Multicast Routing for MANET Extensions to IP Access Networks: The MMARP Protocol

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***Abstract*—Most of the typical IP multicast protocols which are used in fixed IP networks, like IGMP, assume that the terminals are in the same link. However, the multi–hop nature of ad hoc network extensions prevents standard-IP nodes from taking part in IP multicast communications through the ad hoc network. We propose a multicast architecture in combination with a new ad hoc multicast routing protocol called MMARP. MMARP nodes are challenged with special IGMP-handling capabilities allowing our solution to combine the efficiency of multicast ad hoc routing protocols with the support of standard-IP nodes. The use of the IGMP protocol as the interface between standard IP nodes, the fixed network and the ad hoc network extension allows a ready deployment of this approach in existing IP multicast networks.**

I. Introduction

IP Multicast technology provides efficient multipoint communications among a group of nodes and has emerged as one of the most researched areas in networking. The problem of efficient packet distribution to a specific group of destinations has been researched since the late 80's and the majority of network equipment currently supports multicast routing protocols. The main benefit of IP Multicast is that the bandwidth consumption for group communications is dramatically reduced, something of particular interest for 'all-IP' and 'beyond 3G' mobile networks where the number of user terminals is high and the applications are typically interactive and consume significant bandwidth. IP multicast could represent an important added-value for an operator by reducing network costs and differentiating their service offering from others.

The IST project MIND (Mobile IP-based Network Developments)[1] has been formed by Europe's leading telecom operators, manufacturers and universities to research the extension of IP-based radio access networks to include ad-hoc and wireless elements, both within the access infrastructure and attached to it. The overall network architecture is based on an IP Core network which interconnects the many different access networks an operator might deploy. In addition, the access network is extended by ad hoc (wireless) networks which are used to connect several terminals without the need of fixed network infrastructure. In this ad hoc fringe, a user terminal employs those of other users as relay points to provide multi-hop paths between the distant nodes and the fixed network architecture.

The provision of multicast communications in such ad hoc network extensions attached to fixed or mobile IP networks is far more complex than in fixed IP networks. The routing protocol has to address the complexity of routing in mobile ad hoc networks (MANETs) and at the same time preserve compatibility with the protocols used in the fixed part of the network. One additional requirement, which differentiates our approach, is the provision of backward compatibility with standard IP nodes; these are not commonly supported in typical ad hoc networks.

Several multicast routing protocols such as DVMRP[2], MOSPF[3], CBT[4] and PIM-SM[5] have been proposed and deployed in fixed IP networks; however, they are not able efficiently to update their distribution trees with the constant and rapid topology changes which are common in ad hoc networks. To overcome these limitations, other multicast routing protocols [6-13] have been proposed particularly for ad hoc networks. These protocols incorporate specific functionality which enables them to cope with the particular characteristics of ad hoc networks; however, they are only suitable for isolated ad hoc networks and can neither interoperate with a fixed IP network nor support standard IP Multicast sources or receivers.

There are also publications in the literature [14-22] that consider the problem of interconnection of ad hoc networks with IP networks. Unfortunately, these approaches are focused on unicast communications and are not suitable for multipoint interoperation with the access network. They seek to solve a different problem and focus on enabling ad hoc nodes (equipped with special networking stacks) to communicate with nodes in the Internet, whereas we are further interested in making ad hoc nodes serve as a transit network for those nodes which are not within radio range of the access network base stations.

In this paper we propose the Multicast MAnet Routing Protocol (MMARP), a new multicast ad hoc routing protocol which is able to deal with the complexity of supporting traditional IP nodes whilst interoperating smoothly with fixed IP networks. MMARP nodes are able to intercept and process standard IP multicast messages. They further permit standard IP nodes to participate in IP multicast communications as they do when attached to a fixed IP network.

The remainder of the paper is organised as follows: section II comments on the problems and requirements when offering IP mulitcast communications in ad hoc network extensions. Section III explains the proposed IP multicast architecture. A detailed description of the MMARP protocol is given in Section IV and, finally, Section V gives some conclusions and suggestions for future work.

II. Multicasting in Ad hoc Network Extensions

Ad hoc network extensions have been proposed in MIND to allow communications between nodes in the access network and nodes which are not within radio range of the base stations. The creation of these spontaneous ad hoc network extensions is very cost effective because of the limited amount of network infrastructure which is required but in consequence the network resources are limited. In such situations IP multicast communications can help in the reduction of the network bandwidth consumption, especially for real-time multimedia communications.

Neither standard multicast ad hoc routing protocols nor traditional IP multicast routing solutions for fixed networks offer a good performance in our ad hoc network scenario. As an objective for ad hoc network extensions such as those shown in Fig. 1, we seek a trade-off in which at least the following requirements are met.

A. Requirements

Interoperability with the Internet. The mechanisms used in the different parts of the MIND network should be interoperable with Internet protocols.

Unchanged terminal APIs. The MIND network should not require any change to the protocol stacks of standard IP nodes.

Address management. Appropriate address management procedures should be provided so that the routers perform such multicast-related procedures as Reverse Path Forwarding (RPF) checks.

Effective routing within the ad hoc fringe. Internal ad hoc routing mechanisms should also be efficient in providing effective routes between ad hoc nodes.

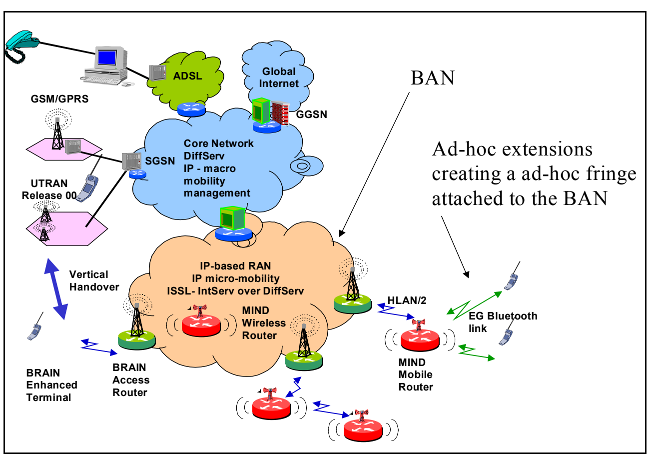

Fig. 1. The MIND reference network architecture consist of three different parts: the core network, the access network and the ad hoc network extension.

Scalability. The basic multicast principle of scalability to support a large number of simultaneous users should be preserved.

Low signalling overhead. Ad hoc network environments require very low overhead signalling protocols for good efficiency.

Resilience. Several gateways to the access network should be supported to eliminate single points of failure.

Robustness. Effective routing should be guaranteed even in the presence of extreme traffic conditions.

Inter-domain multicast routing. Solutions should not affect the inter-domain multicast routing protocols used in the administrative domain.

B. Multicast interoperation with fixed IP networks

For multicast hosts the process of taking part in multicast communications is quite straightforward. When they wish to send multicast traffic they simply use a class-D address as a destination and send the datagrams. When they are interested in receiving multicast traffic, they use the Internet Group Management Protocol (IGMP[23]) as a request to their First Hop Multicast Router (FHMR). This simple operation may become quite complex, however, when dealing with an ad hoc fringe attached to a fixed network.

One of the most important issues is that IGMP uses IP datagrams with a time-to-live (TTL) of one hop for the communication between hosts and routers. Thus, by default, only directly connected hosts are able to join multicast groups since IGMP messages are unable to transit a multi-hop ad hoc network fringe in which mobile nodes can be several hops away from the access network (in MIND / BRAIN the BAN – BRAIN Access Network).

Another problem related to the multi-hop nature of the ad hoc network is that packets sent by sources which are more than one hop away will not automatically be received by the FHMR. Intermediate ad hoc nodes need to ensure that these packets reach the FHMR. Once these packets are received by the FHMR it can use any of the multicast routing protocols for fixed networks (e.g. PIM-SM) to deliver the traffic to any destinations in the fixed network.

The support of standard IP nodes is an issue that requires that ad hoc nodes to incorporate capabilities for the interception and processing of IGMP messages since these are the means by which hosts join IP multicast groups in fixed networks. To date, none of the proposed multicast ad hoc routing protocols is able to handle such types of message.

Finally, there is an issue which relates to the differences between the hierarchical addressing architecture which is used in fixed networks and the flat addressing architecture used in ad hoc networks. The problem is that multicast routers usually perform a process called an ‘RPF-check’ on every incoming packet. This process drops any packet which arrives at an interface which that router would not use to reach the source of the packet. The problem is easily overcome by simply using any of the auto-configuration approaches [20,21] for ad hoc networks.

III. MIND Multicast Network Architecture

We have analysed different alternatives to achieve efficient network layer multicasting support between nodes within the ad hoc network extension and those in the access network. These can be grouped into two separate approaches: tunnel-based and multicast ad hoc fringe.

The tunnel-based approach relies on the establishment of tunnels from the mobile nodes to the FHMR. Conceptually it is the UMTS multicast architecture – except that UMTS does not accept multi-hop ad hoc routing. For MIND, we have selected a multicast ad hoc fringe as our baseline architecture since the tunnel-based approach exhibits some scalability and performance shortcomings: it requires the implementation of changes to the host's protocol stack which leads to excessive overhead and demands that the BRAIN Access Router (BAR) stores individual membership information on a per group basis giving rise to scalability problems. Moreover, inter ad hoc node communications are very inefficient as all packets go via the BAR even when there are no interested parties in the Internet. The routing is sub-optimal because even with two hosts connected directly, the multicast datagrams will go first to the BAR and then return to the destination. Finally, the total bandwidth consumption is increased because for each datagram in the multicast session, one copy is distributed by the BAN to each ad hoc node that has joined the group.

The ad hoc fringe approach, which is shown in Fig. 2, proposes the use of an ad hoc multicast protocol inside the ad hoc fringe with standard IP multicast protocols in the fixed network. This approach does not impair the protocol's efficiency by using additional headers since tunnels are not needed. Further, the BAR needs only to distribute one copy of the packets to all the nodes in its downstream interface instead of needing to forward one copy to each of the mobile nodes belonging to the group. Thus, we achieve real multicast efficiency and scalability. In addition, when one of the downstream nodes sends a packet to a multicast group G in the uplink direction, the BAR will not need to forward this packet to any other downstream nodes that have requested it since the ad hoc multicast routing protocol will ensure that the packet reaches the destinations within the ad hoc fringe. Thus, the BAR does not need to store the individual group membership

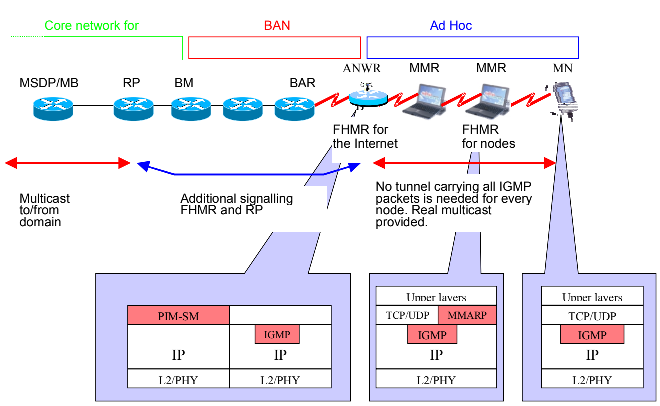

Fig. 2. The proposed MIND architecture with its three constituent parts: the core network, the access network and the ad hoc extension.

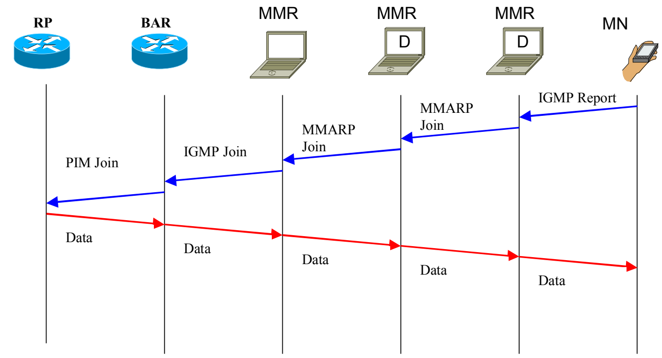

Fig. 3. Example of interaction between the MIND multicast protocols in order to receive a multicast flow

state per mobile node, a task which is not scalable. As demonstrated in [24], our proposed architecture is more efficient and scalable than the tunnel-based approach.

The MIND approach is based on the idea of confining any new functionality to within the ad hoc fringe and using standard protocols for the interaction with non-ad hoc nodes. It does not matter which IP multicast routing protocol is used in the BAN: we can interoperate in the same way with all of them. Thus, no changes are needed in standard IP nodes and routers. Mobile nodes will behave according to the standard IP Multicast model in which there is no requirement for sending and the only requirement for receiving is the use of the IGMP protocol.

Standard IP Multicast routing protocols are not suitable for the ad hoc network fringe, however, and we propose a specific multicast ad hoc routing protocol called MMARP which is described in the next section. An example of receiving a multicast flow is shown in Fig. 3. The BAR and RP are standard multicast-enabled routers running PIM-SM. MIND Mobile Routers (MMRs) are ad hoc nodes and MN is a standard Internet mobile host. The element which allows us to achieve native multicast and provides efficient paths between the elements of the ad hoc network fringe is the MMARP protocol. As we showed in [24] our architecture offers a better scalability and efficiency than the tunnelling (or UMTS-like) approach.

IV. The MMARP Protocol

The MMARP protocol is especially designed for mobile ad hoc networks (MANETs). It is fully compatible with the standard IP Multicast model [25] and it allows standard IP nodes to take part in multicast communications without requiring any change because MMARP supports the IGMP protocol as a means to interoperate both with the access router and standard IP nodes. The interoperation with the access routers is performed by the Multicast Internet Gateways (MIGs) which are the ad hoc nodes situated just one hop away from the fixed network. Every node may become a MIG at any time. The only difference between a MIG and a normal MMARP node is that the MIG is responsible for notifying the access routers about the groups having interested receivers within the ad hoc fringe. The mechanism allows MMARP to work with any IP multicast routing protocol in the access network and, therefore, it shields the MMARP operation from the protocols performing the intra-domain or inter-domain multicast routing.

For the remaining text we use the terms standard IP source or standard IP receiver to refer to a traditional IP Multicast source or receiver and we use the term ad hoc sender or ad hoc receiver to refer to pure ad hoc nodes.

MMARP uses a hybrid approach to construct a multicast distribution mesh. Multicast routes among ad hoc nodes are established on-demand whereas multicast routes to the multicast sources in the fixed network are established proactively.

A. Creation and Maintenance of the Distribution Mesh

MMARP uses a mesh-based distribution structure, similar to the one used by ODMRP, which offers good protection against the mobility of the nodes (see Fig. 5). Both the proactive and reactive parts of the protocol are responsible for building the mesh.

The reactive part of the protocol consists of a request phase and a reply phase. When an ad hoc node has new data to send, it broadcasts a MMARP_SOURCE message which is flooded within the entire ad hoc network to update the state of intermediate nodes as well as the multicast routes. These messages have an identifier which allows intermediate nodes to detect duplicates and avoid unnecessary retransmissions. When such a message is received by an ad hoc node for the first time, it stores the IP address of the previous hop and rebroadcasts the packet. When one of these messages arrives at a receiver, or at a neighbour of a standard IP receiver, it broadcasts a MMARP_JOIN message including the IP address of the selected previous hop towards the source. When an ad hoc node detects its IP address in an MMARP_JOIN message, it recognises that it is in the path between a source and a destination. It then activates its MF_FLAG (Multicast Forwarder Flag) and rebroadcasts a MMARP_JOIN message containing its previously stored next hop towards the source. In this way, a shortest multicast path is created between the source and the destination. The process is shown in Fig. 4.

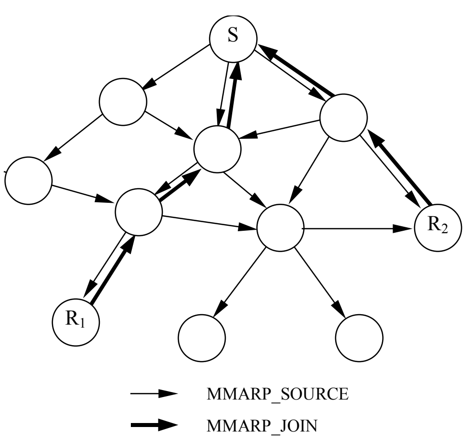

Fig. 4. Two-phases approach for the creation of the multicast distribution mesh in MMARP

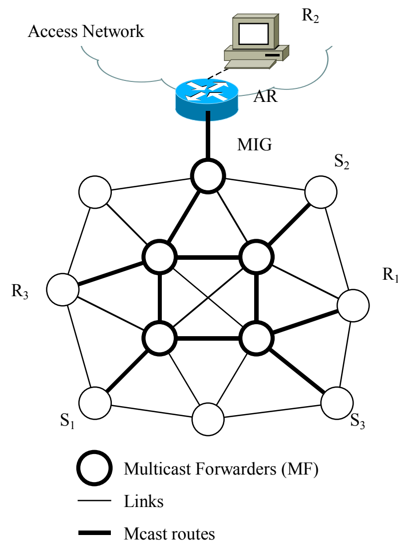

Fig. 5. Example of a MMARP distribution mesh between senders (S) and receivers (R).

When there are different sources and receivers for the same group, the process results in the creation of a multicast distribution mesh such as the one shown in Fig. 5.

The proactive part of the protocol is simply based on the periodic advertisement of the MIGs as default multicast gateways to the fixed network. As the TTL of IGMP messages is fixed at one, when an ad hoc node receives an IGMP Query from the access router it realises that it is a MIG and activates its MIG_FLAG. MIGs periodically broadcast a MMARP_DFL_ROUTE message which is flooded to the whole ad hoc network. The reception of this message informs intermediate nodes about the path towards multicast sources in the access network. When the MMARP_DFL_ROUTE message reaches a receiver or a neighbour of a receiver, this node initiates a joining process similar to the one that we have just described for the reactive approach, except that in this case, the joining is performed towards the MIG rather than the actual source. When the MIG receives the MMARP_JOIN message, it then sends an IGMP Report towards the FHMR, ensuring the IP multicast data from sources in the fixed network reach the destinations within the ad hoc network extension.

In the case of a standard IP node becoming an active source, the process for creating the distribution mesh is similar except that the MMARP_SOURCE message is actually generated by the neighbouring ad hoc nodes which receive the data packets from the source; this behaviour is presented as a state diagram in Fig. 6.

To overcome link breakages during the creation of the distribution mesh, a local repairing mechanism is used. Whenever a node is unable to deliver a MMARP_JOIN message to its next hop after four retries, it broadcasts a MMARP_NACK message to its one-hop neighbours. Upon the reception of this message, the neighbours use their own route to reach that next hop. Should any of them not know an alternate path, they repeat the process until a path is found. Although this recovery

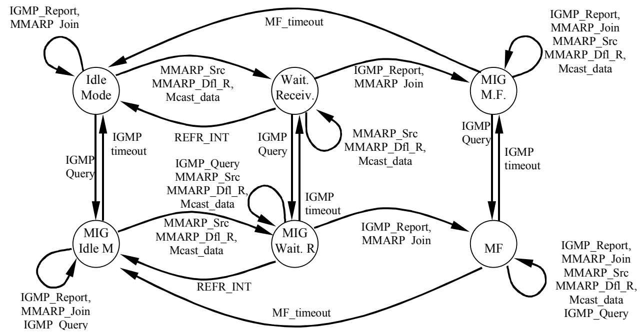

Fig. 6. State diagram illustrating the operation of the MMARP protocol

process does not offer optimal routes, it offers a quick recovery before the next topology refresh.

B. MMARP Structures

Each node is required to use some structures to store the protocol's specific information. This information is mainly stored as entries in the tables presented below. These entries expire after some period of time unless they are explicitly updated by protocol's messages.

1) Routing Table.

It stores individual entries about the next hop that the node uses to reach other nodes. These entries are updated with the reception of new MMARP_SOURCE messages which are generated every refresh interval.

2) MIG Membership Table

It is only maintained by MIG nodes and it stores individual entries for each of the groups for which there are interested receivers within the ad hoc network extension. Its entries are updated on the reception of MMARP_JOIN or IGMP Reports.

3) Forwarding Table

This table stores the groups for which this node is a Multicast Forwarder (MF). The entries are refreshed on the arrival of non-duplicate MMARP_JOIN messages.

4) Message Cache

This table is used by the node to detect duplicate packets and avoid unnecessary transmissions. The unique identifiers of all the packets being forwarded by the node are stored in this table. These entries do not need to be permanently in the table and can be expired as in the other tables.

5) Group Membership Table

This table is maintained by nodes which have standard IP neighbours. It stores the groups in which at least one of its neighbouring standard IP nodes has expressed its interest. The table is updated every time a new IGMP report is received. Entries that are not refreshed by an IGMP Report are expired according to IGMP timers.

6) Senders Table

This is also maintained only by nodes with neighbouring standard IP nodes. Each entry is a pair <S,G> in which S is the IP address of the standard IP source and G is the group to which it is sending data. These entries will be refreshed on the arrival of data packets from these sources.

C. Reliability and loop avoidance

It is very important for the operation of the protocol that the control messages are sent in a reliable way. (i.e. if a control message is lost, it is essential to send it again). Control messages in MMARP are broadcast. This means that in some networks such as IEEE 802.11b in which broadcast frames are not acknowledged automatically by the MAC layer, it is the protocol's responsibility to guarantee that these messages are not lost.

To reduce the overhead found in hop-by-hop explicit acknowledgement we use an approach called passive acknowledgment[25]. The key idea is that if two different nodes are in the same radio range and one of them sends a message which is retransmitted by the second one, then the first node is able to detect that transmission and use it as a "passive acknowledgement". This can be used to guarantee the delivery of MMARP_JOIN messages. When a node does not need to retransmit a packet it has to send an active acknowledgement using an MMARP_ACK message.

Loop avoidance is guaranteed by means of the inclusion of a unique identifier (sequence number) in each packet, which allows intermediate nodes to discard duplicate packets and create only loop-free routes.

D. Data Forwarding

Data packets addressed to a certain multicast group are only propagated by ad hoc nodes which have their MF_FLAG active for that group. When such a data packet arrives at a node whose MF_FLAG for that group has not expired, it checks that it is not a duplicate and in that case retransmits the packet. In any other case the packet is dropped.

E. Support of Standard-IP Nodes

The protocols used by standard IP nodes to perform their basic operation (such as ARP, or IGMP) were designed to operate in BMA (Broadcast Medium Access) networks. However, in multihop ad hoc networks, the link layer has a different semantic. The neighbours of a node are able to receive the frames it sends but it is not guaranteed that they able to directly communicate among all of them.

In traditional ad hoc routing protocols without explicit support for standard IP nodes this is not a problem because each ad hoc node sends its own source announcement or join message. In order to be compatible with the standard IP multicast model, MMARP nodes in the neighbourhood of a standard IP node have to send MMARP_SOURCE or MMARP_JOIN messages on behalf of the standard IP node. This means that messages generated by standard IP nodes, may be received by all neighbours and processed independently, creating unnecessary paths.

The MMARP protocol has been designed to avoid unnecessary generation of these messages. It includes a field which allows identification of the node which actually triggered the sending of the control message; this allows ad hoc nodes to identify all the MMARP packets which are triggered by a specific standard IP node, independently of the

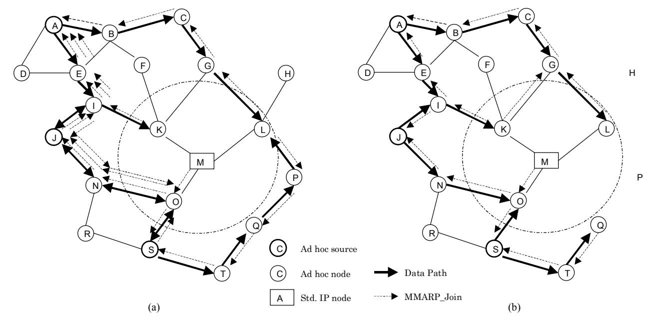

Fig. 7. Two-phases approach for the creation of the multicast distribution mesh in MMARP

ad hoc neighbour which actually generated it. Thus, ad hoc neighbours of standard IP nodes and intermediate ad hoc nodes are able to detect these types of MMARP_SOURCE and MMARP_JOIN messages as duplicate and avoid the creation of unnecessary paths.

The example presented in Fig. 7 illustrates the use of this approach to avoid the creation of unnecessary paths in an ad hoc scenario. The case in which this optimization is not used is presented in Fig. 7(a) and the optimized behaviour is presented in Fig. 7(b).

V. CONCLUSION

We have presented the proposed MIND multicast architecture combined with our MMARP protocol. To our knowledge, this is the first protocol in the literature offering efficient IP multicast communications in ad hoc network extensions to fixed or wireless access networks together with backward IP multicast compatibility. We have analysed the problems of offering such backward compatibility in the challenging scenario of ad hoc network extensions connected to fixed IP networks. We have also proposed extensions to ad hoc multicast routing protocols. In future publications we plan to present our analytical and empirical results which demonstrate that our protocol is able to offer all these new features without a significant increase in overhead, when compared with ODMRP[12].

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