Analysis of decentralized resource and service discovery mechanisms in wireless multi-hop networks

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Abstract

The last few years, research in wireless multi-hop networks or ad hoc networks is mainly driven by a search for efficient routing protocols. From an application point of view, it is obvious that nodes (users) will only setup connections with a specific goal, i.e., in order to use services and resources that are available in or reachable through the ad hoc network. Consequently, resource and service discovery protocols that allow nodes to learn about the available services in the network are indispensable. In this paper, we compare the performance of two basic decentralized resource and service discovery techniques, namely proactive and reactive discovery, through simulations and theoretical analysis. Our results show that the choice between them is not straightforward. It highly depends on the network and service characteristics and on the interaction with the underlying routing protocols. Therefore, our analysis provides protocol developers with some guidelines for developing new or extending existing resource and service discovery protocols for operation in mobile ad hoc networks. In addition, concrete suggestions for developing an integrated adaptive multi-mode solution for both resource and service discovery and routing in mobile ad hoc networks are presented.

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1. Introduction

During the past decade, advances in mobile computing and wireless communication technologies have led to wireless networks offering connectivity to mobile users. One important type of mobile wireless networks is an ad hoc network [1]. Opposed to infrastructured wireless networks, where each user directly communicates with an access point or base station, a mobile ad hoc network or MANET does not rely on a fixed infrastructure for its operation. The network is an autonomous system consisting of mobile nodes that communicate with each other over wireless links. Nodes that lie within each other’s send range can communicate directly. In order to enable connections between nodes that are not directly within each other’s send range, intermediate nodes act as routers that forward packets to the destination, which means that ad hoc networks are essentially multi-hop wireless networks that need routing functionality. In addition, ad hoc networks have a number of other salient characteristics. First of all, nodes are free to move arbitrarily, resulting in random and rapid topology changes the protocols have to deal with. Second, the available bandwidth is scarce and places limitations on the protocols’ amount of control information. Finally, network sizes can range from tens up to thousands of, potentially heterogeneous, nodes.

During the last few years, a lot of research efforts were, and still are, focused on the development of efficient routing protocols, as establishing connections between nodes is one of the primary functions the network has to perform. From a higher level, it is clear that nodes will only setup connections with a specific goal, i.e., in order to use services and resources that are available in or reachable through the
ad hoc network. Possible services or resources include data storage, database access, files, network printer, Internet gateway, etc. (Fig. 1). Therefore, resource and service discovery (R&SD) protocols, which allow nodes to automatically locate available resources and services or to advertise their own capabilities, are also a major component of mobile ad hoc networks, which operates in close relation with the routing protocol.

This article discusses the advantages of decentralized solutions and presents a comparison of two decentralized R&SD techniques, namely reactive discovery, in which nodes request a service when needed, and proactive discovery, in which nodes periodically announce their services. Section 2 presents an overview of related work and the basic principles of proactive and reactive R&SD mechanisms, followed by a general discussion of the main advantages and disadvantages of centralized and decentralized R&SD protocols in Section 3. In Section 4, we present a performance evaluation through simulations. In addition, we assess the performance through an analytical approach in Section 5 and compare the analytical results with the one obtained through simulations. In Section 6, concrete suggestions for a novel integrated adaptive multi-mode solution for both resource and service discovery and routing in mobile ad hoc networks are presented. Finally, conclusions are made in the last section of the article.

2. Related work

Resource and service discovery architectures can be dichotomized into centralized and decentralized architectures [2]. In centralized architectures, nodes register their services with service brokers or service agents. When a node needs a service, a request is sent to a broker, which sends back a reply message containing the requested information (see Fig. 2a). The use of agents or brokers improves the scalability, reduces the response time and can be used for load balancing. Most existing resource and service discovery protocols such as the Service Location Protocol (SLP) of the IETF, Sun's Jini, Microsoft's Universal Plug and Play (UpnP) and IBM's Salutation protocol basically rely on directories for their operation, although some of them are able to function without central agents [3].

Another approach is the use of a decentralized architecture that uses reactive discovery or proactive discovery. When using proactive R&SD, nodes periodically announce the services they offer by broadcasting service announcements (SANN) in the network. Upon reception of these announcements, nodes extract the information from which they learn about the available services in the network and forward these announcements to their neighboring nodes. During reactive R&SD, nodes that need a service send out service requests (SREQ), which are propagated in the network. Nodes offering services actively listen for such messages. If they receive a request for a service they support, a reply message (SREP) is generated and sent back to the requesting node. Fig. 2b presents the concept of reactive and proactive R&SD. The Bluetooth Service Discovery Protocol (SDP) is an example of a decentralized architecture specifically designed for small-scale Bluetooth networks [4].

![Fig. 1. A mobile ad hoc network and its resources and services.](image1)

![Fig. 2. Logical overview of centralized and decentralized architectures.](image2)
3. General discussion of centralized and decentralized R&SD techniques

In the following, we will discuss the trade-offs between centralized and decentralized resource and service discovery in terms of management overhead, scalability, resilience, network load, and latency.

3.1. Management overhead

A centralized R&SD protocol with a centralized organization requires that one or multiple nodes are assigned the task of collecting the service information, exchanging this information amongst each other, keeping it up-to-date and providing service information to nodes that request services. If these central agents are located in the fixed infrastructure, this organization does not impose any problems and can be very efficiently managed. However, deploying a centralized solution in a dynamic wireless multi-hop network environment that consists of battery-powered devices can create additional overhead in managing the central agent(s). In such an environment, no dedicated central agents are present. This implies that a distributed agent selection algorithm is needed to select the most appropriate device that can take up the role of service agent. As the devices can be mobile, can leave and join the network, and are battery-powered, service agents need to be relocated from time to time and their information needs to be transferred. In addition, all nodes in the environment need to become aware of these changes. This means that in this case, managing this centralized organization can introduce a great deal of additional overhead. In a decentralized R&SD solution, whether proactive or reactive, no management overhead is present, as each node independently decides on the actions taken.

3.2. Scalability

In centralized solutions most R&SD control traffic will be unicast (or multicast), whereas irredecentralized solutions broadcasting is mainly used. The unicast (multicast) will put a lower burden on the wireless multi-hop network. In addition, in centralized solutions all control traffic is directed to the central agents and does not propagate throughout the entire network. Finally, using central agents allows better scalability in terms of the number of services that can be handled.

3.3. Resilience

With centralized R&SD protocols, resource, and service discovery functionality entirely relies on central agents. This means that these agents can form a single point of failure. In dynamic wireless network environments where nodes are mobile and battery-powered or agent functionality can be reassigned, resilience can become an issue. Therefore, a decentralized solution can provide an alternative or backup method, as functionality is guaranteed at all times.

3.4. Network load

In a centralized solution, all services are registered at a single location. This implies that the load on this location will increase strongly when the number of nodes that need services increases. In an ad hoc network, this could result in an unfair network load in specific parts of the network. In decentralized solutions, the network load will be more equally spread over the network. Of course, the exact trade-off between the two solutions will strongly depend on the R&SD patterns in the networks.

3.5. Latency

In centralized solutions, the latency to find a requested service depends on the time to forward the request to the central agents and the time to receive a reply. Of course, this latency will mainly consist of routing and forwarding delays. In decentralized solutions, the latency to discover a service or resource is strongly dependent on the type of R&SD: reactive or proactive. The latency in reactive discovery mainly consists of the time to propagate the service request up to a node that offers a service and the time for the service reply to arrive at the requesting node. In proactive discovery, no latency to discover the service is involved.

The above discussion makes clear that decentralized R&SD mechanisms have some interesting characteristics that are highly suited for mobile ad hoc networks. In the following sections, we will therefore investigate their performance in more depth.

4. Performance evaluation

This section presents a simulation analysis of proactive and reactive R&SD techniques. This analysis is focused on the network aspects of the techniques and does not make any assumptions on message syntax, semantics, etc. Fig. 3 and Table 1 present the reference scenario used in the simulations and the relevant network parameters. The network simulator GloMoSim [5] has been used for carrying out the simulations.

4.1. Protocol overhead and delay

Figs. 4 and 5 show the protocol overhead, expressed as the number of R&SD messages (SREQs, SREPms, and SANNs), as a function of the number of services and the number of clients and servers per service. Fig. 4 clearly shows that proactive R&SD scales with the number of clients, as its overhead only depends on the number of servers. On the other hand, Fig. 5 proves that reactive R&SD scales with the number of servers, as it only depends on the number of clients that request services. The choice
whether to deploy proactive or reactive R&SD strongly depends on the service context. This means that developing a scalable decentralized R&SD mechanism should be a hybrid that deploys both reactive and proactive R&SD, where the choice between proactive and reactive depends on the service context and can even be different for different service types. Frequently used services should announce their presence proactively through SANNs, rarely used services should be requested by the clients through SREQs. In addition, if nodes mainly use local services, i.e., services in their local neighborhood, the propagation of the SANNs could be confined within a limited environment around the servers. Nodes outside these areas can find out about these services reactively. This also implies that the preferred decentralized protocol is capable of adapting itself dynamically to the service context in the network.

Wireless multi-hop networks require routing protocols, which also rely on proactive and reactive mechanisms. This observation motivates the need to investigate the interaction of decentralized R&SD mechanisms with the underlying routing protocols. To this end, we evaluated the performance of proactive and reactive R&SD on top of a proactive (WRP) and reactive (AODV) routing protocol (note that in this study the R&SD messages and routing messages are completely separated). In case a reactive routing protocol is used, different degrees of coupling with the reactive R&SD are possible, as depicted in Fig. 6.

In case there is no coupling, AODV will create a route to the client when the server wants to send a service reply (SREP) to the requesting client. In this case, the SREP is

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Network parameters</th>
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<tbody>
<tr>
<td>Link/radio layer</td>
<td>802.11b radio (2.4 GHz, DCF), 1 Mbps, two-ray pathloss, accumulated noise, send range = 250 m (omnidirectional antenna, Tx power: 15 dBm, Rx threshold: −83 dBm, Rx sensitivity: −83 dBm, antenna gain: 0 dBm)</td>
</tr>
<tr>
<td>R&amp;SD</td>
<td>Number of services, number of clients per service (per period of 150 s), number of servers per service, proactive R&amp;SD: service announcement interval, announcement broadcast delay, reactive R&amp;SD: starting hop count, hop count increment</td>
</tr>
<tr>
<td>Application layer</td>
<td>CBR traffic from client to server over UDP</td>
</tr>
<tr>
<td>Mobility</td>
<td>36 nodes placed in grid, mobility: none or random waypoint with constant speed and pause time 0 s</td>
</tr>
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sent directly to the client on IP level, which means that the SREP is transparent for the intermediate nodes. This option rules out the possibility of caching without violating the layered protocol structure. In case of loose coupling, the SREQ will interact with the routing protocol and will be used to create a backward path to the client. In this case, the SREP is sent to the client on a hop-by-hop basis and is processed by the R&SD of each intermediate node. Once the client wants to send data to the server, a forward path still needs to be created (but there is no additional routing overhead for sending back the service reply). The last option is strong coupling, where the SREQ will be used to create a backward path and the SREP will be used to create a forward path. In this case, the reactive R&SD protocol will create a bi-directional path if a client requests a service.

Figs. 7 and 8 illustrate the impact of R&SD and routing protocol combinations on the R&SD delay (time it takes to find the service) and the routing delay (time between finding the service and the delivery of the first data packet). Note that AODV means loose coupling and AODVb means strong coupling. It can be seen that by using proactive R&SD the R&SD delay is reduced to 0 as all nodes in the network know all services. Also, as expected, the use of a proactive routing protocol results in much smaller routing delays. Fig. 8 also proves that a strong coupling between the R&SD protocol and AODV significantly reduces the routing delay.

Again we can observe that the choice of decentralized R&SD mechanism and its interaction with the routing protocol strongly influences the delay. In the ideal case, the R&SD and the routing protocol should adapt their behavior to the network, not only to reduce the network load, but also to deal with the delay requirements imposed by the applications that need services. It can also be observed that a higher number of servers has a positive impact on the resulting delay. Therefore, for delay sensitive services, service replication mechanisms that efficiently duplicate and distribute these services within the network can increase the overall performance.

In the above simulation results, basic versions, without any optimizations, of the reactive and proactive R&SD mechanisms were used. For reactive R&SD, this means that the SREQ is propagated throughout the entire network. For proactive R&SD, this means that servers announce their presence each announcement interval by broadcasting a service announcement in the network. However, a number of optimizations that improve the scalability can be used.

4.2. Scalability improvements

4.2.1. Improvements to reactive R&SD: expanding ring search and caching

Instead of broadcasting the SREQ throughout the entire network, an expanding ring search could be used, where nodes first start to look for the services they need in their immediate environment. If no service has been found, the search area is gradually expanded. Fig. 9 shows the overhead reduction that can be obtained by using the expanded ring search concept. The type of expanding ring search (combination of starting hop count and hop count incre-
4.2.2. Improvements to proactive R&SD: announcement interval and message aggregation

Figs. 11 and 12 show how the value of the announcement interval and the use of message aggregation help reducing the protocol overhead. The announcement interval determines with which interval servers announce the services they offer. Of course, the optimal value of this parameter cannot be increased as is, without taking into account the type of services and the network context. Message aggregation means that nodes store all SANNs that arrive during a certain time period (i.e., announcement broadcast delay interval). At the end of the interval, these announcements are combined into one bigger message, thereby reducing the protocol overhead (or several messages if the value of the announcement broadcast delay is too high, which of course reduces the effect of the aggregation). Note that as we do not make any assumptions on message syntax, we only take into consideration the number of messages, and thus the number of times access to the channel is needed, as a measure for the protocol overhead. Once a choice on the message syntax has been made, more detailed overhead calculations in terms of bytes are possible.
4.2.3. Improvements to proactive and reactive R&SD

Of course, other techniques such as more efficient broadcasting schemes than blind flooding can be used to reduce the protocol overhead of both proactive and reactive R&SD [8].

4.2.4. Impact of mobility

If using reactive R&SD, a node that has found a service can start using it. However, the node will not detect if a better service (e.g., the same service but offered by another server closer to this node) has become available, unless it periodically performs a new discovery. When using proactive R&SD, nodes will become aware of better servers and can switch to a new server when appropriate. Fig. 13 shows how switching to a new server can improve the quality of the delivered service (in this case by reducing the hop count when switching to another server that delivers the same service). Of course, the service type should support switching to a new server: a straightforward example is gateway discovery. An alternative solution would be to migrate services from one node to another (service mobility) in order to obtain an optimal distribution of services in the network. However, service mobility together with service replication requires additional research challenges to be solved at the service and application level and is outside the scope of this paper.

5. Theoretical analysis

In this section, we theoretically derive the performance of proactive and reactive R&SD. A theoretical derivation is given for the message overhead of proactive R&SD, with and without message aggregation, and reactive R&SD, with and without expanding ring search. Analog expressions for the R&SD latency can be derived similarly based on the per hop latency. Table 2 shows the notations that are used.

5.1. Basic proactive and reactive R&SD

The overhead when using proactive R&SD consists of the service announcements that are broadcasted periodically throughout the entire network. Note that, as blind flooding is used, each broadcast costs $N$ transmissions in a network of $N$ nodes. For basic reactive R&SD, the overhead consists of the SREQs that are propagated throughout the entire network and the SREP s that are sent back by all corresponding servers. This leads to the following simple expressions for the message overhead.

$$M_{pro} = Sf_{ano}N,$$

$$M_{re} = Sf_{req}N + Sf_{req}L.$$  \hspace{1cm} (1)

5.2. Proactive R&SD with message aggregation

The amount of aggregation depends on the announcement broadcast delay interval. In the optimal case, the
choice of $f_{del}$ will be such that at the end of the interval multiple SANNs can be aggregated into one single message. Too small values of the interval will reduce the efficiency, as at the end of the interval there are not always SANNs available for aggregation; too high values will also reduce the efficiency as in this case the SANNs will not fit into a single message anymore. For the optimal case, the overhead is approximated by the following expression:

$$M_{pro} = f_{del}N \text{ with } f_{del} < Ss_{f_{pro}}.$$  \hspace{1cm} (3)

3.3. Reactive R&SD with expanding ring search

The probabilities $S(k)$ can be calculated as follows:

$$S(k) = \begin{cases} 
1 & \text{for } N - N(k) < s, \\
1 - \frac{s - N(k) - 1}{N - s} & \text{for } N - N(k) \geq s.
\end{cases}$$  \hspace{1cm} (4)

From $S(k)$ we can easily derive the probabilities $s(k)$.

$$s(k) = \begin{cases} 
\frac{S(0)}{S(MAX)} & \text{for } k = 0, \\
\frac{S(k) - s(k-1)}{s(MAX)} & \text{for } k = 1, \ldots, i_{MAX}.
\end{cases}$$  \hspace{1cm} (5)

Let us define $i_{MAX}$ as the value for which the following equation holds:

$$h_{start} + (i_{MAX} - 1)h_{inc} \leq k \leq h_{start} + i_{MAX}h_{inc}.$$  \hspace{1cm} (6)

Now we can calculate the values of $M_{rc}(k)$ as follows:

$$M_{rc}(k) = \begin{cases} 
N(\min(i_{MAX}, h_{start} - 1)) + k \\
+ (s - 1)\frac{N(\min(i_{MAX}, h_{start} - 1))}{s} \frac{i_{MAX} - i_{MIN} + h_{start} - 1}{2} i_{MIN}, & \text{for } k \leq h_{start}, \\
\frac{i_{MAX} - 1}{2^k} & \text{for } k > h_{start}.
\end{cases}$$  \hspace{1cm} (7)

The first equation, which holds if only one iteration in the expanding ring search is needed, consists of three terms: the SREQ, the SREP of the closest server, the SREPs of other servers in the area covered by the SREQ. The second equation, which holds if there are $i_{MAX} + 1 (i_{MAX} > 0)$ iterations needed in the expanding ring search, consists of four terms: the SREQs of the first $i_{MAX}$ unsuccessful iterations, the SREQ of the last successful iteration, the SREP of the nearest server and the SREPs of other servers in the additional area covered by the last SREQ. Based on the probabilities $s(k)$ and the values of $M_{rc}(k)$, we can compute the total overhead as:

$$M_{rc} = \sum_{k=0}^{i_{MAX}} M_{rc}(k)s(k).$$  \hspace{1cm} (8)

In Fig. 14, a comparison is made between the theoretical and analytical results. We can observe that the obtained results are quite similar, which makes the analytical approach useful and reliable for evaluating the overhead in larger ad hoc networks. The only requirement is the knowledge of the probabilities $i(i)$. For random ad hoc networks, the calculation of these probabilities is a research topic on its own.

6. A proposal for an integrated solution for adaptive multi-mode R&SD and routing

For decentralized resource and service discovery, similar techniques as the one encountered in ad hoc routing protocol solutions can be deployed. However, the above discussion has made clear that:

- No solution is optimal. Each solution, i.e., reactive or proactive R&SD, can outperform the other depending on the network and service context. The same observation holds for ad hoc routing protocols. The results in this paper could therefore serve as a basis for developing an adaptive R&SD solution where the type and scope of service discovery depends on the service context.

- The decentralized R&SD solutions and their performance are strongly entangled with the underlying routing protocol. Therefore, the results presented could be used to further investigate the interaction between R&SD and routing in order to come to a cross-layer design, which jointly optimizes the routing and service discovery solutions.

However, we believe that the most optimal solution would be one that combines adaptivity with joint optimization, by developing an integrated adaptive multi-mode protocol for decentralized R&SD and routing in mobile ad hoc networks:

- **Integrated.** The routing protocol control messages should allow the incorporation of service and resource discovery information (e.g., as an extension of the routing protocol message format). For instance, when reactively searching for a service in the network, the service request/service reply information could be combined with the route request/route reply information into one integrated message format. Alternatively, proactive routing control messages could be extended with the services offered by the nodes.

- **Multi-mode.** The integrated solution should be able to support multiple modes of operation, where each mode is optimized to work efficiently in a given network and service context. For instance, both a reactive and proactive mode of operation could be supported, but alternative modes are possible.

- **Adaptive.** The multi-mode solution should be able to dynamically adapt its mode of operation and change its behavior according to changes in the network or service context in order to achieve an overall optimal performance.
By jointly looking at the problem of routing and service discovery and developing an integrated protocol, a reduction in overhead can be achieved. In addition, by supporting multiple modes of operation and a dynamic adaptation of the multi-mode protocol to the context, an additional gain in overall performance can be achieved.

Fig. 15 presents a high-level potential framework of an integrated adaptive multi-mode R&SD and routing solution. This framework consists of two main components. The first component is a monitoring agent that is responsible for collecting information on the network and service context (e.g., network load, mobility, and number of service requests) in the environment of the node. This is done in two ways. First of all, local statistics from the network layer or other layers are collected in the statistics component of the monitoring agent. Second, non-local statistics are collected through the periodic broadcasting of hello messages to neighboring nodes or through the dissemination of statistics into the local neighborhood [9]. Periodically, the network monitoring information component processes the collected statistics and extracts useful information about the networking and service context. Based on this context,
the R&SD and routing protocol (which is the second main component in the framework) can adapt its mode of operation. Each mode can have its own (or common with other modes) control messages for R&SD and routing. The information contained in these messages will update the routing and service table. The routing table is used for forwarding data packets, whereas the service table should provide an interface to the higher layers so it can be consulted by the applications and services running on top.

Currently we have implemented the adaptive multi-mode routing protocol part of the framework, which supports three compatible modes of operation:

- **MODE 1.** A node in MODE 1 can only be reached by reactively establishing a path to it.
- **MODE 2.** A node in MODE 2 will proactively announce in its neighborhood how it can be reached (with the scope of propagation determined by a time-to-live value). This proactive routing information is only propagated by other MODE 2 and MODE 3 nodes within this neighborhood, creating a subset of nodes that proactively have a path to each other.
- **MODE 3.** A node in MODE 3 will also proactively announce how it can be reached, but compared to a node in MODE 2, this information is now also propagated by MODE 1 nodes, which then also maintain a proactive path to that node.

For more details on this protocol and the challenges involved with multi-mode routing, we refer to [10]. In the future, we plan to extend the routing protocol messages to also include R&SD information (i.e., service requests, replies and announcements) and to further develop the monitoring agent. Nevertheless, Fig. 16 shows already a simple example of how adaptive multi-mode routing, based on predefined knowledge of the service context, can improve the overall performance. In this scenario, 100 static nodes are geographically distributed into two adjacent groups of 50 nodes. Each group has one popular server node to which at each moment 20 other client nodes are simultaneously connected to for an FTP session with an average duration of 60 s. All nodes are in MODE 1, except for the server nodes, which are in MODE 3. Consequently, all nodes will have a proactive path to the server node, but all other paths need to be established reactively. The figure clearly shows that by adapting the routing protocol to the known service context, the same performance as with a proactive or reactive routing protocol can be achieved, however with a much lower network overhead.

7. Conclusion

In this paper, we have discussed the tradeoffs between centralized and decentralized resource and service discovery techniques. As decentralized solutions have some interesting advantages in mobile multi-hop networks, we have evaluated the performance of reactive and proactive R&SD both through simulations and analytically and have looked at techniques to improve the scalability of the solutions. The results can be used as a guideline or to provide better insight when extending the functionality of existing resource and service discovery protocols into the wireless ad hoc multi-hop world or to refine them once a specific message format has been chosen. In addition, our results show that the choice between proactive and reactive R&SD is not straightforward. It highly depends on the network and service context and on the interaction with the underlying routing protocols. Ideally, the R&SD and routing protocols should be developed in close cooperation or even be integrated and should be able to adapt their behavior to the demands of the network and applications. Therefore, we have proposed an integrated solution and corresponding framework for adaptive multi-mode R&SD and routing in mobile ad hoc networks that integrates routing and R&SD and that at the same time is capable of adapting its behavior according to the network and service context, achieving an overall optimal performance.

![Fig. 16. Adaptive multi-mode routing based on predefined knowledge of the service patterns. (a) Packet delivery ratio. (b) Number of routing protocol packets.](image-url)
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References


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