ is a predefined threshold value. The multicast association problem can be represented by the following integer programming problem, where the objective function is non-linear but all the constraints are linear.

$$\text{Maximize} \sum_{j=1}^{n} (r_j^{min} \times m_j)$$

subject to the following constraints:

$$\sum_{j \in S_{AP}} x_{ij} = 1 \; \forall i \in S_{STA} \tag{1}$$

$$\sum_{j \in S_{AP}} x_{ij} \, r_{ij} \geq \tau \; \forall i \in S_{STA} \tag{2}$$

$$\infty(1 - x_{ij}) + x_{ij} \, r_{ij} \geq r_j^{min} \; \forall i \in S_{STA}, \; j \in S_{AP} \tag{3}$$

$$m_j = \sum_{i \in S_{STA}} x_{ij} \; \forall j \in S_{AP} \tag{4}$$

$$r_j^{min} = 1 \, a_j + 2 \, b_j + 5.5 \, c_j + 11 \, d_j \; \forall j \in S_{AP} \tag{5}$$

$$a_j + b_j + c_j + d_j = 1 \; \forall j \in S_{AP}. \tag{6}$$

$$r_j^{min} \geq \tau \; \forall j \in S_{AP} \tag{7}$$

Here ∞ as used in Constraint (3) represents a big positive integer. Constraint (1) ensures that each STA should be associated with exactly one AP. Constraint (2) ensures that STA i can be associated with AP j only if $r_{ij} \geq \tau$. Constraint (3) ensures that r_j^{min} is set to the minimum rate among the rates obtained by all the STAs associated to AP j. Constraint (4) computes the number of STAs associated with AP j. Constraints (5) and (6) together ensure that the value of r_j^{min} belongs to the set of available rates $\mathscr{C} = \{1.0, 2.0, 5.5, 11.0\}$. Constraint (7) ensures that r_j^{min} must be greater than or equal to τ. The objective function represents the overall system throughput.

5 Motivational Examples and the Solution Approach

Our objective is to find an optimal association between the subscribed STAs and the available APs such that the overall system throughput is maximized. To demonstrate the impact of association on the overall system throughput, we consider the following examples.

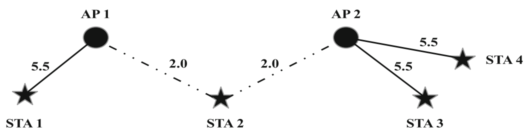

Fig. 1. Motivational Example1: STA 2 gets the same data rate from AP 1 and AP 2.

Consider an network with 2 APs (AP 1 and AP 2) and 4 STAs (STA 1, STA 2, STA 3 and STA 4) as shown in Fig. 1. Here APs and STAs are shown by the filled circles and stars, respectively. The label associated with the edge (solid or dotted) between an STA and an AP indicates the physical rate (in Mbps) at which the STA can be associated with the AP. An association of an STA is termed as *fixed association* if the STA is under the coverage range of a single AP. It can be seen from Fig. 1 that STA 1, STA 3 and STA 4 have fixed associations with AP 1, AP 2 and AP 2 respectively. These fixed associations are shown as solid edges in Fig. 1. If an STA is under the coverage range of several APs, the STA can potentially be associated with any one among them. These potential associations are shown as dotted edges in Fig. 1. Note that though an STA may potentially be associated with many APs, but it must select *only one* AP from them for its association. It can be seen from Fig. 1 that STA 2 has two potential associations, one with AP 1 and the other with AP 2. So STA 2 must select either AP 1 or AP 2 for its association. It is to be noted that STA 2 gets the same data rate (2.0 Mbps) from both AP 1 and AP 2.

If STA 2 selects AP 1 to associate with, then the throughput provided by AP 1 will become (2.0×2) Mb as $r_1^{min} = 2.0$ Mbps and $m_1 = 2$. Similarly, the throughput provided by AP 2 will become (5.5×2) Mb. Hence the overall system throughput will become $(2.0 \times 2) + (5.5 \times 2) = 15.0$ Mb. But, if STA 2 selects AP 2 to associate with, then the overall system throughput will become $(5.5 \times 1) + (2.0 \times 3) = 11.5$ Mb. It is now clear that the first association of STA 2 provides more overall system throughput than the second one though STA 2 gets the same data rate from both the APs. Therefore, it is evident that the selection of an AP for association of an STA plays an important role for the overall system throughput even if the STA gets the same data rate from multiple APs.

We now consider a situation where an STA can potentially be associated with different APs at different rates. For this purpose we consider another example shown Fig. 2. In this situation, if STA 2 selects AP 1 to associate with, then the overall system throughput will become $(2.0 \times 2) + (1.0 \times 2) = 6.0$ Mb. But, if STA 2 selects AP 2 to associate with, then the overall system throughput will become $(2.0 \times 1) + (1.0 \times 3) = 5.0$ Mb. It is now clear that the association of STA 2 with AP 1 provides more overall system throughput than its association with AP 2 though STA 2 gets higher data rate from AP 2 than AP 1. It shows that the association based on RSSI, where an STA associates with an AP from which it gets the highest data rate, may not always provide good overall system throughput. In other words, maximizing r_j^{min} without taking care of m_j may not always produce the best result.

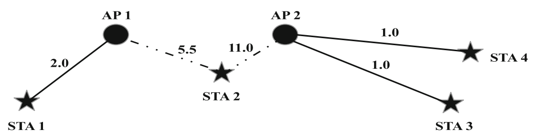

Fig. 2. Motivational Example2: STA 2 gets different data rates from AP 1 and AP 2.

We now consider an association policy based on *in-range STA number*, where an STA associates with an AP which has the maximum number of STAs in its coverage range. For this we consider the example shown in Fig. 1 again. From Fig. 1 it is evident that according to this association policy, STA 2 will select AP 2 for its association. As per our earlier discussion, association of STA 2 to AP 1 produces better overall system throughput than its association to AP 2. Hence the association based on *in-range STA number* may not always provide good overall system throughput. In other words, maximizing m_j without taking care of r_j^{min} may not always be the best option.

Motivated by the above observations, in our approach, we consider r_j^{min} and m_j simultaneously to maximize the overall system throughput instead of considering them independently. In the following section we now present our proposed approach formally.

6 The Proposed Greedy Algorithm

In this section, we present our proposed algorithmic solution to find an appropriate association between the multicast subscribed STAs and the available APs for providing multicast services to them. The objective is to maximize the overall system throughput while taking care of the user fairness.

Our approach works as follows. First we find the association of the STAs having the fixed associations. Then we calculate the overall system throughput considering the fixed associations only. Next we consider the association of the STAs having multiple potential associations. First we consider the set of STAs which get the highest data rate in $\mathscr{C}$ from at least one AP. The association of such an STA to a particular AP may pull up or pull down the current value of the overall system throughput. For an STA, we calculate the overall system throughput obtained from each such potential association and then choose the one which results in the highest pull ups or in the lowest pull downs. Next we consider the set of STAs which get the next lower data rate in $\mathscr{C}$ from at least one AP. The process is repeated until all STAs are covered. The detailed step by step description of the proposed greedy algorithm is stated below.

Input and Output: The proposed greedy algorithm takes the set of APs (S_{AP}), the set of STAs (S_{STA}), the set of available data rates ($\mathscr{C}$), the value of τ, the data rate matrix $R = (r_{ij})$ as inputs and returns the association between the STAs and the APs ($A = (a_{ij})$) and the overall system throughput as outputs. In the resulted association matrix $A = (a_{ij})$, $a_{ij} = 1$ denotes that STA i is associated with AP j, and 0, otherwise.

Step 1: Initialization
Initially, no STA is being associated with and hence the values of r_j^{min}, m_j and σ_j are all set to zero for each AP $j \in S_{AP}$. This implies that initially the overall system throughput σ of the current multicast session is also zero. The association matrix is set to all zeros initially. Sort the available data rates in $\mathscr{C}$ in ascending order of their magnitudes and let $\mathscr{C}_1, \mathscr{C}_2, \cdots, \mathscr{C}_k$ be this sorted order where k is the cardinality of $\mathscr{C}$.

Step 2: Consideration of Fixed Associations

Step 2.1: Compute C_i for all STA i in S_{STA} where C_i is the set of APs from which STA i gets at least τ data rate. That is, compute $C_i = \{\text{AP } j : r_{ij} \geq \tau \text{ and } j \in S_{AP}\}$ for all $i \in S_{STA}$.

Remark 1. It is important to note that STA i must be associated with an AP which belongs to set C_i. If $|C_i| = 0$, STA i can not be associated to any AP of the network and thus will remain uncovered.

Step 2.2: Find $S_{USTA} = \{\text{STA } i : |C_i| = 0 \text{ and } i \in S_{STA}\}$ where S_{USTA} is the set of uncovered STAs. Eliminate all such uncovered STAs from S_{STA} and update the set S_{RSTA} of remaining STAs as $S_{RSTA} = S_{STA} \setminus S_{USTA}$.

Remark 2. Association of STA i is termed as *fixed association* if $|C_i| = 1$. In such case, since $|C_i| = 1$, STA i must be associated with the only AP in C_i.

Step 2.3: Find $S_{FSTA} = \{\text{STA } i : |C_i| = 1 \text{ and } i \in S_{STA}\}$ where S_{FSTA} is the set of STAs having fixed associations. Find $S_{EAP} = \cup_{i \in S_{FSTA}} C_i$ where S_{EAP} is the set of APs each of which covers at least one STA having the fixed association with it.

Step 2.4: Associate the STAs in S_{FSTA} to their respective APs in S_{EAP}. After making all the fixed associations, update the association matrix A and compute the values of r_j^{min}, m_j and σ_j for each AP j in S_{EAP}. Also compute the overall system throughput $\sigma = \sum_{j \in S_{AP}} \sigma_j$. Remove the STAs in S_{FSTA} from the network and update $S_{RSTA} = S_{RSTA} \setminus S_{FSTA}$. If $S_{RSTA} = \emptyset$ then the algorithm is terminated, otherwise, go to the next step for considering the remaining STAs in S_{RSTA} having multiple potential associations.

Remark 3. The STAs in S_{RSTA} having multiple potential associations are associated with the APs with a view to maximizing the overall system throughput. However, to provide the fairness towards the individual throughput obtained by the STAs, we first associate the STAs which get the highest data rate $\mathscr{C}_k$ from at least one AP. Then we consider the STAs which get the next lower data rate $\mathscr{C}_{k-1}$ and so on until $S_{RSTA} = \emptyset$. In this way we maximize the overall system throughput while respecting the fairness of the individual throughput of the STAs.

Step 3: Consideration of Multiple Potential Associations

Step 3.1: Compute $D_j^k = \{\text{STA } i : r_{ij} = \mathscr{C}_k \text{ and } i \in S_{RSTA}\}$ for all $j \in S_{AP}$ where D_j^k is the set of STAs in S_{RSTA} which get the data rate $\mathscr{C}_k$ from AP j. Compute $S_{PSTA} = \cup_{j \in S_{AP}} D_j^k$ where S_{PSTA} is the set of STAs which get the data rate $\mathscr{C}_k$ from at least one AP in S_{AP}.

Step 3.2: In this step, we find the association of STA i in S_{PSTA} to an appropriate AP j in C_i which results in the highest pull ups or in the lowest pull downs of the overall system throughput. Let σ_j be the previous throughput provided by AP j before considering the association of STA i to it. Compute σ'_j, the throughput that can be provided by AP j, if STA i is associated with AP j. The association of STA i to AP j may pull up or pull down the previous throughput σ_j provided by AP j. Compute $\sigma_j^{cost} = (\sigma'_j - \sigma_j)$. If $\sigma_j^{cost} \geq 0$, association of STA i to AP j will pull up the previous throughput σ_j and hence it will pull up the overall system throughput σ as well. Else if $\sigma_j^{cost} < 0$, such association will pull down σ. After computing σ_j^{cost} for all $j \in C_i$, associate STA i to that AP which provides highest pull ups or lowest pull downs. That is, associate STA i to AP j' if $\sigma_{j'}^{cost} = \max_j \{\sigma_j^{cost} : j \in C_i\}$. If multiple such APs are found then break the ties based on the higher value of r_{ij}, lower value of m_j and finally the lower value of AP index. After associating STA i to AP j', update the association matrix A and compute the values of $r_{j'}^{min}$, $m_{j'}$, $\sigma_{j'}$ and σ. Remove STA i from both S_{PSTA} and S_{RSTA} and update $S_{PSTA} = S_{PSTA} \setminus \{\text{STA } i\}$ and $S_{RSTA} = S_{RSTA} \setminus \{\text{STA } i\}$ accordingly. Repeat this step until $S_{PSTA} = \emptyset$.

Step 4: Consideration of Different Data Rates
If $S_{RSTA} = \emptyset$ then the algorithm is terminated, otherwise, set $k = k - 1$ and repeat Step 3 until $S_{RSTA} = \emptyset$.

Time Complexity: The time complexity of the proposed algorithm is $\mathcal{O}(nm^2k)$ where n, m and k are the cardinalities of S_{AP}, S_{STA} and $\mathscr{C}$ respectively.

Remark 4. The proposed algorithm is a centralized algorithm where all the input data needs to be known before execution of the algorithm. Each AP in the network monitors the spectrum and measures the channel condition at a regular interval. This allows the AP to find the number of STAs which are present within its coverage range and also to estimate the data rates that they may get from it. Each AP will send this information to the network controller through the wired backbone network. After receiving this information from all the available APs, the network controller will be able to execute the proposed greedy algorithm.

7 Performance Evaluation

In this section, we evaluate the performance of our proposed greedy algorithm and compare the results with other well-known metrics.

7.1 Simulation Set-Up

We have considered an infrastructure based IEEE 802.11b WLAN where a number of APs and a number of STAs are uniformly placed in an $1000 \times 1000\,\text{m}^2$ area. We vary the number of APs from 30 to 300 with a step of 10 and the number of STAs is varying from 50 to 1000 with a step of 50. The MAP is placed at the position $(0, 0)$ which is the lower left most corner of the considered area. The coverage and interference range of each AP are set to 150 and 240 m respectively. We assume a simple wireless channel model for our simulation where the data rate obtained by a subscribed STA depends on the distance of it from the serving AP [5,6]. The STAs which are within 50 ms from an AP will get 11.0 Mbps, 5.5 Mbps between 50 and 80 m, 2.0 Mbps between 80 and 120 m and when the distance is between 120 and 150 m the data rate is 1.0 Mbps [5,6]. These values are commons with those provided by IEEE 802.11 vendors [27]. An STA will get 0.0 data rate from an AP if it is located beyond the distance of 150 m from it. An STA is not considered to be part of the network if no AP is there within 150 m from it. We consider all the STAs as subscribed STAs for the multicast session under consideration.

7.2 Simulation Results

In this section, we have considered some well-known metrics and a metric namely *normalized cost* [15] to compare the performance of our proposed greedy algorithm. In RSSI metric [4,5,7,8,14–16], an STA is associated with an AP from which it gets the maximum data rate. The *minimum hop-distance* metric tells that an STA will be associated with that AP which has the minimum hop-distance to reach the MAP [7,8,15,16]. In *in-range STA number* metric [7,8,15,16], an STA will be associated with that AP which has the maximum number of STAs in its coverage range. Apart from these three well-known metrics, we also have considered a metric namely *normalized cost* used in [7,8,15]. The normalized cost of an AP is defined as the ratio $\frac{H}{N}$, where H is the minimum hop-distance to reach the MAP from it and N is the number of STAs in its range. In normalized cost metric, an STA will be associated with that AP which has the minimum normalized cost value. Apart from these metrics, we also have compared the performance of our algorithm with the unirate multicasting approach where all the APs transmit their respective multicast data packets at the same basic data rate $r^{min} = \min_j \{r_j^{min} : j \in S_{AP}\}$. The theoretical maximum value of the overall system throughput can be expressed as $\sigma^{max} = \sum_{i \in S_{STA}} t_i$, where $t_i = \max_j \{r_{ij} : j \in S_{AP}\}$ is the largest possible rate STA i can be associated with. It is to be noted that σ^{max} represents a naive upper bound of the overall system throughput which is independent of any association strategy. In fact σ^{max} may not be achievable by any association policy in practice.

In fact there may not exist any association which achieves this σ^{max}.

Table 1 shows the comparison of the results obtained by the proposed algorithm against the said metrics. In this simulation, we have placed 50 APs and 210 STAs uniformly over the considered area. For each result, we have considered 100 different placements of the APs and the STAs and report their average value. Figure 3 shows one such instance where circles denote the positions of the APs and asterisks denote the positions of the STAs. The MAP is placed at the position $(0, 0)$ which is at lower left most corner of the considered area. It can be seen from Table 1 that proposed algorithm provides 27%, 196%, 206%, 239% and 319% more overall system throughput than RSSI, minimum hop-distance, in-range STA number, normalized cost and unirate multicasting respectively, when $\tau = 1.0$ Mbps. When $\tau = 2.0$ Mbps, our proposed algorithm gives 37%, 83%,

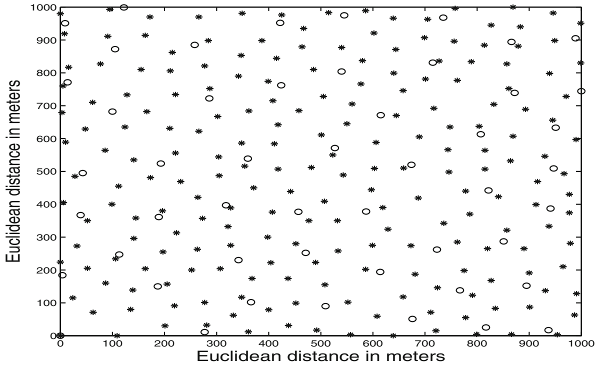

Fig. 3. A possible positions of the considered 50 APs and 210 STAs.

75%, 84% and 128% more system throughput than these metrics, respectively. Note that for the value of $\tau = 1.0$ Mbps, all STAs are served, but for the values of $\tau = 2.0$, 5.5 and 11.0 Mbps, 99.61%, 79.42% and 35.09% of STAs are served by all these metrics and the proposed algorithm. However, the proposed algorithm provides 33%, 33%, 31%, 31% and 41% more overall system throughput than these metrics, when $\tau = 5.5$ Mbps. And when $\tau = 11.0$ Mbps, all metrics and proposed algorithm give the same amount of overall system throughput.

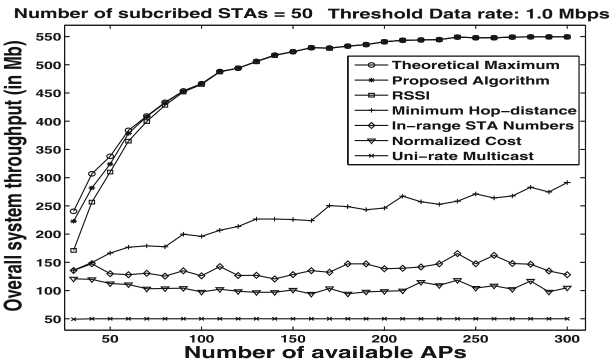

Fig. 4. Number of available APs vs overall system throughput when number of STAs is 50 and $\tau = 1$ Mbps.

Figures 4 and 5 show how the overall system throughput is varying with the number of available APs for a fixed number of subscribed STAs. In Figs. 4 and 5, we have considered 50 and 300 STAs respectively, to represent different traffic load distributions. The number of APs is varying from 30 to 300 with a step of 10 to represent different network densities. The coverage range, interference range and the value of τ are set at 150 m, 240 m and 1.0 Mbps respectively.

It is evident from Figs. 4 and 5 that the overall system throughput obtained by the proposed algorithm is always greater than or equal to that of other metrics. The overall system throughput obtained by RSSI and proposed algorithm increase with the number of APs and get saturated at some point. This saturation point signifies the fact that those APs are sufficient to serve each STA at the maximum available data rate and hence no further improvement is observed after that point. The overall system throughput at the saturation points are 550 (50×11.0) and 3300 (300×11.0) Mb as shown in Figs. 4 and 5 respectively.

Table 1. Performance comparison of the proposed algorithm with different metrics.

Name of metric	Value of τ (in Mbps)	Overall system throughput (in Mb)	% of throughput improvement
Theoretical maximum (σ^{max})	1.0	1408.35	
	2.0	1407.55	
	5.5	1322.75	
	11.0	810.7	
Proposed algorithm	1.0	880.3	
	2.0	955.5	
	5.5	1294.7	
	11.0	810.7	
Unirate multicast	1.0	210	319.19
	2.0	418.4	128.36
	5.5	917.4	41.12
	11.0	810.7	0
RSSI	1.0	691.75	27.25
	2.0	696.85	37.11
	5.5	972.4	33.14
	11.0	810.7	0
Minimum Hop-distance	1.0	296.55	196.84
	2.0	520.15	83.69
	5.5	971.85	33.22
	11.0	810.7	0
In-range *STA* number	1.0	286.85	206.88
	2.0	544.3	75.54
	5.5	987.25	31.14
	11.0	810.7	0
Normalized cost	1.0	259.35	239.42
	2.0	518.55	84.26
	5.5	984.5	31.50
	11.0	810.7	0

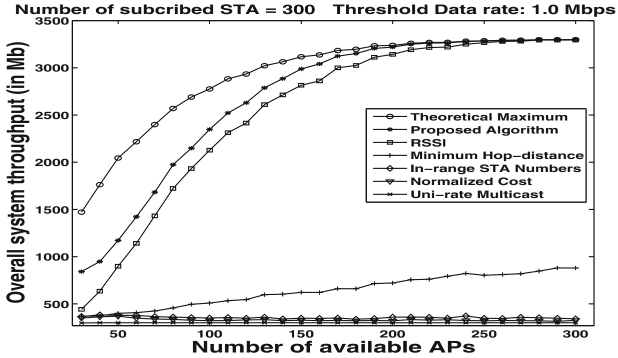

Fig. 5. Number of available APs vs overall system throughput when number of STAs is 300 and $\tau = 1$ Mbps.

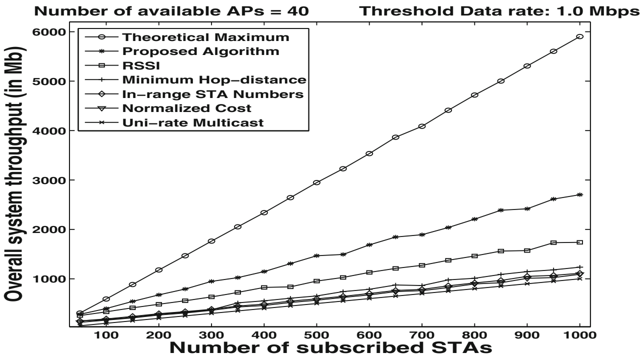

Fig. 6. Number of subscribed STAs vs overall system throughput when number of APs is 40 and $\tau = 1$ Mbps.

It is seen from Figs. 4 and 5 that both proposed algorithm and RSSI touch the theoretical maximum value. However, the proposed algorithm touches the theoretical maximum value earlier than the RSSI. It can be observed that the overall system throughput provided by minimum hop-distance increases as the number of APs increases but the rate at which it increases is very low. The overall system throughput more or less remains constant in both in-range STA number and normalized cost. However, the magnitude of overall system throughput in in-range STA number is slightly higher than that of normalized cost. It is seen from Figs. 4 and 5 that the value of overall system throughput obtained by unirate multicasting remains constant at 50 (50×1.0) and 300 (300×1.0) Mb respectively. This happens because in unirate multicasing, multicast packets are transmitted at the same basic data rate (1.0 Mbps) to all the subscribed STAs. So we can infer that the overall system throughput not only depends on the relative positions of APs and STAs but also on the association strategy.

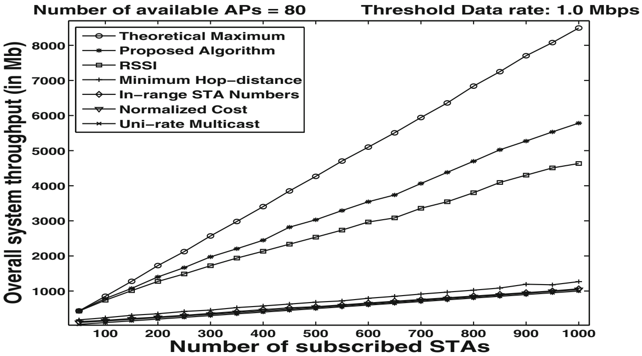

Fig. 7. Number of subscribed `STAs` vs overall system throughput when number of `APs` is 80 and $\tau = 1$ `Mbps`.

Figures 6 and 7 show how the overall system throughput varies with the number of subscribed `STAs` when the number of available `APs` is fixed. In this case we have assumed that an `AP` can serve at most 32 `STAs` simultaneously [15,16,29]. In Figs. 6 and 7, we have considered 40 and 80 `APs` to represent different network densities. We vary the number of `STAs` from 50 to 1000 with a step of 50 to represent different traffic load distributions. It is seen from Figs. 6 and 7 that the overall system throughput obtained by the proposed algorithm is always greater than or equal to that of other metrics. For a fixed number of available `APs`, the overall system throughput obtained by all metrics, increase with the number of subscribed `STAs` though at different rates. It increases at the fastest rate in proposed algorithm and at slowest rate in unirate multicasting. The difference between the overall system throughput obtained by these metrics and the theoretical maximum increases with the number of subscribed `STAs`. This difference decreases with the increase in the number of available `APs` as evident from Figs. 6 and 7. This signifies the fact that we have to place a sufficiently

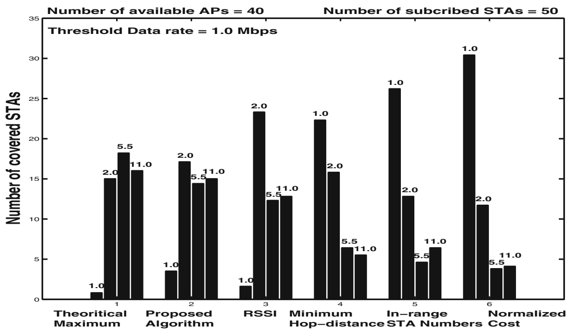

Fig. 8. Number of `STAs` (50) covered at different rates for different approaches when number of available `APs` is 40 and $\tau = 1$ `Mbps`.

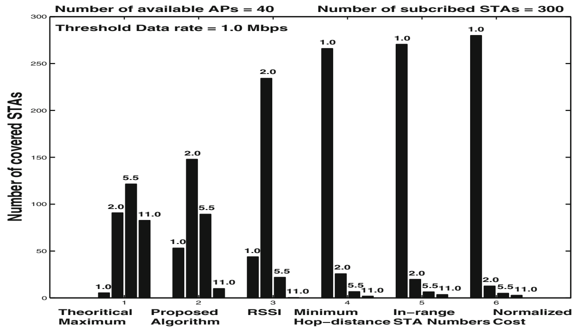

Fig. 9. Number of STAs (300) covered at different rates for different approaches when number of available APs is 40 and $\tau = 1$ Mbps.

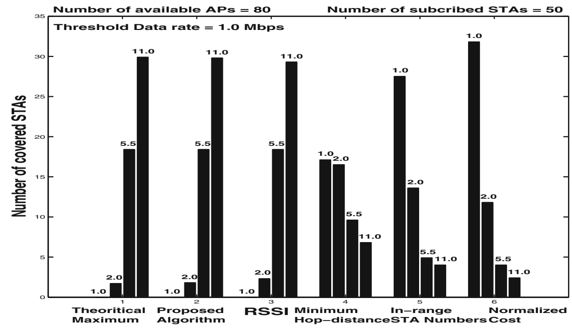

Fig. 10. Number of STAs (50) covered at different rates for different approaches when number of available APs is 80 and $\tau = 1$ Mbps.

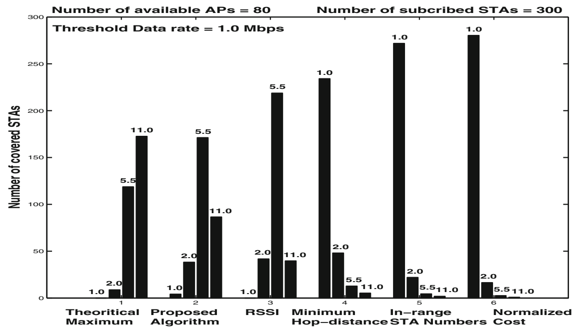

Fig. 11. Number of STAs (300) covered at different rates for different approaches when number of available APs is 80 and $\tau = 1$ Mbps.

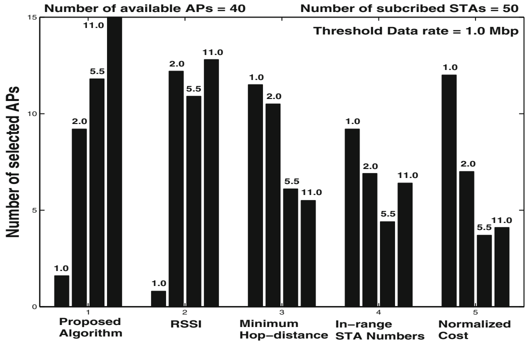

Fig. 12. Number of selected APs (40) at different rates for different approaches when number of STAs is 50 and $\tau = 1$ Mbps.

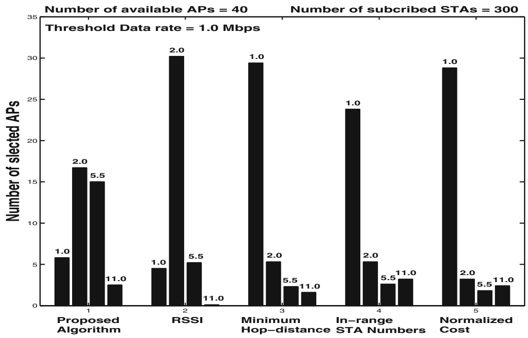

Fig. 13. Number of selected APs (40) at different rates for different approaches when number of STAs is 300 and $\tau = 1$ Mbps.

large number of APs to achieve throughput equal to the theoretical maximum, i.e., to reduce this difference to zero.

Figures 8, 9, 10 and 11, show the number of STAs served at different rates by our proposed algorithm as well as other metrics. Similarly Figs. 12, 13, 14 and 15, show the number of APs are being selected for operation at different rates by our proposed algorithm as well as other metrics. In these figures, we have considered 50 or 300 STAs and 40 or 80 APs to represent different traffic load distributions and different network densities. The coverage and interference range of each AP is set to 150 and 240 m respectively. The value of τ is set at 1.0 Mbps.

It is seen from Figs. 8 and 9 that our proposed algorithm serves more STAs at 11.0 and 5.5 Mbps rates than other metrics. Also, it maintains a balanced distribution of STAs served at different rates. Figures 10 and 11 also show the similar trend but the magnitude of the number of STAs served at different rates are different. From Figs. 8, 9, 10 and 11, we can conclude that our proposed algorithm maintains a good amount of fairness between the individual throughput

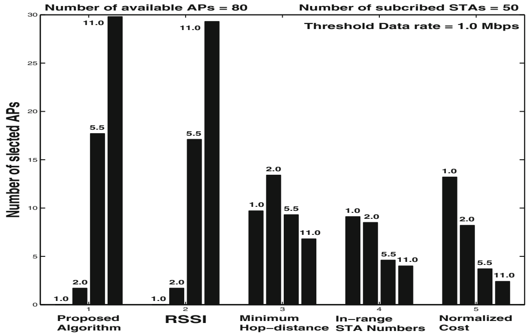

Fig. 14. Number of selected `APs` (80) at different rates for different approaches when number of `STAs` is 50 and $\tau = 1$ `Mbps`.

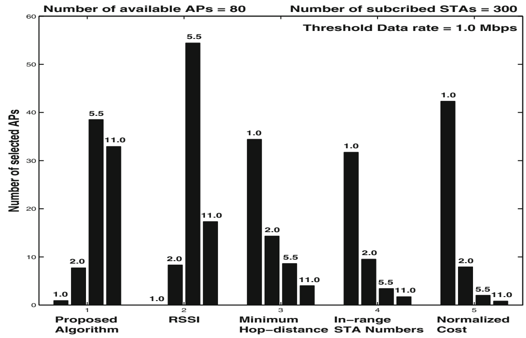

Fig. 15. Number of selected `APs` (80) at different rates for different approaches when number of `STAs` is 300 and $\tau = 1$ `Mbps`.

obtained by the `STAs`. From Figs. 12, 13, 14 and 15, it can be observed that our proposed algorithm selects more number of `APs` to operate at higher data rates, than other metrics. It also maintains a balanced distribution of selected `APs` operated at different data rates.

8 Conclusion

An efficient greedy algorithm to find an optimal association for multirate multicasting in `WLAN` is developed which maximizes the overall system throughput while taking care of the user fairness. We have evaluated and compared the performance of the proposed algorithm with other well-known metrics. The obtained results show that the proposed algorithm significantly improves the overall system throughput in comparison to these metrics. Our future work is to implement the proposed algorithm in a distributed as well as online setup.

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