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Protocol Independent Multicasting in Wireless Mesh Networks

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Abstract

Multicast in wireless networks received a lot of attention, from ad-hoc networks, to structured multi-hop meshes. However, the support of the standard Protocol Independent Multicast (PIM) protocol has been dismissed as non important (or non feasible), given that its straightforward application on wireless networks does not work properly. In this work we analyse the reasons why PIM standard implementations interacts badly with wireless networks and propose simple countermeasures that do not require modifications of the standard, but only small modifications of the implementation. The Dense Mode version of PIM is implemented in ns-3 and results are presented showing the performance of the protocol and its overheads in mesh networks with fixed mesh routers and both fixed and mobile end-user clients.

1 Introduction

Many entertainment applications, from live streaming of audio and video to gaming, require, or may be enhanced by, multicast distribution. The use of multi-hop, or mesh, wireless networks is rapidly expanding due to their low cost and high bandwidth availability, their intrinsic support for proximity- and location based services, and their simple deployment (often not requiring licencing permits or high capital investments). In a mesh network, each node has a limited view of the whole system, communicating with just several of its neighboring nodes. Hence, routing mechanisms must be used to direct packet flows. Multicast distributions cannot simply rely on the broadcast nature of a single shared wireless medium.

Several protocols have been proposed to address multicast routing in ad-hoc networks [2, 3, 4]. In the latter papers, the authors have constructed efficient multicast mechanisms for mobile ad-hoc wireless networks through the dynamic synthesis of mobile backbone networks. In [5], authors observe how the validity of multicast routing protocols designed for wireline networks is undermined by the broadcast nature of the wireless channel and network dynamics. In [6], the authors consider the use (for wireless multicast) of modified versions of commonly employed wireline multicast routing protocols such as the Distance Vector Multicast Routing Protocol (DVMRP), Multicast extension to Open Shortest Path First (MOSPF), and Protocol Independent Multicast (PIM).

Extending standard wireline Internet multicast protocols to mesh wireless networks is not straightforward, due to the intrinsic differences between the underlying media. Several studies [7, 8, 9] have pointed out that the execution of multicasting in a wireless network under the use of a PIM protocol does not lead to acceptable performance behavior. Nevertheless, to the authors' knowledge, only few works have engaged in studying the use of the PIM-SM protocol [10, 11], across wireless networks; We know of no study that presents analysis of the PIM-DM scheme over wireless ad-hoc networks. Also, its operation over mesh wireless networks has not yet been addressed.

The PIM protocol [12] defines a class of multicast routing protocols which are independent of the unicast routing protocol that is employed. PIM protocols impose the construction of a multicast tree by using the underlying unicast routing tables, assuring the coverage of all distributed session participants. Since building a multicast tree has distinctly different flavors based on the density of the network's destination hosts, two PIM protocol versions have been identified: Sparse Mode (SM) and Dense Mode (DM).

Multicast participants subscribe a specific multicast session they are interested in. A session is formed to include the users that are involved in interactive communications relating to certain applications. A source user that has joined the session is then able to communicate with clients that are members of the same multicast session. The multicast routing protocol is in charge of distributing packets across the network to other members of the multicast session. Routers that are elected members of this multicast session are configured to forward packets to other routers in the same session. Multicast group end-users are attached to some of the routers that are included in the multicast session. Packets of the multicast session are normally flooded on the distribution tree that includes all the routers in the session.

The reason for focusing on the PIM-DM protocol is explained by the following. Considering the networking of packet flows over a wireless mesh networks that are generated by using applications such as live streaming events and gaming oriented processes, we note that user locations will be highly correlated. Consequently, many user nodes that are concentrated over distinct neighborhood clusters will tend to share the multicast tree. Consequently, a dense mode operation is applicable. In turn, over the global Internet, the use of the PIM-SM protocol is employed when conditions are such that the density of user nodes that are interested in a specific multicast, compared to that of the routers, is rather small.

The contributions provided in this paper include the following: *(i)* We discuss whether the PIM-DM protocol scheme can be used over wireless ad-hoc networks as it currently stands, and identify the limitations of its operation; *(ii)* We present a simple mechanism for resolving the identified limitations, enabling the PIM-DM based scheme to properly operate over wireless mesh networks. We perform this task by introducing simple modifications to the protocol's management process, while not changing the protocol itself, so that it remains compatible with the underlying Standard recommendation; *(iii)* We show how the characteristic features of PIM, such as its protocol independence and easy implementation properties, can be effectively exploited; and *(iv)* We present results that depict the performance of the protocol when used over regular wireless mesh networks, providing insight into the process to be used in planning and designing such networks.

The rest of this paper is organized as follows. In Section 2 we provide a brief description of the PIM-DM protocol, identifying mechanisms that adapt its operations to a wireless network. In Sections 3 and 4, we describe our evaluation methodology and the experimental setup, respectively. In Section 5 we present results that confirm the performance efficiency over wireless networks of the Wireless-PIM-DM protocol, as modified by the use of the proposed adaptations. Conclusions and future work notes are discusses in Section 6.

2 PIM-DM Over Wireless Networks

PIM-DM is a data driven protocol that is designed to support multicast sessions where the end-nodes are densely distributed in the network; i.e., the probability that a multicast router has end-nodes attached to it is high. The approach used is based on performing flooding and pruning operations, rather than defining rendezvous points: the source node floods the network with multicast packets and the routers apply the forwarding rule. Whenever a leaf router has no end-user clients for a specific multicast group (or session), it sends a PIM Prune message towards the upstream router; this is used to prune the link branch connecting this leaf node across the multicast tree to this upstream neighbor node. PIM-enabled routers that execute the PIM-DM protocol are called PIM-routers; they construct the multicast tree from the source node towards all PIM-routers that have associated end-nodes, called PIM-clients. PIM-clients join the multicast group, so that the nodes involved in a multicast session are either PIM-routers or PIM-clients.

PIM-DM has been designed for wired networks and it is based on the use of routers' interfaces. These are classified into two categories: upstream and downstream. The upstream interface is the one connecting the router to the next hop router toward the source node, based on the use of the reverse path forwarding (RPF) process. The others are identified as downstream interfaces. The forwarding rule is defined in terms of interfaces: whenever a data packet is received from and upstream interface $\mathcal{U}_{\mathcal{G},\mathcal{S}}$, relative to source node $\mathcal{S}$ for multicast group $\mathcal{G}$, the router computes the set of downstream interfaces $\mathcal{D}_{\mathcal{G},\mathcal{S}}$ to which it will sequentially send P:

$$\forall P \leftarrow \mathcal{U}_{\mathcal{G},\mathcal{S}}, \textsc{Send}\ P \rightarrow d, \forall\, d \in\ \mathcal{D}_{\mathcal{G},\mathcal{S}} \quad (1)$$

Albeit apparently trivial, the operation defined by (1) meets several difficulties when it is applied across a wireless network.

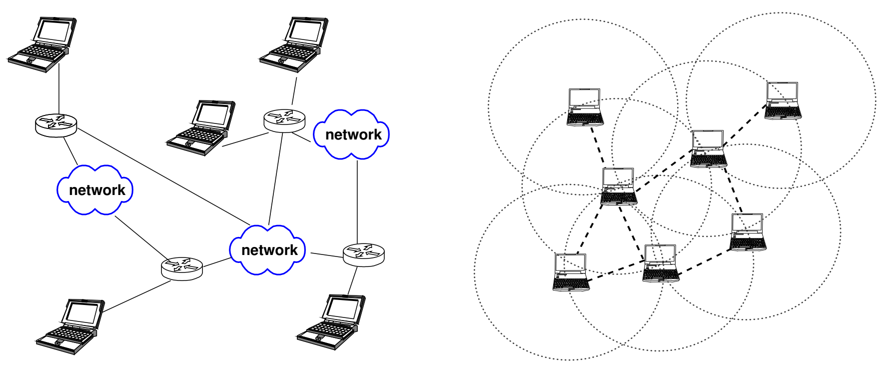

Figure 1: Physical interfaces mapping to routers and subnets for PIM purposes. Left: automatic in wired networks. Right: wrong in wireless networks.

In wired networks, a router's interface provides access to either a specific router or to a subnet. In turn, in a wireless network in which radio broadcast links are used, an interface is usually used to cover all the nodes that are located within the node's radio transmission range, regardless of whether they are end-nodes or routers, and regardless of whether the routers are located downstream or upstream in the multicast tree, or whether they are situated on pruned branches, making the forwarding rule in (1) ambiguous. Fig. 1 exemplifies this difference.

Moreover, it is not known *a-priori* which routers are covered by a wireless link transmission. The correct reception of packets transmitted across such links is highly impacted by channel quality features. Normally, attached to the same interface, we often have an upstream router as well one or more downstream ones, making the forwarding rule in (1) ambiguous.

In case nodes employ a single radio module (say radio a), this module is used to provide for the upstream interface. When a node uses two radio modules (say a and b), radio module a can be employed to realize links along the multicast tree; radio b is often used for host access purposes, or to collect packets from source nodes. In the latter case two situations are possible: *i)* the multicast packet P is received on b (the end-node's interface) which means that the source $\mathcal{S}$ is attached across this interface; the received packet is forwarded by module a (if the interface has not been pruned); or *ii)* the multicast packet P is received by module a; Since a is the upstream receiving module, the only radio module that can forward the packet is module b, so that the multicast delivery process is interrupted. Under this scenario, the packet P is able to reach at most the second level of the tree.

This problem is caused by having the interfaces along the wireless network correctly (from the PIM and multicast point of view) matched among the routers' interfaces and the proper subnets. To solve this issue, we propose to properly define the concept of 'virtual interfaces', and configure them by having them serve to provide proper mapping between router interfaces and and designated subnets. We then operate the PIM protocol scheme by using virtual rather than physical interfaces. This is described as follows. Let a virtual *Wired Equivalent Interface* (WEI) be defined as the pair {<physical interface>; <router/subnet>}. A WEI is the interface used to reach a single neighboring (i.e., reached within a single hop) router, or a group of end-nodes residing in the same IP subnet in the wireless network. In this manner, a wireless node with one interface, N neighboring router nodes and M subnets, will configure $N + M$ WEIs. Notice that in a mobile or in general a dynamic mesh network the number of WEIs must be continuously adapted to the changing physical topology of the network.

This definition of WEI resolves the above mentioned problem, since it allows routers to properly classify upstream and downstream WEIs, as illustrated in Fig. 2. WEIs retain the same properties (w.r.t. PIM) as those displayed by the use of wired interfaces, so that upstream an downstream WEIs can be used as the standard interfaces for operating in accordance with the PIM process. The associated introduced overhead rate is noted to be negligible.

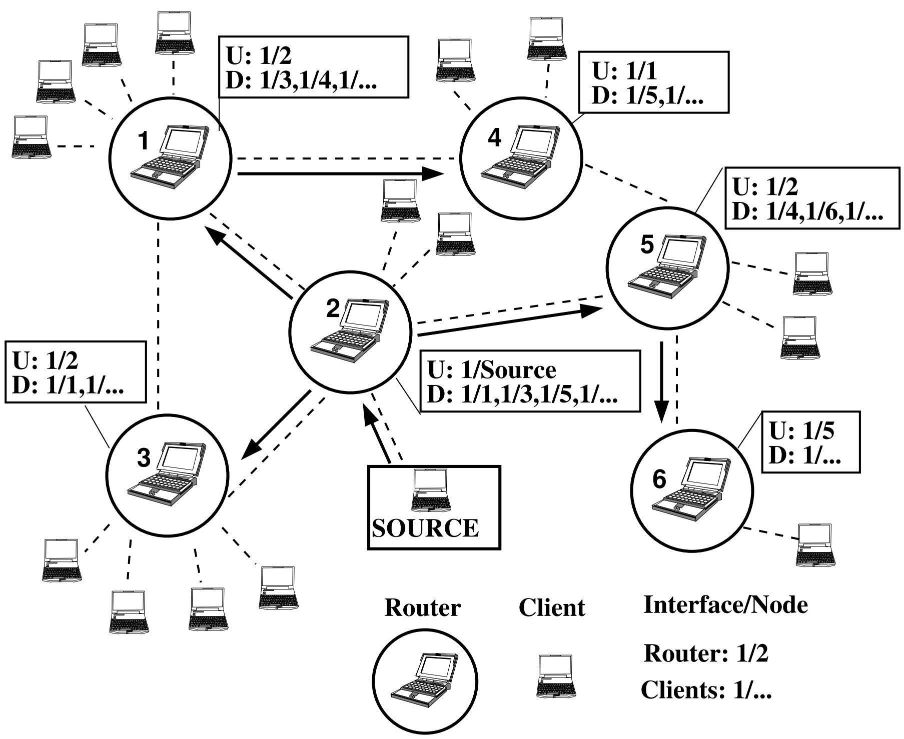

Figure 2: Matching WEIs to routers and IP subnets for single physical interface.

However, without the use of proper countermeasures, such an operation will introduces additional traffic, because each node will separately transmit a multicast packet P across each one of its downstream WEI. The latter packet transmissions are sent and received across a single physical channel. This overhead may lead to traffic congestion,channel saturation, increased collision rates and transport quality degradations. To avoid creating such excess overhead, we dynamically cluster WEIs into $\mathcal{D}_{\mathcal{G},\mathcal{S}}$ oriented groups based on their physical interface, and then instruct the router to transmit only a single copy of P across the designated group. In this manner, we exploit in an effective manner the broadcast nature of the wireless medium, making also use of the structure of the IP multicast process under which the destination address is used to identify the IP multicast group. Such an implementation is readily performed by adding a few program lines to the code that defines the operation of the Wireless-PIM-DM scheme. No change is induced in the actual definition or scope of the protocol's multicasting delivery mechanism.

In this manner, the processes used to compute WEIs and to group them lead to a consistent operation of the protocol over wireless networks, yielding a simple and transparent modification to PIM.

Another challenge is represented by the network's topological layout. Wired networks are generally static, so that the lifetime of interfaces is long and statically mapped to subnets (unless router failures occur). On the other hand, due to nodal mobility or link degradation events, this is not the case in wireless networks. The resulting topology is continuously changing and may contain nodes, or clusters of nodes, that are temporarily isolated either from the entire network or from specific routes. Isolated nodes may not be able to receive multicast packet transmissions. To determine the impact of changing topological layouts and nodal mobility on the multicast operation of the PIM-DM protocol, experimental and/or simulation evaluations must be carried out. The identification and possible resolution of induced issues and multicast distribution degradation phenomena depend also on the underlying unicast routing protocol that is employed (e.g., on the speed at which a link failure is detected and eventually recovered) and on the involved scenario (e.g., including the frequency of topology change and the characteristics of involved isolated nodes).

3 Performance metrics

The notation we use in this paper is reported in Table 1. We use the following metrics to assess the performance efficiency of the Wireless-PIM-DM protocol scheme introduced above:

Symbol	Description
$\mathcal{S}$	Multicast source
$\mathcal{G}$	Multicast group
$\mathcal{V}$,	Set of PIM-routers
$\mathcal{K}$,	Set of PIM-clients
$\mathcal{C}$	Set of data packets
T	Simulation time
T_{ss}	Stability period in PIM
P	Generic packet/chunk of the stream

Table 1: Notation and symbols used in the paper.

Control messages traffic We measure the control traffic rate generated by configuring and employing WEIs, exploiting the broadcast properties of the wireless channel. Usually, control traffic is related to protocol reactivity to discover node failures, or to identify changes in network topology. We monitor both transmitted and received message flows, for both control and data traffic, computing the involved control to data message ratio. The involved control message is set as

$$H_m(j) = \frac{1}{T}\int_{t=0}^{T} h_m(j,t)dt \tag{2}$$

$$\overline{H_m} = E[H_m(j)] \tag{3}$$

where $h_m(j,t)$ designates the control traffic level involving either transmitted or received packets processed at PIM-router j at time t, while T represents the duration of the scenario that is simulated. Eq. (3) defines the average control message rate, averaged over all involved PIM-routers.

Convergence time We measure the actual time needed to build the multicast tree. The protocol process is said to converge when the process that involves the distribution of all PIM Prune/Join messages reaches steady state. Clearly, the protocol continues to maintain the tree and dynamically adapt it to changes the topology or in the identity of PIM-clients. Assume that the protocol convergence rate is faster than nodal mobility rate. Steady state is reached when PIM-routers stop exchanging Join/Prune messages for a suitable period of time T_{ss}. This period is defined as a function of the PIM-DM timeout, i.e., the idling time after which the tree is rebuilt and Join/Prune messages are sent againfrom maintenance purposes:

$$\tau_c = \min\{t \,|\, \forall j \in \mathcal{V}, (h_p(j,t,T_{ss}) = 0) \wedge (h_n(j,t,T_{ss}) = 0)\}$$

where $h_p(j,t,T_{ss})$ and $h_n(j,t,T_{ss})$ represent the number of Prune and Join messages transmitted/received at PIM-router j within a time interval $[t \div t + T_{ss}]$, while $\mathcal{V}$ is the set that consists of the involved PIM-routers. The convergence time τ_c is influenced by the topology, the number of PIM-clients subscribing the multicast group $\mathcal{G}$, and also by the amount of data transmitted by the source $\mathcal{S}$ since PIM-DM is data driven.

Data delivery Defines the fraction of issued multicast packets P that are successfully delivered to PIM-clients. Clearly this metric depends on the topological layout, the number of PIM-clients subscribing to multicast group $\mathcal{G}$, and also on the type and intensity of the multicast traffic flow. In our experiments, we have computed this metric by running a video streaming session originating at a source $\mathcal{S}$ that is external to the wireless network, so that the stream is injected into a selected PIM-router that is acting as a gateway node. We set the streams rate to 1 Mbit/s with constant size chunks of 1200 bytes, so that they fit in a standard Ethernet packet. The stream from the source $\mathcal{S}$ has not impairments before entering the wireless mesh. We have then measured, over the duration of the process, the number of received and missing video chunks, at every PIM-client, as well as accounted for duplicate copies due to multiple wireless transmissions triggered by PIM-DM from different PIM-routers, which are all within reception range from the target PIM-client. We have also measured the end-to-end delay levels incurred by delivered data packets. Let i be the generic PIM-client, while $\mathcal{K}$ is the PIM-clients set, and P the generic chunk/packet of the multicast stream. The fraction of chunks received by PIM-client i is computed with using Eq. (4), while Eq. (5) is used to compute the throughput rate when averaged over all PIM-clients. Eq. (6) and (7) are the complement, i.e., the chunk loss rate.

$$R_P(i) = \frac{1}{|\mathcal{C}|} \sum_{P \in \mathcal{C}} r(P) \ , \quad r(P) = \begin{cases} 1 & \text{if } P \text{ is received} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$\overline{R_P} = E[R_P(i)] \tag{5}$$

$$L_P(i) = 1 - R_P(i) \tag{6}$$

$$\overline{L_P} = E[L_P(i)] \tag{7}$$

where P is the generic chunk/packet of the multicast stream, and $\mathcal{C}$ is the set of packets composing the stream. We note that packet duplication is unavoidable on wireless networks, and can also be employed for positive spatial redundancy, but it obviously has a cost in terms of network load. A PIM-client receives normally one or more copies (one from its upstream PIM-router, and others from PIM-routers within reception range that have PIM-clients associated). An excessive number of duplicates may indicate that the network design and topology is not optimal, and will definitely indicate a potential congestion problem on the wireless channel. Eqs. (8),(9) are used to compute the average number of packet copies C_P received by PIM-client i, and the overall level $\overline{C_p}$ when averaged over all PIM-clients. Notice that this measure is meaningful only when the $R_P(i)$ is very close to 1.

$$C_P(i) = \frac{1}{|\mathcal{C}|} \sum_{P \in \mathcal{C}} c(P) \tag{8}$$

$$\overline{C_P} = E[C_P(i)] \tag{9}$$

In addition, the chunk's diffusion delay is defined in eq. (10) as

$$\delta_i(P) = T_i(P) - T_{out}(P) \tag{10}$$

$$\overline{\delta}(i) = \frac{\sum_P \overline{\delta}_i(P)}{|\mathcal{C}|} \tag{11}$$

where $T_i(P)$ is the time in which PIM-client i receives the chunk P, while $T_{out}(P)$ is the time the source generates P, while Eq. (11) measures the average chunk diffusion delay at PIM-client i.

4 Experimental setup

We have implemented the Wireless-PIM-DM [13] scheme within the ns-3 [14] simulator. This module will be made available to the research community after completing the documentation and code integration; prior to the latter, it is available on request from the first author. The protocol complies with the standard PIM-DM, and the implementation is modified in accordance with the Wireless-PIM-DM scheme described in Sect. 2 based on the WEI approach.

Since the IGMP (including the processes for session setting and end-user joining) protocol has not yet been implemented in the current version of ns-3, we have implemented a simple group membership protocol.

After a brief description of the wireless environment, we will describe the scenario used to analyze our wireless implementation.

Large-scale propagation models have been used to compute the path loss between transmitter and receiver pairs under different channel conditions. Theoretical and measurement based models show that the average received signal power (in dB units) across a link decreases logarithmically with distance.

We set the transmission power to 16 dBm, as commonly used by wireless platforms; We use the Log-Distance path loss model to model power attenuation as given by Eq. (12) with the path loss exponent $n = 3.5$, which is

Parameter	Value
TxPower	16 dBm
EnergyDetection	-95 dBm
CCA 1 Threshold	-62 dBm
Reference Loss $(\overline{PL_0})$	30 dBm
Path loss exponent n	3.5
Simulation time	180 s
Runs	20
Stream rate	1 Mbit/s
Packet size	1200 bytes
PIM-clients speed	1.4 m/s
TxRange	[15÷40] m
PIM-routers topology	4x4 grid

Table 2: Parameters used in the experiments.

suitable for an urban scenario [15], while the reference loss is set to 30 dB; d_0 is the reference distance (i.e., one meter), and d is the distance between transmitter and receiver:

$$\overline{PL}(dB) = \overline{PL_0} + 10\, n\, log\left(\frac{d}{d_0}\right) \tag{12}$$

To focus on the behavior of PIM-DM, the impact of fading effects is left for future work.

In our experiments, we use the IEEE 802.11 MAC scheme [16] as the simulated MAC protocol. The channel data rate is set to 54 Mbit/s. The parameters used in our experiments are summarized in Table 2. To compute the radio transmission range (identified as the $TxRange$), we have simulated a simple source-sink scenario where the sink was made to move away from the source at speed of 1 meter/sec. The average radio transmission limit for such a configuration is obtained to be equal to 45 meters. We used the AODV [17] mechanism as the underlying ad-hoc unicast routing protocol. We observe that the proposed protocol will work equally well with other unicast routing protocols, as the latter interact through queries to the unicast routing table. Although our Wireless-PIM-DM protocol accounts for mobile PIM-routers, in this paper, we focus on demonstration the operation of our proposed scheme for a static mesh network layout. Thus, PIM-routers are fixed in place while PIM-clients may roam over a specified region that is served by these PIM-routers. Future studies will account for the accommodation of mobile PIM-routers.

The first scenario involves a wireless mesh network that consists of 16 fixed PIM-routers arranged in a 4×4 grid. The distance between two adjacent nodes in the grid is used as a parameter in our simulation. It is set to be no longer than the radio propagation range (i.e., 45 m). The number of PIM-clients is also used as a parameter in our simulation, varying over the range $[1 \div 238]$. PIM-clients are placed randomly within radio propagation range of the PIM-routers.

We analyze the performance of the protocol as groups of clients move within the network, resulting in activation and, at times, deactivation of several PIM-routers. In the second scenario, we use a Random Waypoint Mobility model [18] to model the mobility of a group of PIM-clients over an area which is covered by the installed static PIM-routers. A typical representation of this scenario may be a university campus scenario, where roaming students access the network to view academic news or sports events. Groups of students may move from one area (e.g., a lecture building) to another one at given speed, waiting for a given time (i.e., the pause time) before moving again. We set a group speed of 1.4 m/s, which represents the speed of an average pedestrian; the pause time is 40 s, allowing four changes of positions to occur during the simulation run time. Each simulation run lasts for 180 s. Performance results have been calculated by averaging over 20 runs, varying seed levels; the settings serve to permit convergent behavior and guarantee high confidence levels.

5 Simulation Results

In Fig. 3, we depict the average convergence time of our protocol scheme, for both the static and roaming scenarios. We observe it to show that the wireless PIM-DM protocol converges rather quickly, independently of the number of PIM-clients. Although one may expect a longer convergence time for the mobility scenario, this is noted to not be the case. By increasing the number of PIM-clients, we note that a set of several PIM-routers is selected to form a multicast tree, such that the same routers are employed in feeding roaming clients with multicast packets for the complete duration of the session. We observe the average protocol convergence time to be limited to 8 s; it increases (slightly) to 11 s when the network serves a smaller number of clients. In this case, several PIM-routersare pruned.

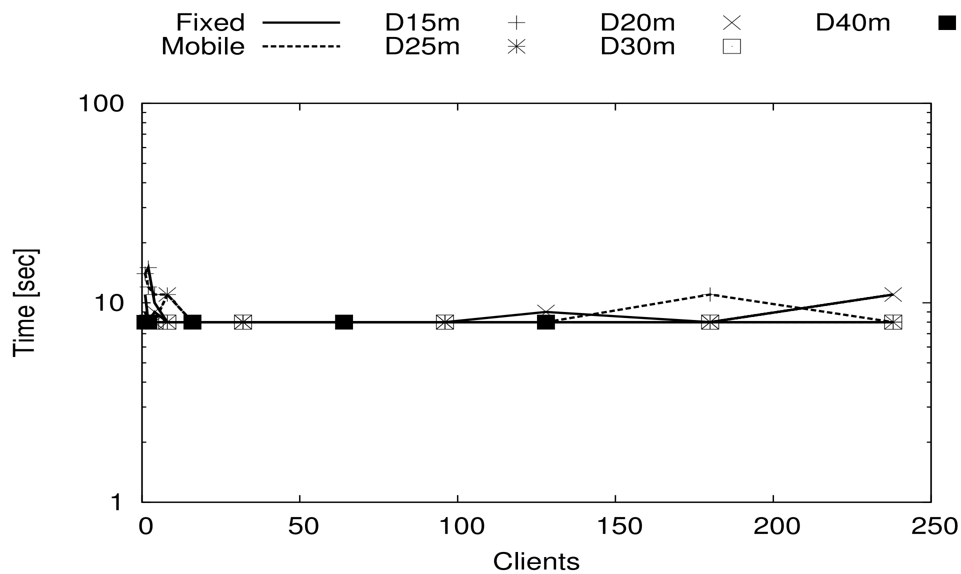

Figure 3: Average convergence time τ_c for static and roaming clients.

Fig. 4 displays the average transmitted and received traffic levels, including both control and data messages. We observe that the control traffic overhead $\overline{H_m}$ is affected only marginally by the number of PIM-clients, except for the case that involves many fewer PIM-clients. In the latter situation, many PIM-routers issue prune messages and are removed from the multicast tree. Hence, we observe that the control traffic rate level incurred is related to the average level characterizing the distance between PIM-routers. By increasing the grid range used for the placement of PIM-routers, we reduce the ensuing control traffic overhead rate, noting it for the underlying scenario to decrease from 10 kbit/s, when the grid range is set to 15 m, to 500 bit/s for a grid range of 40 m. The increase of the distance between PIM-routers reduces the size of the overlapped area, resulting in a reduction of prune and graft messages. We conclude that the resulting PIM-DM associated control traffic rate generated with the incorporated use of WEIs and dynamic grouping does not represent a bottleneck element in the system. Its level is noted to be comparable, if not lower, than the traffic rate generated by a typical unicast ad-hoc routing protocol.

Similar observations are made for the roaming scenario shown in Fig. 5.

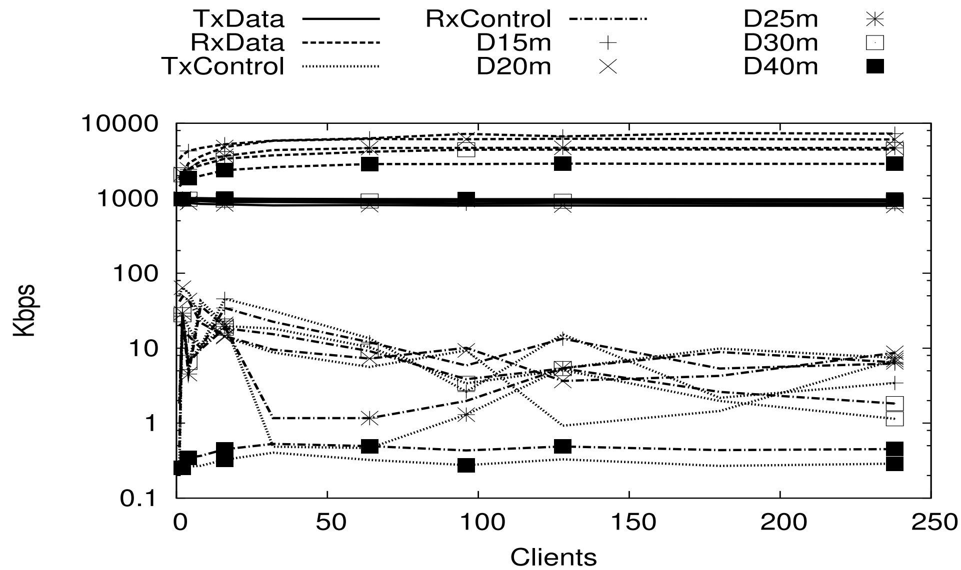

Figure 4: Average traffic rate generated by PIM-routers with static clients.

Here, we observe that the control traffic overhead rate is slightly higher than that generated under the static scenario. As they travel, roaming nodes may either activate or deactivate certain PIM-routers, resulting in graft or prune messages that are used for join or leave operations.

Let we focus on the scenario with 128 static PIM-clients shown in Fig. 6. We observe both transmitted and received datarate per node. Small grid range values (i.e., 15 m) results in a dense network where nodes are closers, increasing the collision probability and the channel contention, leading to a lower average transmission rate while increasing the number of copies received; By increasing the grid range up to 40 m, the network is more sparse, PIM-routers have a few neighbors, reducing the probability of collisions, leading to a trasmission rate closer to streaming rate (i.e., less packets are actually lost) and a lower number of copies received. We remark that PIM-clients receive copies from the other PIM-routers that have clients attached, due to the broadcast nature of the wireless medium.

Similar observations are made for the mobility scenario. We however observe a moderate increase in received traffic rate than that incurred under the static scenario. This is induced by the mobility of PIM-clientswhich activate several PIM-routers during their travel, leading PIM-clients to receive sev-

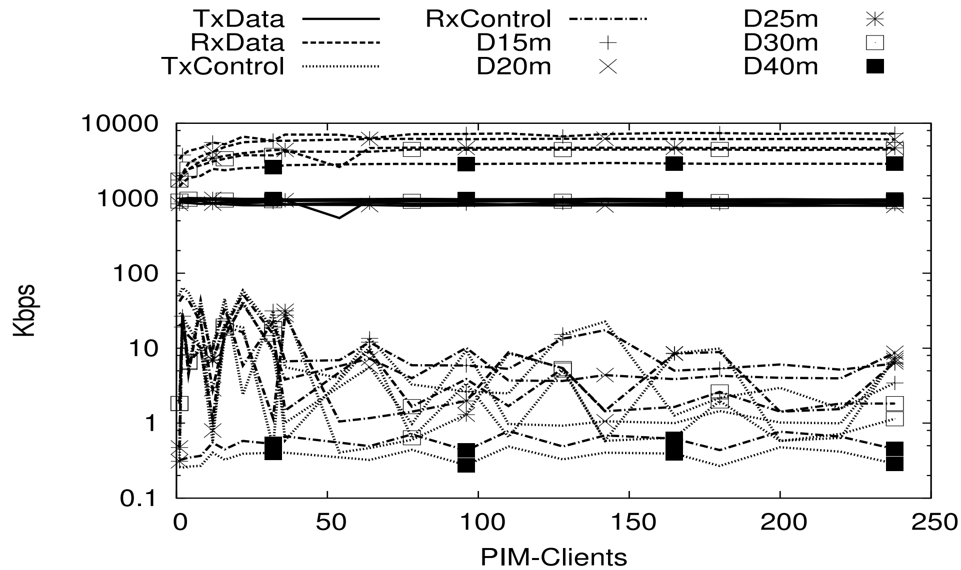

Figure 5: Average traffic rate generated by PIM-routers with roaming clients.

eral copies of the same packet, resulting in an increasing rate of data traffic received. In addition, PIM-routers activation implies an higher level of congestion on the channel, resulting in packet collisions, as shown in the traffic transmitted rate, that is lower than the streaming rate, as well as lower than that in the static scenario.

Fig. 8 shows the average fraction of packets correctly received, missed and duplicated at PIM-clients, under different distance levels between PIM-routers. We conclude that the protocol operation scales well as the number of PIM-clients grows, limiting the fraction of missed chunks to a value that is lower than 0.02 in dense networks (i.e., for PIM-routers inter-distance levels of 15 m). By increasing the PIM-routers' inter-distance level to a value that is close to the maximum allowed range (i.e., 40 m), the average fraction of missing chunks increases slightly, but is still lower than 0.05. The relation between missing/duplicate chunks and the distance between PIM-routers is obvious: PIM-clients are used to recover missed chunks by using the duplicate ones received by other PIM-routers. Thus, (i) short distance values result in a higher rate of duplicate chunks, which reduce the fraction of missed chunks, while the control message overhead increases; (ii) The use of longer ranges results in a reduction in the number of duplicate chunks, lead-

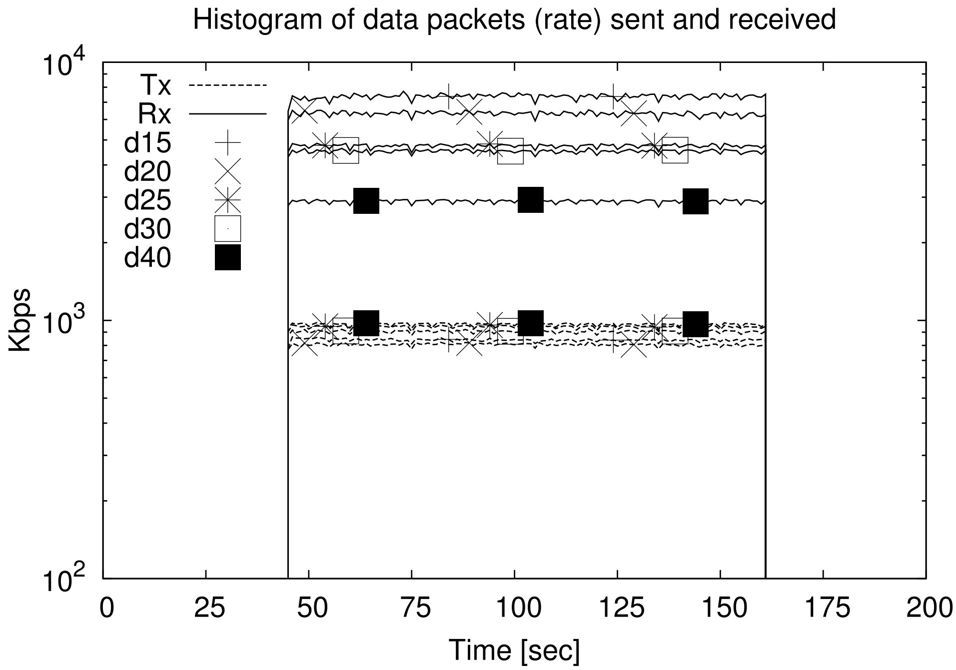

Figure 6: Histogram of the average traffic rate generated by PIM-routers with 128 static PIM-clients.

ing to an increasing fraction of missed chunks, while reducing the control message overhead (i.e., reducing prunes). The 40 m configuration performs better than the 30 m one, as explained in the following. By increasing the distance between PIM-routers, we reduce the probability of frame collision events, increasing the spatial diversity element (spatial reuse factor) of the operations. The gap is present until we add more PIM-clients that activate all PIM-routers, making both configurations exhibit similar performance results. The fraction of received chunks is about 98% (for grid range of 15 m) and 95% (for grid ranges of 30 m and 40 m). As we have expected, the distance between PIM-routers in the grid plays an important role, limiting the number of missed chunks, or increasing the number of replicas. In particular, in a dense grid (i.e., 15 m), PIM-clients receive on average about 8 replicas per chunk, while when stretching the grid (i.e., to 40 m), the corresponding value drops to about 2 replicas per chunk.

Fig. 9 provides the same information for the second scenario, where PIM-clients move within the area covered by PIM-routers. Although we expect

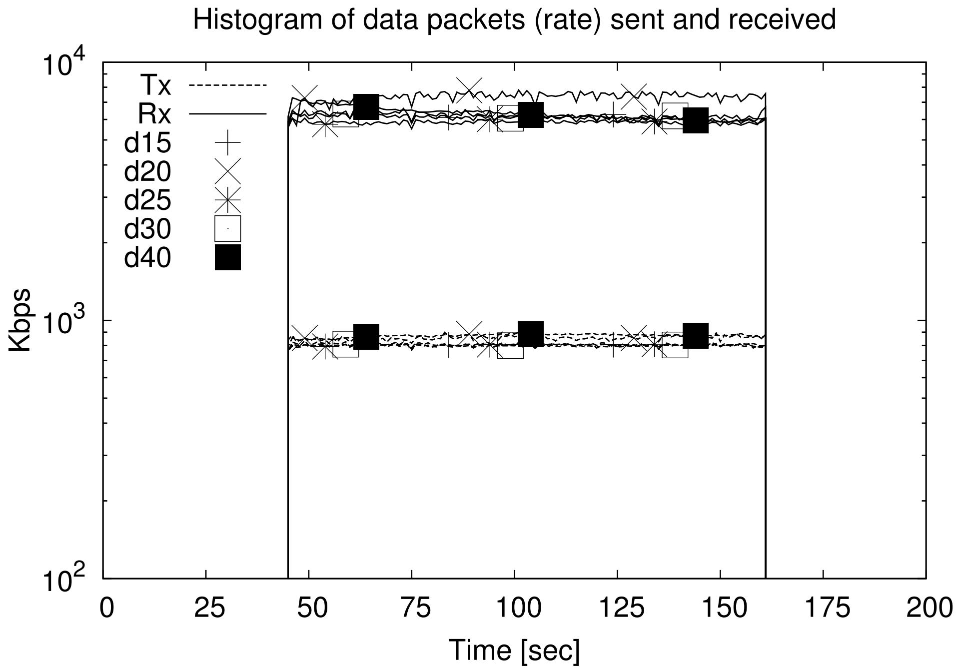

Figure 7: Histogram of the average traffic rate generated by PIM-routers with 128 roamingPIM-clients.

a moderate increase of the fraction of missing chunks, this is not observed to be the case. Rather, we have observed a slight increase to take place in many cases, and at times, we noted the rate to be reduced. This is explained by noting that: PIM-clients, during the roaming phase, (i) might receive chunks from those PIM-routers that are broadcasting packets to other PIM-clients; and (ii) might activate PIM-routers, increasing the number of duplicate chunks, and thus reducing the fraction of missed chunks; and (iii) the pause time is not short (i.e., 40 s), holding their positions for a moderate amount of time.

Next, we focus on a particular configuration involving 128 PIM-clients. The cumulative cumulative distribution function (CDF) of the average chunks diffusion delay is shown in Fig. 10. We consider only those nodes that have received at least 95% of all the chunks, for both the static and roaming scenarios. As observed above, the grid range level affects the chunks delivery delay, since by increasing it, the number of PIM-routers traversed by each

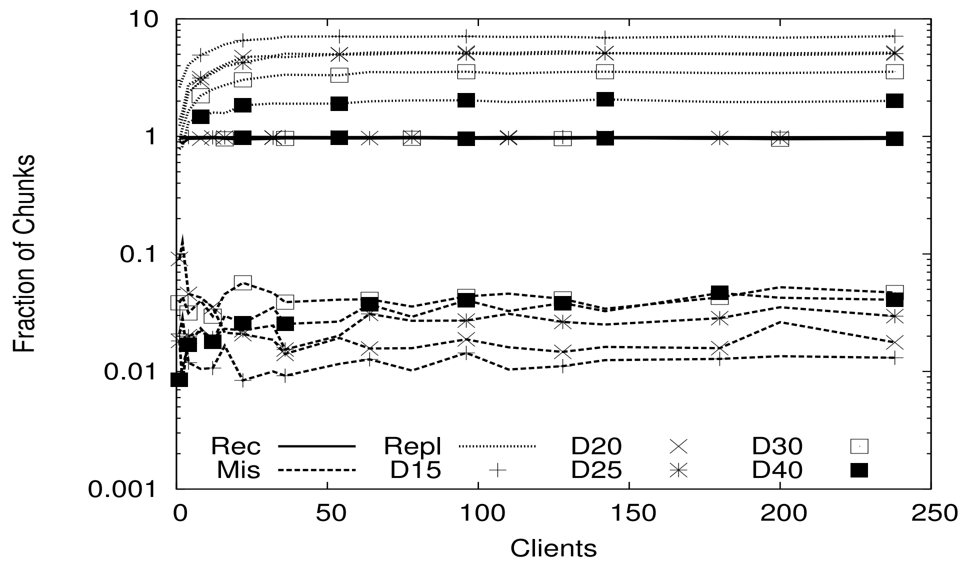

Figure 8: Fraction of chunks received, missed, and replicas for static PIM-clients.

chunk, in reaching all PIM-clients, increases. Moreover, we observe that PIM-clients that are associated with PIM-routers that are located closer to the source node will receive chunks that have experience lower delay values than those associated to PIM-routersthat are located at a longer distance. Similar observations are made for the mobility scenario. We however observe a moderate increase in the chunks' diffusion delay than that incurred under the static scenario. This is induced by the mobility of PIM-clients. We note the involved delay level to be lower than about 10 ms, so that it does not hamper the distribution effectiveness of real-time multicast traffic flows.

Next, we analyze the system scalibity on the average chunks delay. Fig. 11 shows the average chunks delay in a network with 64 and 238 static PIM-clients. We observe the chunks delay is not affected by the number of PIM-clients, thus the protocol scale well with the number of PIM-clients. Similar observation can be done for the mobility scenario in Fig. 12, where we

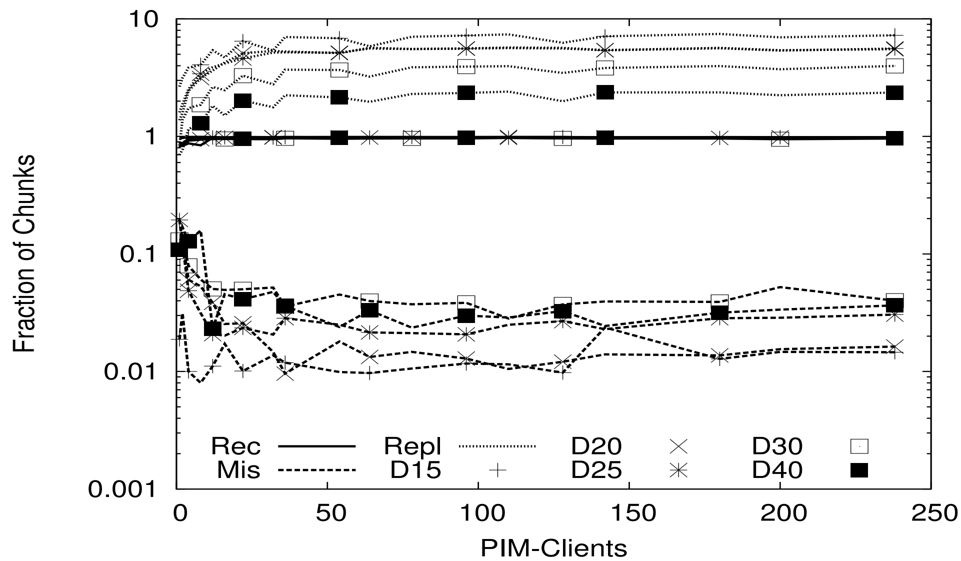

Figure 9: Fraction of chunks received, missed, and replicas for roaming PIM-clients.

6 Conclusions and Future Directions

In this paper, we introduce a "wireless" version of the PIM-DM protocol and verify that it works properly in mesh networks with ad-hoc routing and both static and mobile clients. The approach proposed is to slightly modify the wireline version of the PIM-DM protocol using Wired Equivalent Interfaces (WEIs), that avoid the ambiguity between upstream and downstream interfaces, that is the main reason why PIM does not work properly in wireless networks.

We show this modification to yield a Wireless-PIM-DM protocol version that works properly across a wireless network, while demanding only minor changes to be applied to the commonly employed protocol. In illustrating the performance of a wireless network system that uses the modified protocol, we consider a network system that serves static or roaming users that connect to a wireless mesh network. We show that Wireless-PIM-DM is capable of scaling well with the number of clients. Through the use of an illustrative video streaming session, we demonstrate the underlying system to yield effective throughput and packet delay performance behavior.

Future work can develop along several directions. First, we plan to exam-

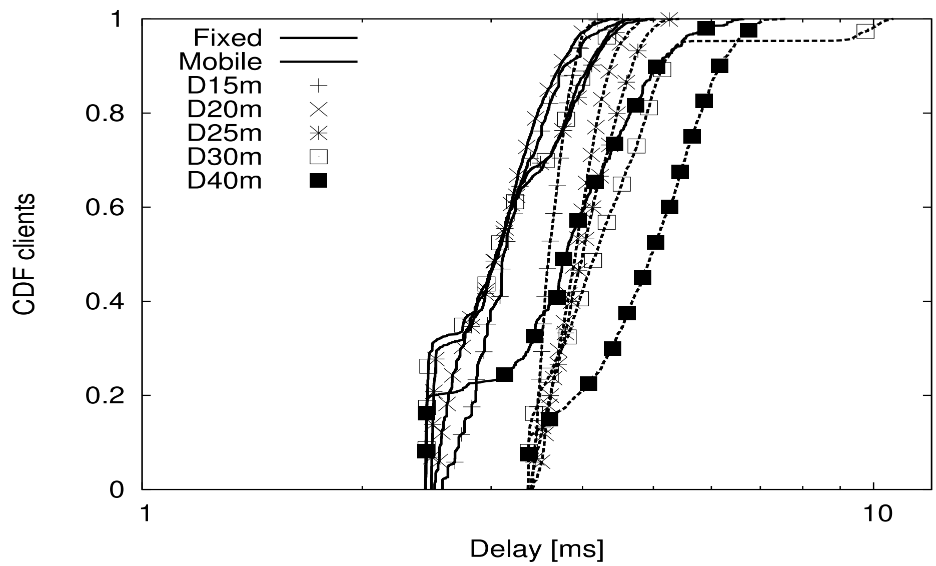

Figure 10: CDF of the average chunks delay for the 95-perc. vs grid ranges.

ine the effect of mobile PIM-routers, in particular on ensuring the minimum number of PIM-routers activation. Next, we aim to analyze the impact of bandwidth resources and noisy channel on multicast tree construction and multicast delivery in the Wireless-PIM-DM protocol. Finally, we intend to investigate the effect of different unicast routing protocols, both flat and hierarchical, on multicast tree construction and convergence of the Wireless-PIM-DM protocol.

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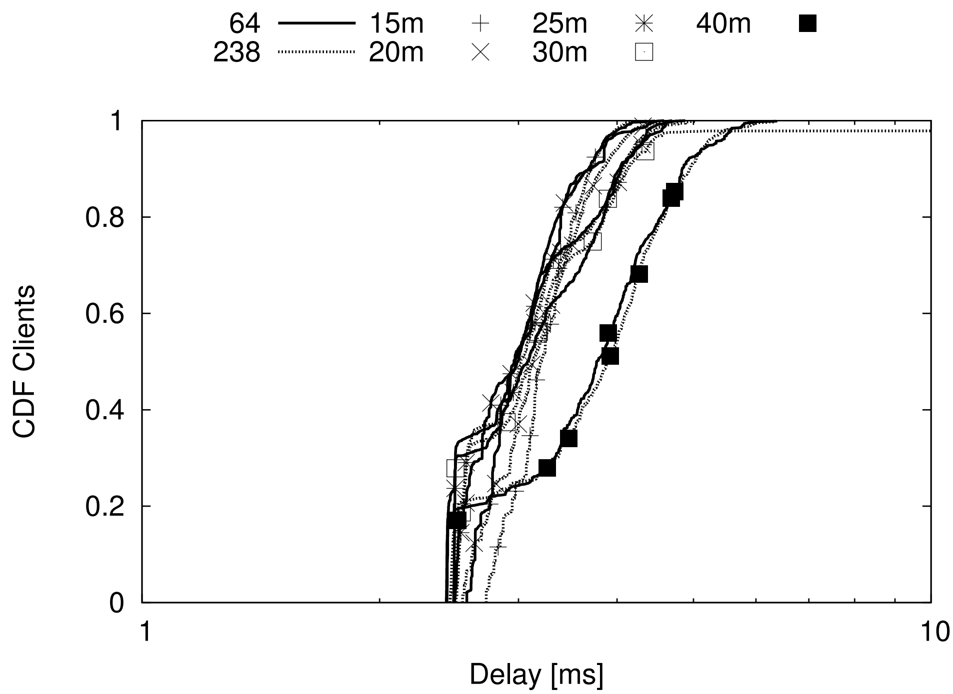

Figure 11: CDF of the average chunks delay for the 95-perc. vs grid ranges with 64 and 238 static PIM-clients.

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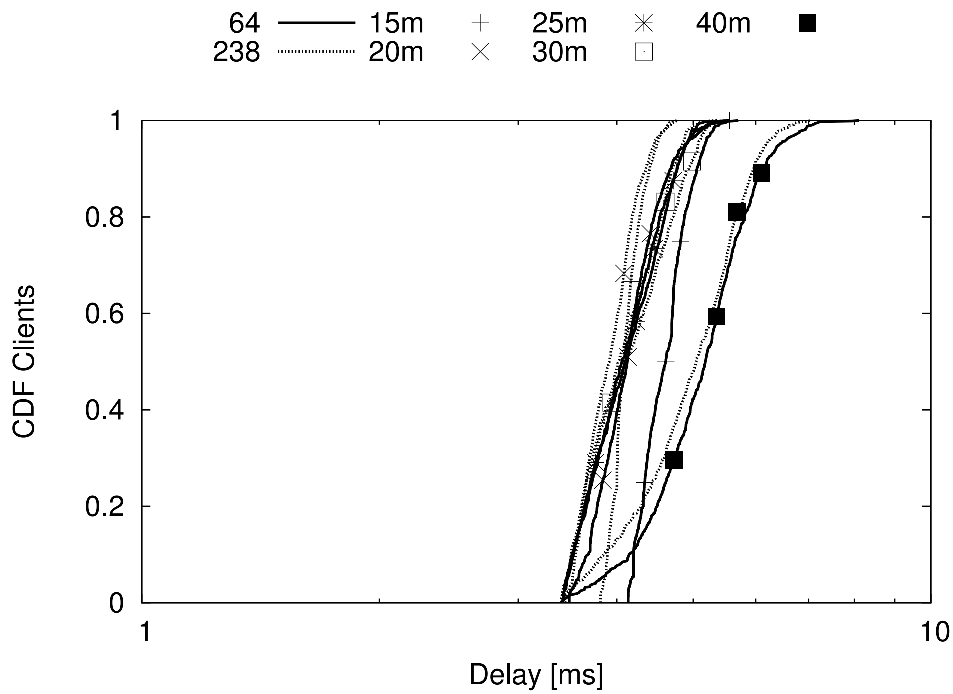

Figure 12: CDF of the average chunks delay for the 95-perc. vs grid ranges with 64 and 238 static PIM-clients.

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