ARSM: a cross-layer auto rate selection multicast mechanism for multi-rate wireless LANs

J. Villalón, P. Cuenca, L. Orozco-Barbosa, Y. Seok and T. Turletti

Abstract: Multicast is an efficient paradigm for transmitting data from a sender to a group of receivers. According to the IEEE 802.11 standard, the multicast service is defined as an unreliable service, that is, it does not include the use of ACK frames. Furthermore, different to the unicast service, the multicast service makes use of a single rate out of the various rates included in the basic service set defined by the IEEE 802.11 standard. Even though various proposals have recently appeared in the literature addressing these issues, none of them has come out with a structured set of control mechanisms taking into account the varying conditions characterising the wireless channels as well as the requirements of various applications. A novel cross-layer auto rate selection multicast mechanism for multi-rate wireless LANs, namely auto rate selection for multicast, capable of adapting the data transmission to the varying conditions of the channel and taking into account the characteristics of various applications, is introduced. The simulation results show that our proposal outperforms the IEEE 802.11 standard and the mechanisms recently proposed in the literature.

1 Introduction

The IEEE 802.11 wireless LANs (WLANs) are one of the fastest evolving network technologies in the wireless communications field. Nowadays, the IEEE 802.11 Media Access Control (MAC) protocol makes use of a physical (PHY) layer capable of operating at various rates [1]. The original IEEE 802.11 protocol could only support a single base rate, typically 2 Mbps, whereas the multi-rate enhancement enables the data transmission at various rates. The rate to be used is selected by taking into account the wireless channel conditions, given by the signal-to-noise ratio (SNR). Within the IEEE 802.11a standard [2], the set of possible data rates includes 6, 9, 12, 18, 24, 36, 48 and 54 Mbps, whereas for the IEEE 802.11b standard [3], the set of possible data rates includes 1, 2, 5.5 and 11 Mbps. Since the multi-rate enhancements are implemented into the PHY layer, the MAC mechanisms should be adapted in order to fully exploit them. The Auto Rate Fallback (ARF) protocol is the best known commercial implementation of the IEEE 802.11 MAC making use of this feature [4]. Under the ARF protocol, after the reception of ten consecutive acknowledgement (ACK), the next higher mode is selected for future data frames. If the delivery of the 11th frame is unsuccessful, it immediately falls back to the previously supported mode. During other cycles with less than ten consecutive ACKs, it switches to a lower rate mode after two successive ACK failures.

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Since the ARF protocol selects the data rate taking into account the channel conditions between the access point (AP) and a given mobile terminal (MT), it is only suitable for point-to-point communications. In the case of point-to-multipoint communications, that is, multicast and broadcast services, it is more difficult to determine the highest data rate to be used since the channel conditions between the AP and each one of the MTs in the multicast group may differ and no feedback is available. In most current set-ups, it is left to the network administrator to set up the data rate to be used by the point-to-multipoint service. This rate is then used to provide network connectivity to all the MTs covered by the AP. It is obvious that, in order to ensure full coverage, the rate to be used is determined by using the channel conditions between the AP and the MT exhibiting the worst channel conditions. Furthermore, since the coverage of the AP is inversely proportional to the transmission data rate, the administrator should then select the proper data rate according to the distance between the AP and the worst MT. As the distance increases, the data rate has to be reduced in order to compensate for the increased range that the AP has to cover. Moreover, as shown in [5], the performance of an IEEE 802.11 WLAN is severely affected when operating at such low PHY data rates. This simple approach does not efficiently support the point-to-multipoint communications service.

In this paper, we introduce a novel cross-layer auto rate selection multicast mechanism for multi-rate WLAN, from now on referred as the ARSM mechanism. Wireless links create several new problems for protocol design that cannot be handled well in the framework of the layered architectures [6]. Cross-layer design refers to protocol design done by actively exploiting the dependence between protocols layers to obtain performance gains [7, 8]. Basically, the ARSM mechanism dynamically selects the multicast data rate based on the channel conditions perceived by the MTs. The main idea behind the proposed scheme is to identify the AP to MT channel exhibiting the worst conditions, expressed in terms of the SNR ratio. In auto rate selection for multicast (ARSM) scheme, the PHY and MAC layers collaborate in the ARSM services of a WLAN system. It is interesting to note that the collaborative design between the PHY and MAC layers tend to blur the boundary between these two adjacent layers [9].

2 Background

In IEEE 802.11 WLANs, multicasting is specified as a simple broadcasting mechanism that does not make use of ACK frames. According to the IEEE 802.11a/b/g standards, all frames with multicast and broadcast receiver address should be transmitted at one of the rates included in the basic rate set.

Most research efforts on multicasting in IEEE 802.11 WLANs have focused on improving transmission reliability by integrating ARQ mechanisms into the protocol architecture. In [10], the leader-based protocol (LBP) ARQ mechanism has been introduced to provide the multicast service with some level of reliability. The main issue to be addressed when implementing such mechanism has to do with the number of ACK messages required to successfully complete the reliable transmission of the multicast packets to all group members. The LBP addresses this issue by assigning the role of group leader to the multicast receiver exhibiting the worst signal quality in the group. The group leader holds the responsibility of acknowledging the multicast packets on behalf of all the multicast group members, whereas other MTs may issue negative acknowledgement (NACK) frames when they detect errors in the transmission process. The transmission of the NACK may result in a collision with the acknowledgment issued by the group leader. Upon this event, the sender will once again re-issue the multicast frame.

Gupta *et al.* [11], present a reliable multicast MAC protocol, namely the 802.11MX protocol. The 802.11 MX uses an ARQ mechanism supplemented by a busy tone signal. When an MT associated to a multicast group receives a corrupted packet, it sends an NACK tone instead of actually transmitting an NACK frame. Upon detecting the NACK tone, the sender will retransmit the data packet. On the contrary, if the AP does not detect the NACK tone, the AP assumes that the transmission of the multicast packet has been successfully completed. Since the 802.11MX mechanism does not need a leader to operate, it performs better than the LBP protocol in terms of both data throughput and reliability. However, this mechanism is very costly because it requires a signalling channel to send NACK and busy tones. Moreover, both the LBP and 802.11MX schemes do not adapt the multicast PHY rate to the state of receivers.

Seok and Choi [12] present the necessity of a multicast rate adaptation mechanism for WLANs. On this purpose, they present the multicast rate selection algorithm based on the traffic load of the WLAN and the channel condition of the multicast receivers. If the WLAN is congested, a multicast rate is selected to the higher PHY rate than the data rates in basic service set (BSS) basic rate set parameter for mitigating the congestion. Otherwise, the multicast rate is adjusted according to the worst channel condition among channel conditions of all multicast receivers. However, this mechanism assumes that the AP knows the channel conditions of each multicast receivers.

Very recently, the RAM scheme has been proposed in [13] for reliable multicast delivery. Similar to the LBP and 802.11MX schemes, the transmitter has to first send an RTS frame to indicate the beginning of a multicast transmission. However, in RAM, the RTS frame is used by all the multicast receivers to measure the receiver signal strength. Then, each multicast receiver has to send a variable length dummy CTS frame whose length depends on the selected PHY transmission mode. Finally, the transmitter senses the channel to measure the collision duration and can adapt the PHY rate transmission of the multicast data frame accordingly. This smart solution is more practical than 802.11 MX since it does not require a signalling channel but still requires the use of RTS/CTS mechanism and targets reliable transmission applications.

Note that at the exception of [12, 13], the mechanisms just described above only focus on solving the reliability of the multicast service in WLANs. Only the mechanisms presented in [12, 13] adapt the PHY transmission rate of the multicast data frames. In this paper, we define a protocol architecture by integrating the following facilities: (i) the optimal channel rate adaptation of the multicast service in IEEE 802.11 WLANs, (ii) a more reliable transmission of the multicast data and (iii) the limitation of the overhead required for the mechanism to operate. The definition of the proposed cross-layer architecture is based on the multirate capabilities present in the PHY layer of IEEE 802.11 WLANs.

3 Auto rate selection for multicast

The ultimate goal of the ARSM protocol to be introduced herein is to enable the deployment of a reliable and efficient multicast protocol to be integrated later into the cross-layer architecture proposed for multi-rate WLANs. By efficient, we mean that the overhead required by the ARSM to operate should be kept to minimum levels. As previously stated, ARSM enables the exchange of information pertaining to the PHY channel conditions as perceived by each and every MT. This information expressed in terms of the SNR of the channel can be used by the multicast protocol, that is, ARSM, to determine the transmission rate accordingly. The design of our proposal follows the principles of cross-layer protocol engineering. In other words, the multicast protocol to be proposed is able to adapt the transmission rate by making use of information, the PHY channel conditions, normally not available to the link layer. In ARSM scheme, the PHY and MAC layers collaborate in the ARSM services. The cross-layer design has been to design two adjacent layers (PHY and MAC) together such that the service provided by the new superlayer is the union of the services provided by the constituent layers (Fig. 1). This does not require any new interfaces to be created in the stack. Architecturally speaking, the superlayer can be interfaced with the rest of the stack using the interfaces that already exist in the original architecture. The collaborative design between the PHY and MAC layers tends to blur the boundary between these two adjacent layers. For ARSM, the cross-layer design has been merging the two adjacent layers (PHY and MAC). This manifests in an iterative loop between the two layers, with

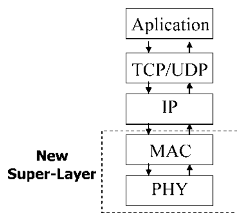

Fig. 1 *Cross-layer design for ARSM*

information flowing back and forth between them. In the following sections, we introduce the various mechanisms making part of ARSM.

3.1 Multicast channel probe operation of ARSM

ARSM is an adaptive mechanism in which the AP selects the PHY data rate to be used for multicast data transmission. The PHY data rate to be used is determined by taking into account the channel conditions perceived by each and every MT belonging to a given multicast group. Under the proposed scheme, the AP starts by multicasting a control frame, namely the MP frame, to the multicast group members. Upon receiving the MP frame, each multicast member estimates the SNR of the channel, that is, the quality of the wireless medium. On the basis of SNR, each MT will determine the point in time for replying to the AP. According to the proposed mechanism, an MT having detected the lowest SNR will be the one in charge of first replying to the AP, by issuing a multicast response (MR) frame. Upon detecting the transmission of the reply and in the absence of errors, all the other group members should normally refrain from replying to the AP. The AP assigns the role of group leader to this MT. The group leader holds the responsibility of acknowledging the multicast packets on behalf of all the multicast group members, whereas other MTs may issue NACK frames when they detect errors in the transmission process, in that case the AP retransmit the frame. The AP will select its PHY data rate using the SNR value contained in the received ACKs coming from the leader.

Fig. 2*a* shows the format of the MP frame. The duration field of the MP frame is initially set to $CW_m \times$ SlotTime, where CW_m is the length of the contention window, expressed in slots, during which the group members may attempt to transmit the MR frame back to the AP. The destination address field of the MP frame represents the address of the multicast group being addressed by the AP, and the SNR_{leader} field is set to the SNR received in the latest ACK received by the AP.

After having sent the MP frame, the AP will wait for a period whose length is given by the short inter frame space parameter of the IEEE 802.11 standard, before changing its interface from transmission mode to listen mode. At the time of sending the multicast frame, the AP starts a timer, namely the MP_timer, initially setting to CW_m slots. The timer is then decremented by one slot whenever the channel has been sensed idle for a period of time equal to one time slot (SlotTime). On the contrary, whenever the AP detects activity in the channel by means of the clear channel assessment mechanism, it immediately freezes the MP_timer.

When an MT receives the MP frame, it checks whether it is a member of this multicast group. If it is not, it sets the NAV parameter to $CW_m \times$ SlotTime by using the duration field included in the MP frame. In this way, the MTs that are

2	2	6	6	1	4
Frame Control	Duration	Dest Address	Source Address	SNRleader	FCS

a

2	2	6	1	4
Frame Control	Duration	Dest Address	SNRmp	FCS

b

Fig. 2 *Special multicast control frames*
a MP frame
b MR frame

no members of the multicast group will not interfere with the on-going multicast transmission. Fig. 2*b* depicts the format of the MR frame.

In the MR frame, the SNR_{mp} field contains the SNR value of the previously received MP frame. When an MT replies to the AP with an MR frame, an MT uses a backoff timer in order to reduce the collision probability with other MR frames. The backoff timer used for transmitting the MR frame is set according to the following expression

$$\text{Backoff timer} = \begin{cases} [0, 2] & SNR_{mp} < Th_{\leftarrow 2} \\ [3, 5] & Th_{\leftarrow 2} \le SNR_{mp} < Th_{\leftarrow 1} \\ [6, 7] & Th_{\leftarrow 1} \le SNR_{mp} \end{cases} \quad (1)$$

where $Th_{\leftarrow i} \in \{Th_{1\leftrightarrow 2}, Th_{2\leftrightarrow 5.5}, Th_{5.5\leftrightarrow 11}\}$, for $i = 1$ and 2, are the thresholds of the channel rates corresponding to one or two modes down of the mode being currently used by the AP and having been previously fixed by the current value of the SNR of the multicast leader, SNR_{leader}. That is to say if $Th_{5.5\leftrightarrow 11} \le SNR_{leader}$, then $Th_{\leftarrow 1} = Th_{5.5\leftrightarrow 11}$ and $Th_{\leftarrow 2} = Th_{2\leftrightarrow 5.5}$. Otherwise if $Th_{2\leftrightarrow 5.5} \le SNR_{leader} < Th_{5.5\leftrightarrow 11}$, then $Th_{\leftarrow 1} = Th_{2\leftrightarrow 5.5}$ and $Th_{\leftarrow 2} = Th_{1\leftarrow 2}$). A special case is when $Th_{1\leftarrow 2} \le$ $?SNR_{leader} < Th_{2\leftrightarrow 5.5}$; in this case, $Th_{\leftarrow 1} = Th_{1\leftrightarrow 2}$ and $Th_{\leftarrow 2} = Th_{\leftarrow 1}/2$. The thresholds $Th_{1\leftrightarrow 2}$, $Th_{2\leftrightarrow 5.5}$ and $Th_{5.5\leftrightarrow 11}$ are selected to optimise the throughput performance of an IEEE 802.11b WLAN by taking into consideration of MAC, PHY and retransmission overheads. A more in-depth analysis of how these thresholds have been selected can be found in [14]. From (1), one of the MTs classified as belonging to the group of MTs having sensed the worst SNR chooses the shortest backoff window. In this way, such MT will be able to place its reply before the stations having sensed much better channel conditions. In order to reduce the probability of collision of the MR frames, a random number of slots have been assigned to each one of the three intervals. When all the other MTs detect the transmission of the MR frame, all the other MTs refrain from transmitting. In this way, ARSM avoids the MP frame implosion problem.

Following the multicast channel probe operation (MCPO), the AP selects the appropriate PHY data rate using the feedback information that contains the channel conditions of the MTs. According to the received information, and the value of the MP_timer, the AP could receive three different kinds of feedback information: explicit feedback, implicit feedback, no feedback.

Explicit feedback: the AP receives the MR frame from an MT within the multicast group. In this case, the AP determines the SNR value of the MT with the worst channel quality. Then, it transmits the multicast data frames accordingly. In the scenario depicted in Fig. 3*a*, STA1 selects the shortest backoff time since STA1 shows the worst received SNR of MP frame. STA1 then sends the MR frame to the AP after three slots; this period is determined through (1).

Implicit feedback: the AP receives a corrupted MR frame and the MP_timer of the AP has not expired. This condition occurs when several MTs reply to the MP frame simultaneously and the MR frames have collided. In this case, the AP can predict the SNR value ($\overline{SNR_{mp}}$) of the MTs having sensed the worst channel quality. Through the current MP_timer of the AP, the AP identifies the lowest backoff timer among all the MTs in the multicast group. It must be mentioned that the MT with the lowest backoff timer first replies to the AP using an MR frame.

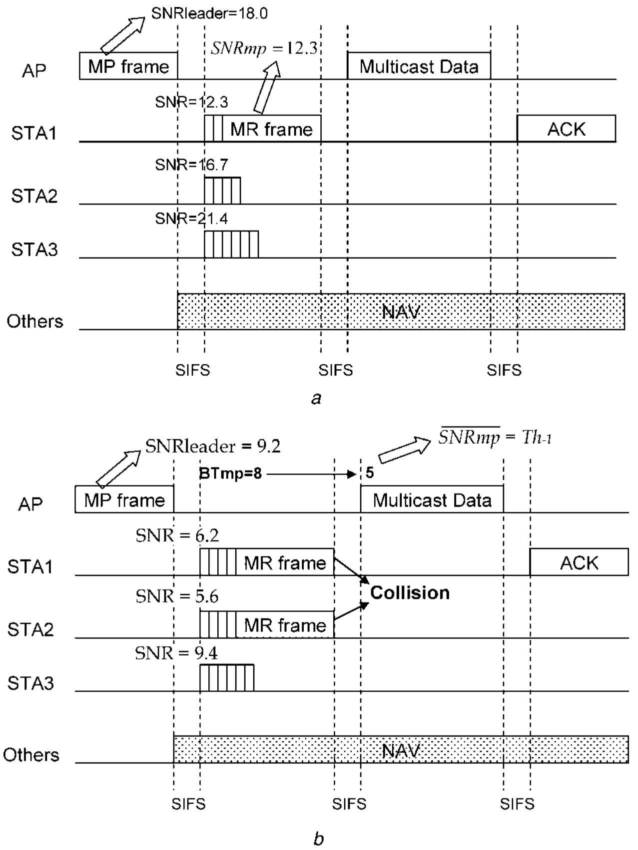

Fig. 3 Feedback information

a Explicit feedback scenario
b Implicit feedback scenario

The AP should already know the value of the backoff timer chosen by the MT to send MR frame. Using (2), the AP can inversely estimate the SNR range with the lowest backoff timer, where BT_{mp} is the current MP_timer value in AP and $\overline{SNR}_{mp}$ is the estimated worst SNR value.

$$\overline{SNR}_{mp} = \begin{cases} 0 & BT_{mp} \geq 6 \\ Th_{\rightarrow 2} & 6 > BT_{mp} \geq 3 \\ Th_{\rightarrow 1} & 3 > BT_{mp} \geq 1 \end{cases} \quad (2)$$

Fig. 3*b* shows an example of implicit feedback scenario of the ARSM mechanism. The AP does not receive the MR frame because both MTs, STA1 and STA2, simultaneously have sent an MR to the AP. The MR frames will collide before the MP_timer of the AP expires. By using the value of the remaining period of the MP_timer of the AP, ARSM is able to estimate the lower bound of MT exhibiting the worst SNR. In this scenario, the worst SNR estimated from the MTs ($\overline{SNR}_{mp}$) is greater than $Th_{\leftarrow 1}$; the AP then chooses the multicast rate corresponding to $Th_{\leftarrow 1}$dB.

No feedback: The AP does not receive an MR frame and the MP_timer of the AP expires. So, none of the MTs in the multicast group reply to the MP frame. This condition occurs when either all the MTs in this group have left or that the MP frame has been corrupted during its transmission. In this case, the AP will retransmit the MP frame after waiting for a period of time defined by the DCF backoff mechanism. The number of retransmission attempts for a given MP frame is limited to 4. When the maximum number of retransmission attempts is selected, the AP assumes that there are not more MTs in the multicast group.

From the description above, it should be clear that the AP can determine the SNR as well as the identity of the MT to

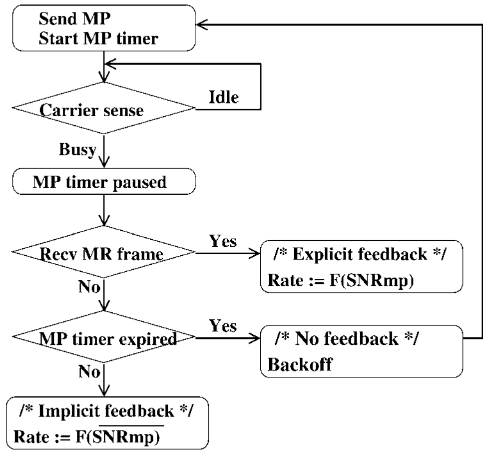

Fig. 4 *MCPO of ARSM*

become the group leader in the first case (explicit feedback). However, if the MR frame collides (implicit feedback), the AP is unable to identify the new leader. In this case, the AP will have to send a second MP frame before sending the following multicast data frame. The new MP frame to be sent out will set the SNR_{leader} field to a negative value. When the MTs in the multicast group receive the MP frame with the SNR_{leader} field equal to a negative value, only those MTs having sent the previous MR frame (the MTs with smaller SNR) sent to this a new MR frame. Since these MTs will have a very similar SNR, they do not use the backoff mechanism based on the SNR of the received signal, but a random value between [0, $CW_m - 1$]. This different backoff mechanism is used to further reduce the probability of collision of the MR frames.

Fig. 4 shows the MCPO procedure of ARSM. As shown in Fig. 4, after having sent an MP frame, the AP will activate its MP_timer with the initial value CW_m. The timer will remain active as long as the AP detects that the channel is busy. If the AP receives an error-free MR frame before the timer expires, it will adapt its transmission rate using the explicit feedback. On the contrary, if the AP receives a corrupted MR frame, once its timer expire, the PHY data rate will be selected based on the implicit feedback mechanism.

3.2 Dynamic multicast data transmission procedure

Through the MCPO described above, the AP can estimate the SNR value of the group leader. In order to reduce the amount of processing to be carried out by the MTs, we propose a dynamic multicast data transmission procedure by making use of several multicast data transmissions. Under this scheme, the AP can be found in one of two different states depending on the feedback signals received.

- While the AP successfully delivers multicast data frame, the MCPO is deactivated. In this state, the AP will adapt its PHY data rate using the SNR value contained in the received ACK coming from the group leader.
- If the AP shows a failure of N_{th} consecutive multicast transmissions (detected via NACKs), it initiates the MCPO.

Fig. 5 shows an example of the operation of the ARSM mechanism. The mechanism starts by using the MCPO in order to determine the multicast group leader. In this example, the group leader becomes STA1 which is the MT with the lowest SNR value. The AP then turns off the

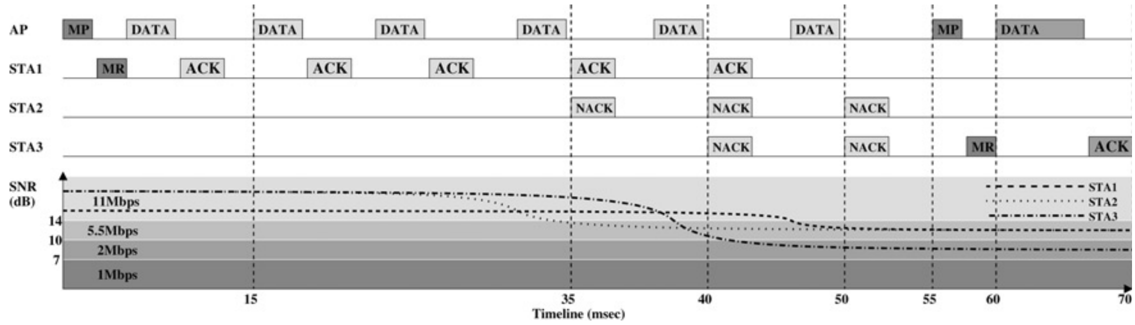

Fig. 5 *Dynamic multicast data transmission procedure*

MCPO and starts sending the data frames. After two successful transmissions, it is assumed that STA2 becomes the MT with the worst SNR. This happens at 35 ms of operation. Since the AP has not become aware of the SNR change of STA2, the AP continues sending the data frames at the same data rate. After the N_{th} transmission failure, the AP turns on the MCPO. With the explicit feedback information from STA3, the AP sets STA3 as the group leader. This happens at 60 ms of operation.

4 Performance evaluation

In this section, we carry out a performance analysis on the effectiveness of our proposed mechanism. Throughout our study, we have made use of the OPNET Modeler tool 11.0 [15], which already integrates the IEEE 802.11 DCF simulator. We have integrated into it the ASRM, RAM and the LBP mechanisms.

4.1 Scenarios

Our performance evaluation has been structured in the following way: first we analyse the performance limitations of the multicast service of the IEEE 802.11 standard. We then evaluate and compare the ARSM, RAM and LBP schemes. To this end, we have conducted two sets of simulations. In the first set, we have studied the performance of the three schemes by varying the size of the multicast group and using three different network sizes, expressed in terms of the area covered by the AP and MTs. In the second set of simulations, we have varied the network size (coverage area) and used two sizes for the multicast groups.

In our simulations, we model an IEEE 802.11b WLAN consisting of an AP, several multicast wireless MTs, and five unicast wireless MTs. All MTs are located within a BSS, that is, every MT is able to detect a transmission from any other MT. The AP is located in the centre of the BSS, the cell size of which will be changed throughout the different scenarios under study. The multicast MTs move randomly within the BSS with a constant speed of 5 km/h, whereas the unicast MTs are static and placed close to the AP. We assume that the unicast packets are always transmitted at 11 Mbps. This set-up of the unicast MTs will allow us to focus on the evaluation of each one of the multicast schemes under consideration. For the ARSM schemes we have found that setting $N_{th} = 3$ is a good compromise to limit the number of MP frames to be sent and the time to react to a change on the network operating conditions. Similar findings have been reported in [14].

In order to model the wireless channel, we have used the Ricean model to characterise the propagation of the signal throughout the medium [16]. When there is a dominant stationary signal component present, such as a line-of-sight propagation path, the small-scale fading envelope has a Ricean distribution. This is often described in terms of a parameter k, which is defined as the ratio between the deterministic signal power and the variance of multi-path fading. If k is equal to 0, the Ricean distribution reduces to the Rayleigh distribution, in which the signal is only transmitted by reflection. In this work, we have set the parameter k to 32.

In our scenarios, we have assumed the use of two types of traffic flows: multicast traffic downlink flows and unicast traffic uplink flows. For the downlink traffic, the AP transmits a video stream to the multicast MTs group. For the video streaming source, we have used traces generated from a variable bit-rate H.264 video encoder [17]. We have used the sequence mobile calendar encoded on CIF format at a video frame rate of 25 frames/s. The average video transmission rate is around 400 kbits/s with a packet size equal to 1000 bytes (including RTP/UDP/IP headers). This video application is randomly activated within the interval [1, 1.5] seconds from the start of the simulation. In order to limit the delay experienced by the video streaming application, the maximum time that a video packet may remain in the transmission buffer has been set to 2 s. Whenever a video packet exceeds these upper bounds, it is dropped. For the unicast traffic, we assume greedy sources. The unicast packet size is equal to 1000 bytes (including the RTP/UDP/IP headers). The unicast sources are also randomly activated within the interval [1, 1.5] seconds from the start of the simulation. Throughout our study, we have simulated the 2 min of operation of each particular scenario.

In the first set of simulations, we have started by simulating a WLAN consisting of five unicast MTs, and three multicast MTs. We have then gradually increased by three the number of MTs in the multicast group up to a maximum of 18 MTs. A multicast group of up to 30 MTs has been used allowing us to characterise the trend of the performance for all schemes. Throughout this first set of simulations, three different network sizes in terms of the coverage area have been considered, namely, a small-sized network with a coverage area of 50 m × 50 m, a medium-sized network of 90 m × 90 m, and a large-sized network of 130 m × 130 m. For the second set of simulations, we have used two different sizes for the multicast group: 9 and 18 MTs per multicast group. The network size has been initially set to a geographical area of 50 m × 50 m. We have then increased the network size in both dimensions by 10 m × 10 m to a maximum network size of 140 m × 140 m.

4.2 Metrics

For the purpose of our performance study, the four metrics of interest are: multicast throughput, unicast throughput, multicast packet loss rate and overhead.

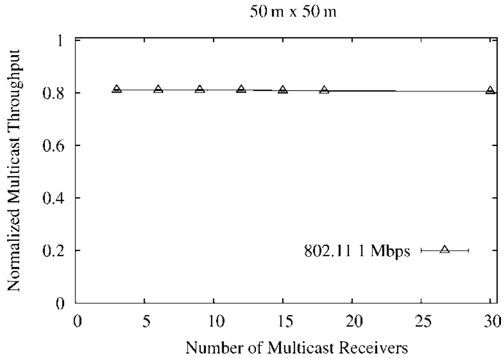

Fig. 6 *Limitations IEEE 802.11 standard for the multicast traffic*

The multicast throughput shows the successfully received average data rate by all the multicast MTs. To be able to better evaluate the various schemes with respect to the optimum case, we plot the normalised throughput rather than the absolute throughput. The normalised throughput is calculated with respect to the multicast downlink traffic generated by the AP.

The unicast throughput shows the total throughput received by the AP from all the unicast MTs. This metric will allow us to estimate the bandwidth not used (available for unicast sources) of each one of the multicast schemes under consideration.

The multicast packet loss rate shows the ratio between the packets not having been received by at least a member MT of the multicast group over the total number of packets submitted to the network.

The overhead is defined as the ratio between the number of control bits (P_{control}) and the total number of bits having been transmitted ($P_{\text{control}} + P_{\text{MulticastData}}$). It is given by

$$\text{Overhead}(\%) = \frac{\sum P_{\text{Control}}}{\sum P_{\text{Control}} + \sum P_{\text{MulticastData}}} \times 100 \qquad (3)$$

and where (P_{control}) will be dependent on the method used.

Our measurements started after a warm-up period (about 3 s) allowing us to collect the statistics under steady-state conditions. Each point in our plots is an average over 30 simulation runs, and the error bars indicate 95% confidence interval.

4.3 Results

In the first part of our performance study, we first look at the multicast service as defined by the standard. We have first considered a small-sized network; this set-up represents the most manageable of all setups being considered, that is, the potential number of corrupted packets is limited. Fig. 6 shows the results for this first scenario. From the results, it is clear that the standard is unable to effectively provide multicast services. This is due to the fact that the standard does not take any action to recover those packets having been corrupted or lost during their transmission. A loss rate of 18% is far below all expectations, especially if we do consider the deployment of video streaming applications.

Figs. 7–9 show the performance results for the ARSM, RAM and LBP schemes, with various transmission rates and network sizes. In the case of small-sized networks, (Fig. 7), all schemes exhibit excellent performance results: a 100% multicast throughput rate. Because of the reduced distance between the AP and the MTs, the quality of the

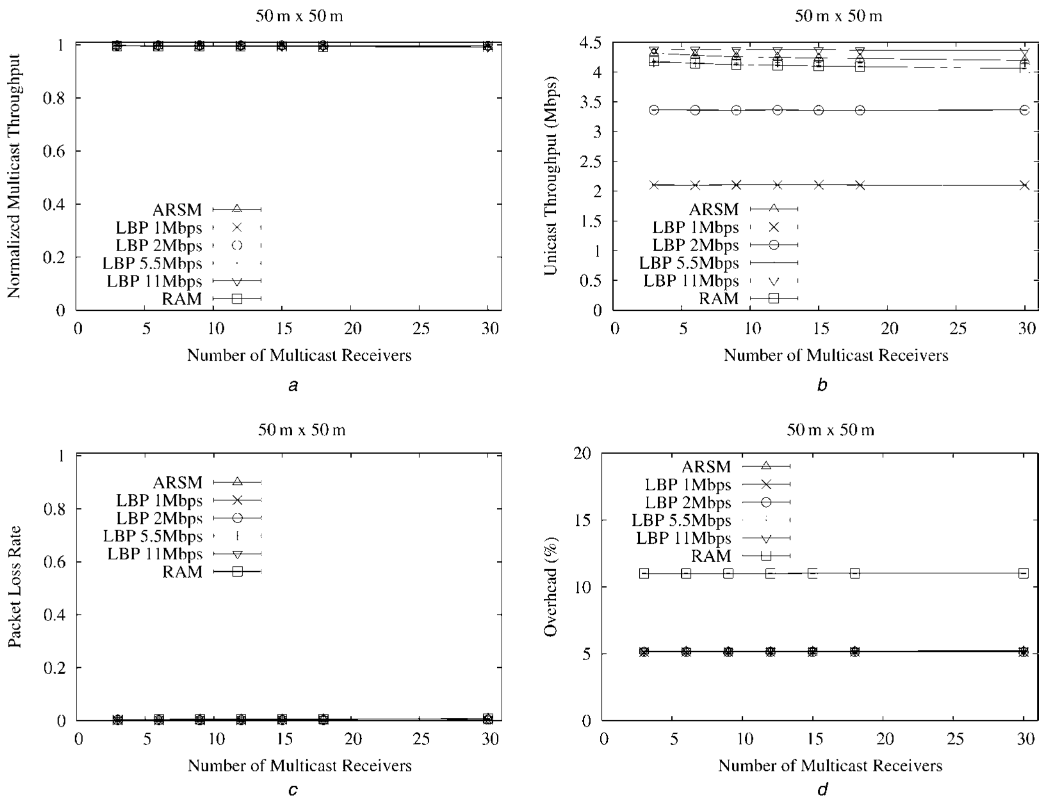

Fig. 7 *Performance evaluation – small size network (50 m × 50 m)*

a Throughput of multicast traffic
b Total throughput of unicast traffic
c Packet loss rate of multicast traffic
d Overhead

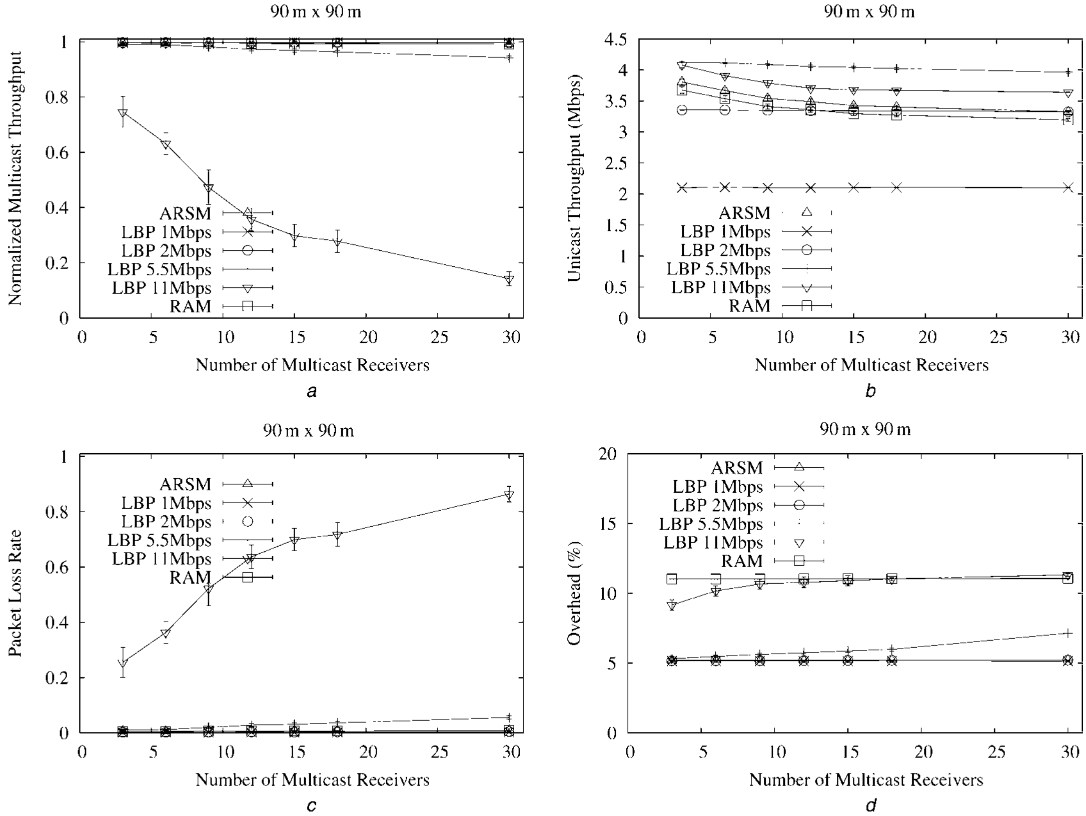

Fig. 8 *Performance evaluation –medium size network (90 m × 90 m)*

a Throughput of multicast traffic
b Total throughput of unicast traffic
c Packet loss rate of multicast traffic
d Overhead

signal is not severely affected. Furthermore, in case of error in the transmission, the ARSM and LBP schemes take care of retransmitting the packets. In the case of the unicast traffic, Fig. 7*b* shows that the LBP scheme offers the best results when the channel rate is set to 11 Mbps. In all other cases, the ARSM scheme offers the best performance results.

Fig. 8 shows the performance results for the ARSM, RAM and LBP schemes operating in a medium–sized network. The results clearly show the benefits of adapting the transmission rates taking into account the channel conditions. While Figs. 8*a* and *c* show that the LBP is unable to provide good support to the multicast service even at rates as low as 5.5 Mbps, the ARSM and RAM schemes are capable of effectively transmitting all the multicast traffic. Regarding the unicast traffic, the ARSM mechanism also exhibits better performance results than the LBP scheme at 1 and 2 Mbps and RAM scheme Fig. 8*b*. On the contrary, LBP will keep transmitting at constant rate regardless of the channel conditions. These results clearly show that the ARSM scheme effectively sets up the transmission data rate to be used for the transmission of the multicast traffic. Fig. 8*d*. shows the overhead for all schemes under study. As seen form the figure, ARSM outperforms the RAM scheme. By requiring the exchange of RTS/CTS control frames for every multicast data frame to be sent, the RAM scheme introduces as much as twice the overhead required by ARSM. On the contrary, the MCPO mechanism used for ARSM is invoked when needed. Fig. 8*d*. also shows that ARSM requires less overhead to properly operate than LBP, except for LBP at 1 Mbps. From the results, it is clear that at high PHY data rates, the AP is forced to retransmit a large number of frames due to the high error rate. The overhead then increases due to the ACK/NACK control frames sent to overcome this anomaly.

Fig. 9 provides the performance results when all schemes are implemented in a large-sized network. A reliable multicast is obtained for ARSM and RAM schemes and when the transmission rate for LBP is fixed to 1 Mbps. For all other rates, the LBP scheme is unable to provide good support to the multicast services. Regarding the unicast traffic, the ARSM mechanism exhibits better results than the ones provided by LBP at 1 Mbps and RAM schemes. This is once again due to the fact that the ARSM scheme requires less overhead to properly operate (Fig. 9*d*). and it transmits the multicast traffic at the highest possible transmission rate taking into account the channel conditions, while LBP will keep transmitting the multicast traffic at 1 Mpbs

Figs. 10 and 11 show the results for the second scenario. Fig. 10 shows the results for all schemes under study for a multicast group consisting of nine MTs and various network sizes. The results depicted in Fig. 10*a* show that ARSM, RAM and LBP (1 Mbps) schemes are able to provide a reliable multicast for all network sizes. For all the other rates, the performance of LBP decreases as the network size is increased. This is expected since adapting the transmission helps to compensate for the signal impairments due to the distance to be covered by the signal.

For the case of the unicast traffic, Fig. 10*b* shows that the ARSM outperforms the RAM and LBP 1 Mbps for all network sizes. Furthermore, in the case of small-sized network, ARSM is even able to deliver twice the load carried by the LBP 1Mbps scheme. The figure also shows

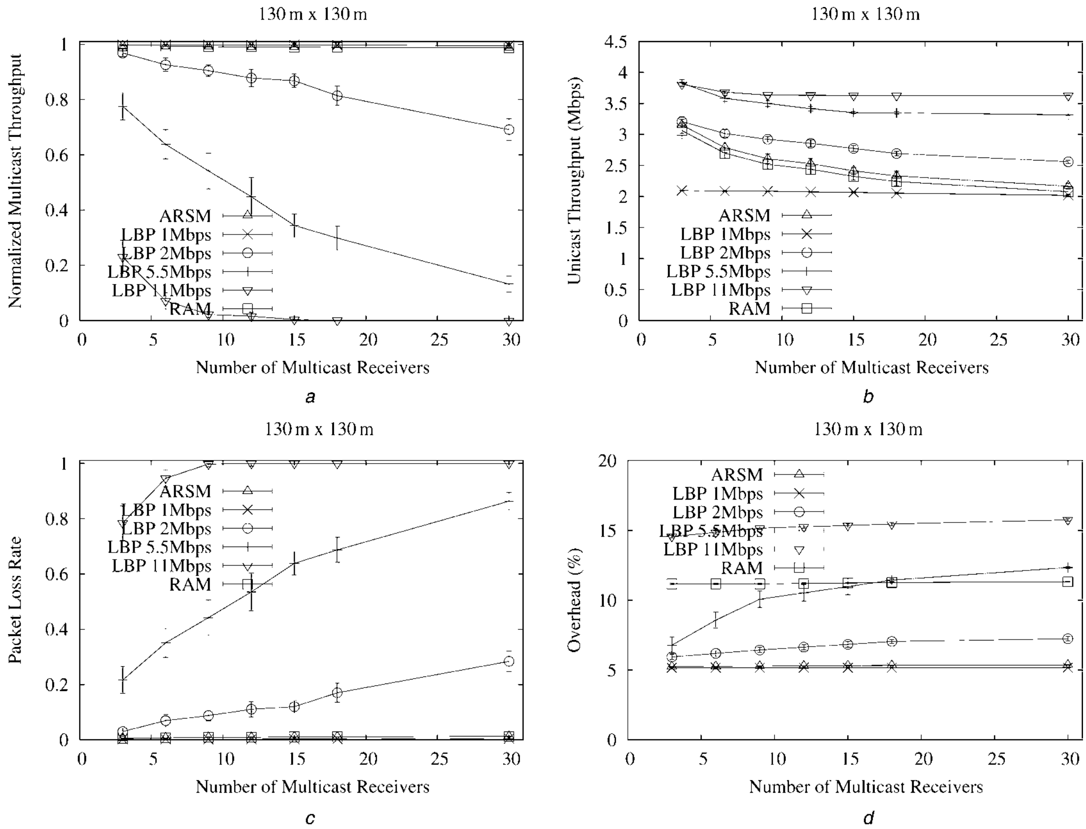

Fig. 9 *Performance evaluation – large size network (130 m × 130 m)*

a Throughput of multicast traffic
b Total throughput of unicast traffic
c Packet loss rate of multicast traffic
d Overhead

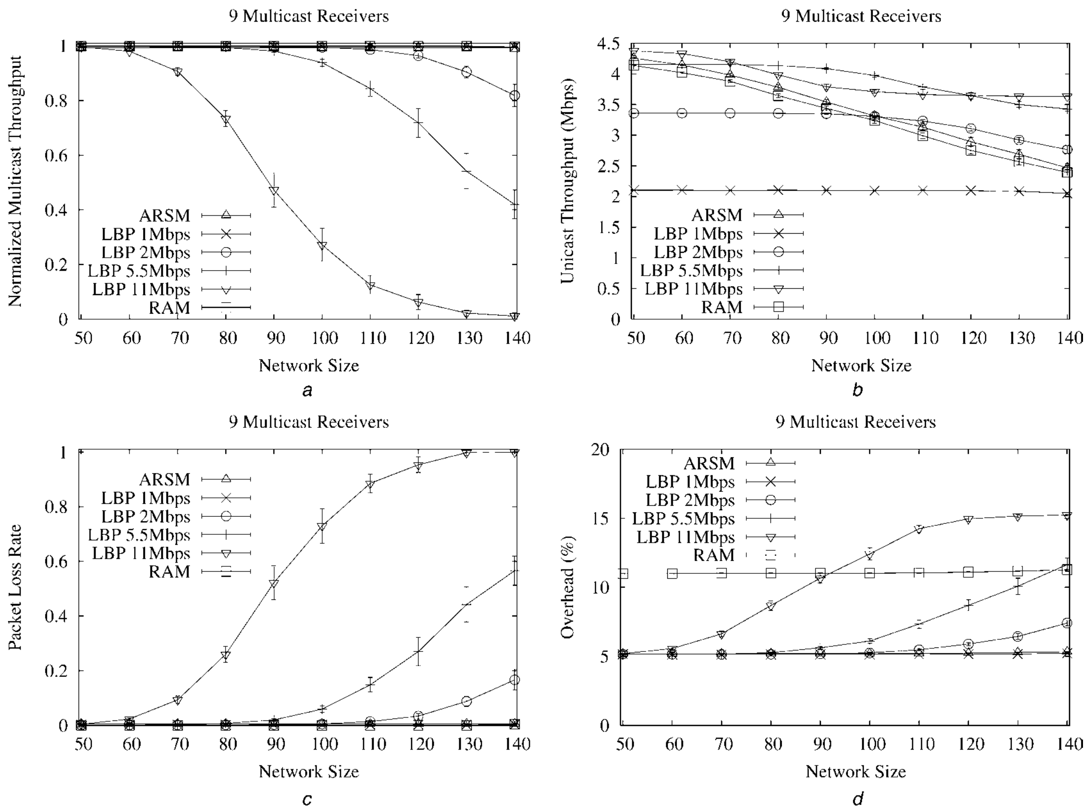

Fig. 10 *Performance evaluation – multicast group size = 9*

a Throughput of multicast traffic
b Total throughput of unicast traffic
c Packet loss rate of multicast traffic
d Overhead

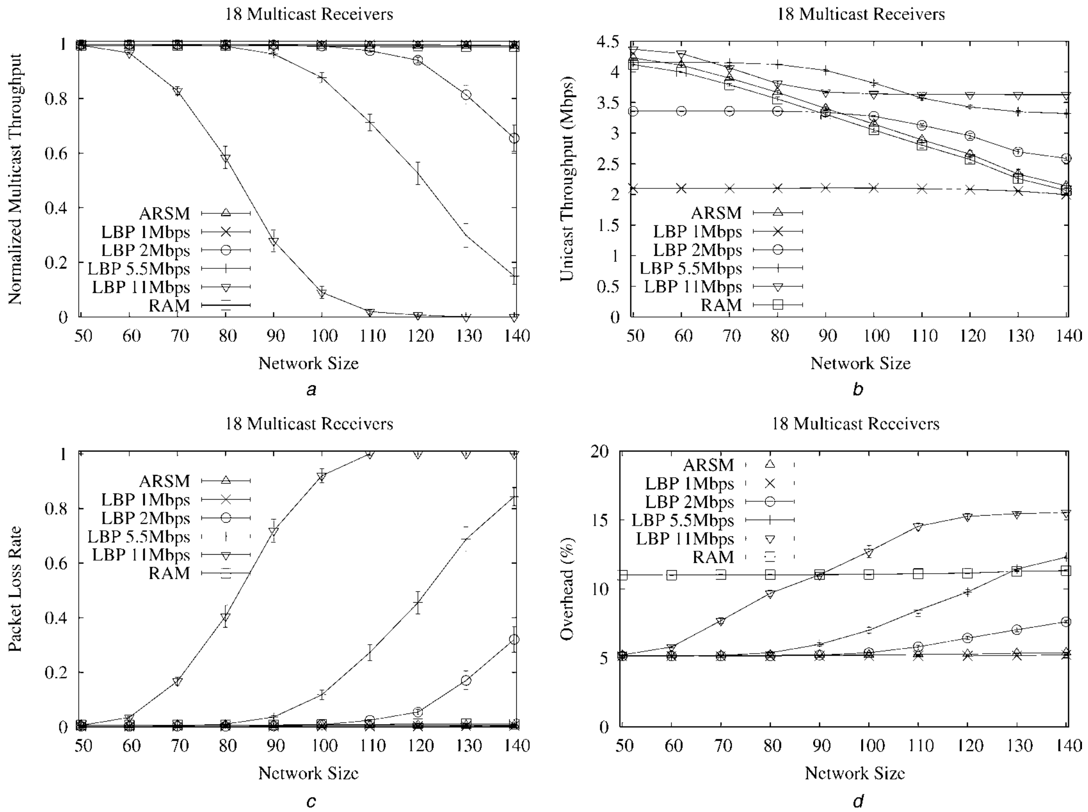

Fig. 11 *Performance evaluation – multicast group size = 18*

a Throughput of multicast traffi
b Total throughput of unicast traffic
c Packet loss rate of multicast traffic
d Overhead

that the ARSM outperforms the RAM and LBP schemes when this latter is able to fully deliver the multicast traffic. Finally, the results in Fig. 11 show that the ARSM scheme is able to cope with large multicast group sizes.

5 Conclusions

We have proposed an adaptive IEEE 802.11 multicast protocol design that takes into account the dynamic channel conditions. This mechanism has been designed following the principles of cross-layer protocol engineering. The mechanism requires knowing the operating conditions of the channel as perceived by the multicast group members. The transmission rate to be used for the multicast traffic is determined based on the feedback received by the group leader. We have also paid particular attention to limit the overhead introduced by the multicast rate adaptation mechanism. We have carried out an extensive campaign of simulations aiming to analyse the impact of various key parameters, mainly the network size and the size of the multicast group, over the performance of the proposed scheme. Our results have shown that the ARSM mechanism outperforms the IEEE 802.11, RAM and LBP mechanisms.

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