Hierarchical Routing for Small World Wireless Networks

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Abstract — **The number of embedded systems capable for wireless machine-to-machine service communication has continuously been increasing in recent years. In these kinds of dynamic ecosystems, the problems related to complexity and heterogeneity seriously challenges interoperability. As a contribution to this research, the small world paradigm from social sciences is being applied in a wireless networks context. A novel hierarchical networking concept, related routing algorithm and network optimization solutions are created to enable solving these problems. Logical short cuts are established between neighboring overlay nodes in order to avoid global flooding in distant route searches. In addition, physical short cuts may be created to remove the bottlenecks from the communication paths. The concept has been evaluated by graph theoretical analysis of the Hi-Search algorithm, simulation of the network optimization step and service discovery procedure. The evaluation results indicate that the algorithm with network optimization functions is able to lower the search delays, make the physical routes shorter and also improve throughput. In addition, solving the complexity and heterogeneity problems is made possible by localizing route search and abstracting communication to two hierarchical routing layers.**

Keywords- dynamic wireless networks; small world; routing

I. INTRODUCTION

The number of wirelessly communicating embedded systems has been increasing continuously in recent years. This trend is assumed to lead to novel types of dynamic wireless networks, which are more and more necessary for communication between machines instead of only human-machine communication. Such dynamic wireless networks have previously been studied for example in the context of ad hoc and peer-to-peer overlay networks.

Ad hoc networks usually refer to a wireless network that can be established without any preceding configuration on the fly whenever required. The challenges in ad hoc networking solutions arise from the heterogeneity of operating environments, because of the different delay requirements, reaction times for route changes, power capabilities of the routing devices, and the limitations of the bandwidth usage, quality of service level and security. Because of these challenges, it can be assumed that the solution should be modular enough to enable smooth configuration and usage of multiple ad hoc routing protocols in different domains of the network. When multiple ad hoc routing solutions are applied, then their interoperability will become one of the most critical requirements.

A well-known solution for solving the interoperability problem has been building overlay networks. In such an overlay network, a number of peers are connected to each other in a logical sense, and they can thus route messages between each other at a logical level even if no direct physical connections exist. Such solutions are able to improve robustness, availability, error resilience and even help in the transition to improved technological systems. One essential drawback of overlay networks is the overhead caused by the additional headers in the messages. Therefore, more processing power and memory is required in the overlay network nodes. However, there are still several open problems in communication between the nodes in dynamic wireless networks, such as heterogeneity of nodes, their dynamic existence, mobility, security, multiple radios, unreliable paths and topology, and continuous changes occurring in the network.

The motivation for the hierarchical routing arises from these challenges, especially complexity and heterogeneity of dynamic wireless networks. In addition, the wireless paths between communicating nodes usually tend to be too long and they go via nodes, which are not appropriate or willing to act as a router, which also makes the performance to be weak. Therefore, we focus here on hierarchical routing. This article is an extended version of the CTRQ 2012 conference paper [1]. The original CTRQ 2012 paper is here extended to clarify the main results of the hierarchical routing as a whole, including enhanced clarifications of the selected essential details also discussed in previous publications [2], [3], [4], and [5].

The selected approach for solving the problem in this research is the application of the small world paradigm for wireless networks. The small world paradigm has initially been studied in the context of social networks, where a small-world phenomenon has been detected [6], [7]. According to this, the average number of intermediate steps in a successful social communication chain is between five and six, “six degree of separation”. It is here expected that the well-connected nodes in wireless networks tend to behave in a networking sense like the well-connected people in social networks. Thus the small world paradigm from social sciences is here applied in wireless networks context. Based on this paradigm, a novel hierarchical networking concept related routing and network optimization solutions and their evaluation results are provided in this work. The hierarchical route search algorithm provided is based on a graph theoretical system model and network search tree analysis both on overlay and at a physical level. Logical short cuts are established between neighboring overlay nodes to avoid global flooding in distant route searches. In addition, physical short cuts may be created in a network optimization step to make the end-to-end delays shorter, physical routes shorter and improve throughput. The Hi-Search algorithm is evaluated in terms of search path depths, number of control messages, and delay in the search, which are compared against the flat physical routing approach. The related network optimization step and procedures enabling service discovery for a user are evaluated by means of simulations.

The paper is organized as follows: The related work of small world wireless networks is described in section II. The conceptual system model for hierarchical networking and its reasoning is clarified in section III. The hierarchical routing solution is described in section IV. The simulation-based evaluation results are provided in section V, and finally, conclusions are given in section VI.

II. SMALL WORLD WIRELESS NETWORKS

A. Small World

The small world phenomenon originates from the observation that individuals are often linked by a short chain of acquaintances - “six degree of separation” [6], and [7]. Watts & Strogatz produced the network model, showing that rewiring a few links, called short cuts, in a regular graph can decrease the average path length between any two nodes while still maintaining a high degree of clustering between neighboring nodes [8]. The concept of small worlds is characterized by the facts that average path length is short and clustering is high degree. This means that most nodes are on average a few hops away from each other. High clustering means that most of the nodes’ neighbors are also neighbors of each other. The small world phenomenon has been detected, for example, in email delivery experiments, and in the context of the Internet and the World Wide Web [9], [10], and [11].

Complex dynamic self-organizing wireless networks tend also to be scale-free [12]. They usually expand continuously by the addition of new nodes, and the new nodes tend to attach to nodes that are already well connected. The dynamic growth and preferential attachment lead to a scale-free property. Scale-free means that majority of nodes have very few neighbors, and only a few nodes have many neighbors. Thus, only a few well-connected nodes nicely connect a large number of poorly connected nodes. This phenomenon is independent of the network size, and such a scale-free network is also a small world.

Application of small world and scale-free features has also been studied in the context of wireless networks [13]. The dynamic wireless networks are spatial graphs that are usually much more clustered and have higher path length characteristics than random networks. In such a network, the links depend on the radio range, which is usually a function of the distance. Adding a few wired short-cuts into the wireless networks, the degree of separation may be reduced drastically. Such short-cut links need not be random but may be confined to a limited number of hops, which is only a part of the network diameter.

Strategies for adding long-ranged links to centrally placed gateway node in wireless mesh networks are provided in [14]. The constraints of wireless networks, such as transmission range of long-ranged links (LL), limited radios per mesh router and limited bandwidth for wireless links are discussed. As a result, the constrained Small World Architecture for Wireless Mesh Networks is provided with three addition strategies of LL, which are able to provide a 43% reduction in average path length (APL). The LL addition strategies are random LL addition strategy (RAS), Gateway aware LL addition strategy (GAS), and Gateway aware greedy LL addition strategy (GAGS). In RAS, the links are randomly chosen and then some checks related to distance and the availability of radio are carried out. In GAS, there is an additional check and logic related to improving the gateway APL (G-APL). In GAGS, the logic for improving the G-APL is further optimized. Significant performance improvements in wireless mesh networks have been detected as the results of the LL addition strategies provided .

Summarizing, it has been discovered in the earlier theoretical small world-related research that, by adding a few short-cut links, average path length can be reduced significantly. However, the previous work has been mainly related to the application of wired links as short-cuts [13] or long-ranged links in mesh networks [14]. While in our approach, the dynamic wireless networking situation with multiple radio accesses, interoperability of routing protocols, and the problem related to the heterogeneity of nodes and links are taken as the starting point. Moreover, both logical and physical short cuts are created to solve these problems in practical situations.

B. Routing Protocols

The ad hoc networking protocols, such as, e.g., Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [15], Ad hoc On-Demand Distance Vector (AODV) [16], Optimized Link State Routing Protocol (OLSR) [17], and Dynamic MANET On-demand (DYMO) [18] are not optimal for specific operating environments due to differences in delay requirements, reaction times for route changes, the power capabilities of the routing devices, and the limitations of the bandwidth usage, quality of service level and security. Delay-Tolerant Networks (DTN) and opportunistic networking [19], [20], and [21] solutions enable communication also when the source and destination nodes are not necessarily reachable at the time of communication need. Therefore, usage of multiple ad hoc routing protocols optimized for different domains and situations of the dynamic wireless network should be enabled. A possible solution approach to these challenges is overlay networking. However, the *heterogeneity* of nodes, radio links, and dynamic topologies still triggers challenges for both overlay networking and ad hoc networking systems.

There are multiple routing solutions implemented for overlay networking, such as the concept of a Content Addressable Network (CAN), which is a distributed application-level overlay infrastructure providing hash table functionality at an Internet-like scale [22]. A hash table is a data structure that efficiently maps keys into values. The CAN resembles a hash table, and the basic operations are the insertion, lookup and deletion of (key, values) pairs. Each CAN node stores a chunk (zone) of the entire hash table. In addition, the node holds information on a smaller number of adjacent zones in the table. Requests (insert, lookup, delete) for a particular key are routed by intermediate CAN nodes towards the CAN node whose zone contains that key. There are also several other routing overlay solutions, such as Chord [23], Tapestry [24], and Pastry [25]. Tapestry and Pastry differ from CAN and Chord in the sense that they take the network distances into account when constructing the routing overlay. SkipNet differs from Chord, CAN, Pastry and Tapestry in the sense that it provides controlled data placement and guaranteed routing locality by organizing data primarily by string names [26]. Tapestry, Chord, Pastry and CAN assume that most nodes in the system are uniform in resources such as network bandwidth and storage. Brocade provides a secondary overlay that exploits knowledge of the underlying network characteristics [27]. Usually, in peer-to-peer systems, nodes are connected to a small set of random neighboring nodes, and queries are propagated along these connections. Such a query tends to be very expensive in terms of bandwidth usage. A possible solution is the semantic overlay network (SON), which connects nodes having the same type of content to each other [28]. Queries are routed to the appropriate SONs, increasing the chances that matching files will be found quickly and reducing the search load on the nodes that do not have any related content. The hierarchical routing schemes with distributed hash tables (DHT) are discussed in [8]. The challenge with the DHT-based hierarchical routing schemes and also with most of the other overlay routing solutions is that they do not take physical level routing into consideration at all.

Small world-based routing, called SWER, dedicated to supporting sink mobility and small transfers has been provided in [29]. The hierarchy is based on clustering and cluster heads, and short cuts are applied for long-range links between clusters. The cluster head selects a sensor node to act as agent node to form the short-cut. The challenge in this solution is that the weak sensor nodes and radio links are still applied in realizing the short-cut. Hierarchical routing based on clustering using adaptive routing using clusters (ARC) protocol is provided in [30]. A new algorithm for cluster leader revocation to eliminate the ripple effect caused by leadership changes is provided. The ARC starts from the need to select a cluster leader. However, in our work we assume that the capability to act as a cluster head is preconfigured into the overlay nodes. Then there is no need to select a cluster head, but instead they need only to discover each other.

Helmy *et al.* have developed a contact-based architecture for resource discovery in large-scale wireless ad hoc networks (CARD) [31]. The mechanism is suitable for resource discovery as well as routing very small data transfers or transactions, in which the cost of data transfers is much smaller than the cost of route discovery. In CARD, resources within the vicinity of a node, up to a limited number of hops, are discovered using a proactive scheme. For resources beyond the vicinity, each node maintains links to a few distant nodes called contacts. The contacts help in creating an efficient way to query for distant resources. Two protocols for contact selection were introduced and evaluated: (a) probabilistic method, and (b) edge method, which was found to be a more efficient way for contact selection. Comparison with other schemes shows overhead savings reaching over 93% (vs. flooding) and 80% (vs. border casting or zone routing) for high query rates in large-scale wireless networks. The concept of contacts can be compared to our concept of overlay nodes. However, the contact nodes act as short-cuts in CARD, while our short-cuts are either logical or physical wireless links. Our approach in particular further enhances the system in such a way that the network optimization checks whether it is also possible to establish the physical wireless short cuts between overlay nodes as direct radio connections.

Variable-length short-cuts are constructed dynamically using mobile router nodes called data mules in disconnected wireless networks [32]. The data mules transfer data between nodes, which do not have a direct wireless communication link and belong to otherwise isolated networks. Their simulations indicate that even a small number of data mules can significantly reduce average path length. The overlay nodes might also act as mobile routers, but network optimization may not be possible or at least is not trivial in disconnected networks.

P2P network can be established using small world concepts, and it has been realized as SWOP, small world overlay protocol [33]. The average hop distance between P2P nodes can reduce the numbers of link traversals in object lookup, reduce the latency and can effectively satisfy a large number of users requesting a popular data object. However, the physical level routing is not taken into concern at all in the SWOP approach.

There are also quite a number of solutions for neighbor discovery such as [34], and [35]. However, route discovery is usually executed in a flat manner, e.g. [17]. The problem in such a search is that the search queries are also forwarded into the deep leaves of the search trees. Our approach is different in the sense that only the nearest logical overlay nodes are searched at the physical route level, and the network can be optimized by removing non-optimal radio links and physical routers from the path.

III. HIERARCHICAL NETWORKING CONCEPT

The applied system model of heterogeneous wireless network is shown in Figure 1. The system consists of heterogeneous nodes, which are shown using color codes for the different node types. In addition, the colors in the dotted circles represent the usage of different radio access types.

Each node may have one or more radio access capabilities, which can also be applied to temporarily connect the heterogeneous wireless network with legacy static Internet (blue clouds). The referred nodes may be switched on and off at any given time, which means that their presence is dynamic. Therefore, dynamic life cycle management is required for both the nodes and the networks.

The network nodes are categorized according to their capabilities. *U* node is a user interface (UI) node, which is able to host the network and services, which it may visualize for a user. *S* node is service node, which may provide set of services, act as super peer (cluster head) for services and overlay router. *R* node is a physical router node, which can route data traffic between different interfaces of the node. T node can for example be a sensor (*Ts*), actuator (*Ta*) or camera (*Tc*). P node is a special node in the sense that it is usually plugged in to be a logical part of U or S node. Each of the referred nodes may not always be on, and they may be mobile and can apply whatever wireless/wired access means for communication with the neighbor nodes.

The problem is related to the heterogeneity of nodes; some of the nodes do not have good capabilities for routing, while others do. For example, the radio access may not be power-efficient enough and the device may be battery-operated. In addition, some of them do not want to route at all for some owner-originated reasons. Having flat routing in such a system seems to lead to long path lengths and low performance, or even to the impossibility of establishing a connection at all.

The heterogeneous nodes may have several different radio accesses for communication with neighbor nodes. Some of the nodes may act as a relay for the specific radio technology. The lowest level of routing can thus be considered to be radio specific, and its main function is to relay ("route") the received signal forward so that the nodes, which are not in the radio coverage of the original sender can also receive it. This kind of "radio relay routing" solution is dependent on the radio technology applied, which means that it needs to be realized in a specific way for each different radio technology.

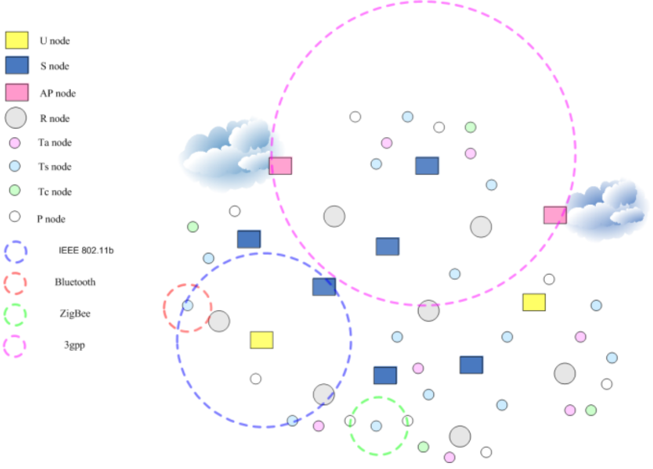

Figure 1. System model of a heterogeneous wireless network.

Some clusters of the network may need a specific method and optimized algorithm for physical level routing. Such optimization may be needed, for example, because of the limited power capabilities of the sensor nodes. For some network clusters such ad hoc routing protocol, like AODV, may be good enough; however, some of the nodes such as very limited capability sensor networks may require more optimized ad hoc routing protocol in the sense of memory and battery consumption. In addition, it may be more efficient to have a proactive protocol in operation when the network cluster is more static and not mobile. This means that the heterogeneous wireless network may consist of network clusters applying different physical routing algorithms. Therefore, several different physical ad hoc routing methods and protocols should be supported. When several different radio access and physical routing protocols are integrated into a single system, interoperability will be very big challenge. As a solution for interoperability, the overlay approach has been used in this work.

Thus, our hierarchical networking concept relies on the overlay approach, in which the radio relay routing, physical ad hoc routing and overlay routing are executed on top of each other, as in Figure 2. The overlay routing is applied on top of the physical networking and radio access specific networking. In the overlay routing, the application level messages are stored in packets called bundles, which are routed between logically neighboring overlay routers, e.g., a, b, and c. There can be several physical routers between the referred neighboring overlay routers, for example 1-5. And there can also be several radio relays between physical routers respectively. However, radio relays are beyond the scope of this paper.

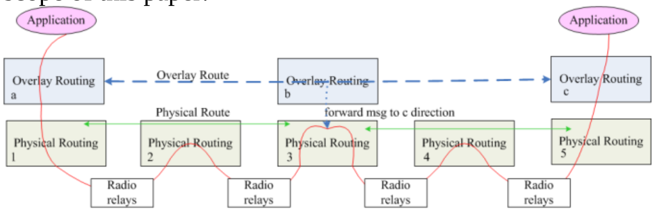

Figure 2. An example of hierarchical routing configuration.

IV. HIERARCHICAL ROUTING

Hierarchical routing is analyzed in this chapter with the aid of network graphs. A novel hierarchical routing algorithm is provided, based on the reasoning. Finally, a procedure for the hierarchical search and network optimization is discussed.

A. *Network Graphs*

An example of a heterogeneous wireless network system is shown in the form of a graph in Figure 3. In the example, a physical network graph (G_{PN}), vertex ($V_{PN}=0$) i.e., node (0) represents the User node. Each vertex has certain characteristics such as location (*L*), overlay routing capabilities (*OR*), physical routing capabilities (*PR*), radio capabilities (*R*), power capabilities (*P*) and computing power (*Cp*), $V_{PN}\{L, OR, PR, R, P, Cp\}$. The edges ($E_{PN}$) represent the possible physical communication links between two or more nodes. Each edge has certain characteristics such as, for example, distance (*D*) and delay (*Δt*), $E_{PN}\{D, \Delta t\}$. In the example, the overlay network graph (G_{ON}) is established by the U, and S vertices (V_{ON}). The dotted lines represent the edges of the overlay network (E_{ON}). The overlay network graph is here said to be a *virtual* graph of the physical network graph (G_{ON} c G_{PN}). Respectively, we can define the radio network graph (G_{RN}), which shows the radio network below the physical network (G_{ON} c G_{PN} c G_{RN}). Therefore, the system model is here said to be hierarchical.

The G_{PN} can be represented in the form of a (search) tree (T_{PN}) from the perspective of the $V_{PN}=0$, *i.e.*, user node 0 (A), shown in Figure 4. Such a tree does not have cycles, and the source of the search is represented as the root of the tree (T_{PN} ($V_{PN}=0$)). A search path is a route from the root of the tree to the leaf of the tree, representing the destination of the search. Such a search tree can be created for each node of the G_{PN} respectively.

Respectively, G_{ON} can be represented in the form of a tree (T_{ON}) shown in Figure 5. It is easy to see that the height of the overlay network tree is smaller than the height of the physical network tree. This means that the overlay network path from source to the destination usually contains a smaller number of hops.

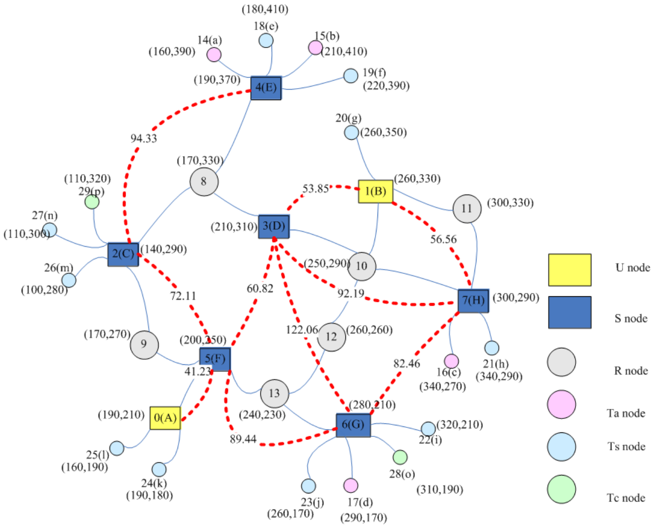

Figure 3. Example System Graph (G_{PN} and G_{ON}).

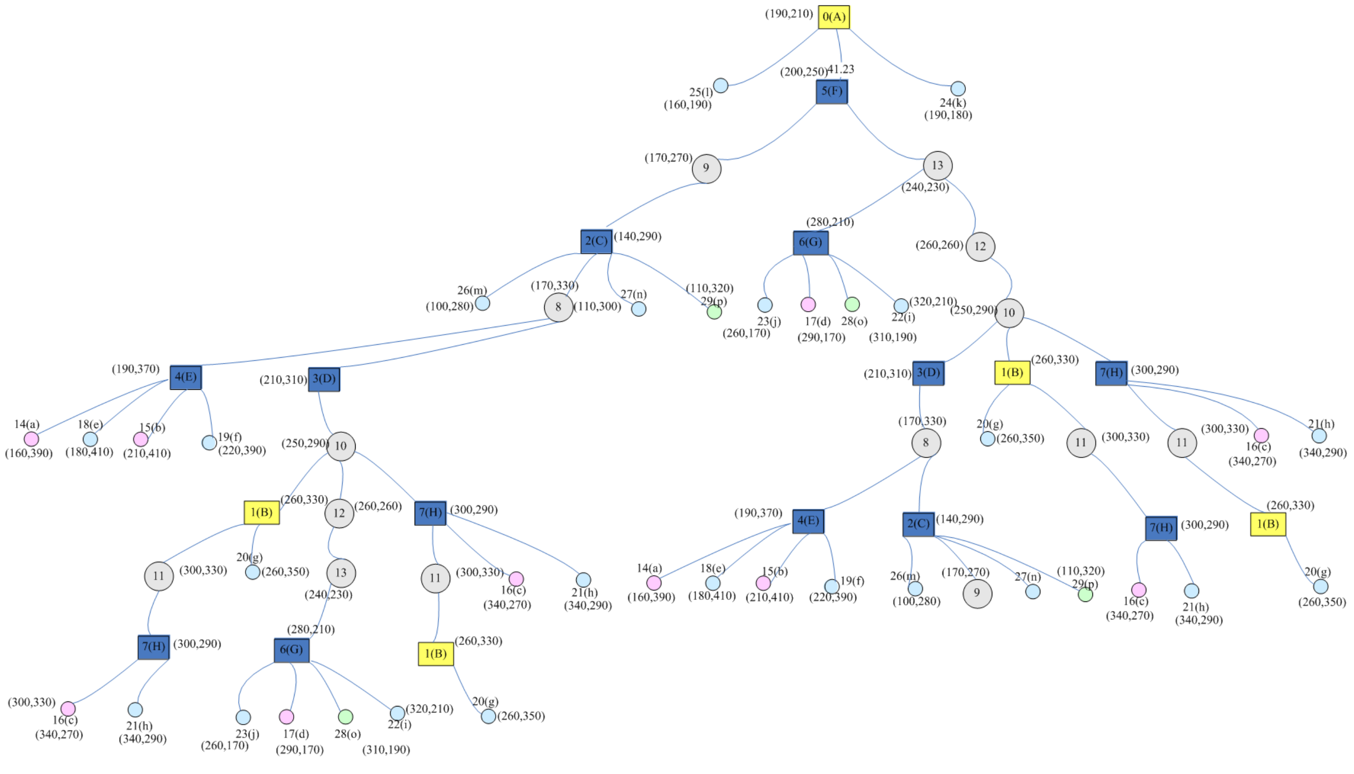

Figure 4. Example System physical network Tree (T_{PN}).

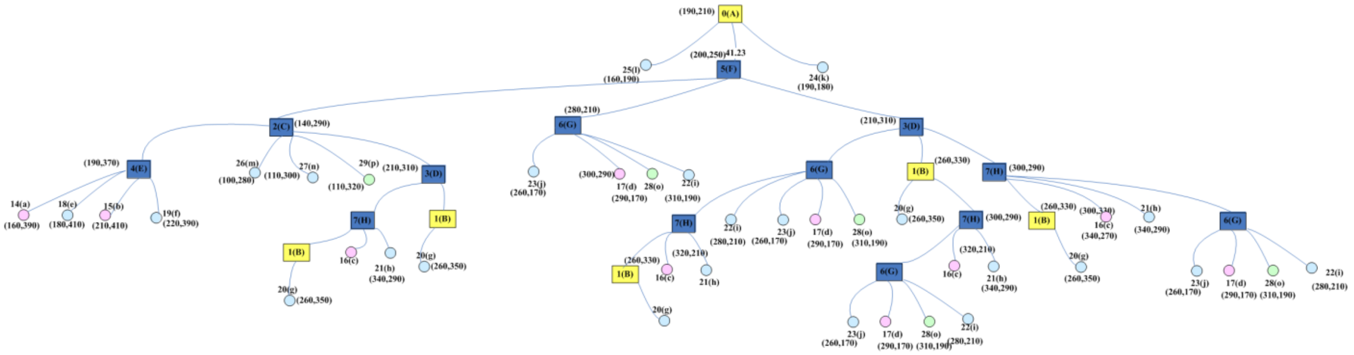

Figure 5. Example System Overlay Network Tree (T_{ON}).

B. Reasoning

The reasoning of the hierarchical search algorithm is represented in the following:

- Each edge in the search path means an additional communication delay for the search. Therefore, the number of levels in the search tree needs to be minimized. For example, if the search proceeds into deep sub trees, which do not have the destination, the search unnecessarily disturbs the vertices and consumes the radio bandwidth in the area of the leaf sub tree.
- Each vertex in the search tree processes the search, and it adds processing delay (Δt_p) to the search. Therefore, the number of vertices in the search path needs to be minimized. It can be claimed that the search unnecessarily disturbs all vertices in the search path, if the vertex is not the destination. Unnecessary disturbance of any vertex should be minimized.
- Let us call the minimization of the search tree levels, minimization of the number of vertices in the search path and minimization of vertex disturbance *search tree minimization*.
- The number of levels in the search tree is lower for the T_{ON} than for T_{PN}. Therefore, it is assumed that the search tree can be minimized by relying on hierarchical search, in which the search is executed in the overlay level (T_{ON}) and the physical level search is limited to the discovery of the physical paths between each pair of neighboring S nodes (T_{PN} is split into sub trees). This also means that the hierarchical search is executed in T_{ON} (Figure 5.) and in the split sub trees of T_{PN} visualized in Figure 6. In this way, the physical level search results in a local optimum physical path, called a *logical short-cut*, between neighboring S/U nodes, and the overlay level search results optimum path between source and destination (S/U or T_* nodes).
- Some of the vertices are more powerful than others, for example, some can have good power sources and a good computing platform while others may be battery-operated. It is clear that powerful vertices are better nodes for routing. Therefore, they are preferable nodes in the search path, and the usage of limited capability nodes (bottlenecks) will be minimized.
- When looking at different search paths in G_{PN}, T_{PN} it is assumed that removing the bottleneck nodes from the search path reduces the total communication delay (Δt_c) of the search. Let us here call the removal process *network optimization*.
- The network optimization process is focused on the split sub trees of T_{PN}; see Figure 6. Because, the R nodes are assumed to be the bottleneck nodes, the S/U nodes actively try to remove them from the local physical communication paths, and create a *physical short cut* between the neighboring S/U nodes. As a result of successful network optimization, the search tree is like the T_{ON} visualized in Figure 5.

Summarizing, the hierarchical search with search tree minimization and network optimization processes results in a situation, where the search path consists only of powerful and well-connected S/U nodes and not bottleneck nodes.

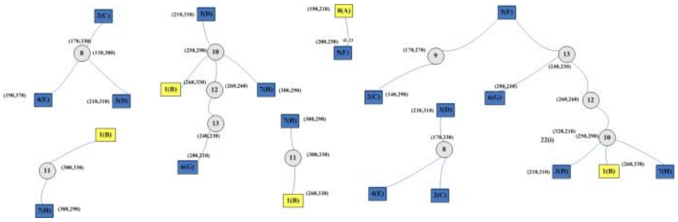

Figure 6. Split sub trees of T_{PN}.

C. Hierarchical Search Algorithm

The hierarchical search algorithm is represented in Figure 7. When the power of a U/S node is switched on, the device will broadcast *DiscoverReq* to all of its neighbors with the information of the node itself. Each overlay node receiving the *DiscoverReq* stores its key contents and replies with *DiscoverRep*, which is sent in a unicast manner to the source of the DiscoverReq. The *DiscoverRep* contains overlay level routing and service information, which will be delivered to the original source of the *DiscoverReq*. Sending the *DiscoveRep* triggers searching for the physical route between the neighboring overlay nodes, for example using the AODV RREQ/RREP procedure. When the original source receives *DiscoverRep* via the discovered physical route, the system has established a *logical short cut* between the neighboring overlay nodes, and is ready to provide messaging services for applications.

When an application message *(APP-msg)* is received from the upper layer and the overlay route is known, it is forwarded towards its intended destination. Otherwise, an overlay route is searched first, and then the message is forwarded towards the destination. In this manner, the application message will be delivered to the destination using hierarchical search. At any time after the system is ready, the network optimization can be initiated. In the network optimization, direct wireless communication links for the neighboring overlay nodes may be created as *physical short-cuts* in the cases where it is physically possible with the available radio access technologies of the overlay nodes.

```
Algorithm HI-Search                              /* Hierarchical Search */

1. WHEN n(OFF) →n(ON) THEN
2.          send (DiscoveryReq, Bcast)
3. WAIT until receive (Msg)
4.          SWITCH Msg
4.                    CASE DiscoverRep (ucast)
5.                              store (DiscoverRep)
6.                              start (timer, Net-Opt)
7.                    CASE DiscoverReq (Bcast)
8.                              IF n == ON THEN
9.                                store (DiscoverReq)
10.                               send (DiscoverRep, Ucast)
11.                             ELSE
12.                               update (DiscoverReq)
13.                               forward (DiscoverReq, Bcast)
14.                   CASE applicationMsg
15.                             IF no route THEN
                                  send (ON-RouteReq)
16.                             IF route THEN send APP-msg
17.                   CASE ON-RouteReq
18.                             IF n == destination THEN
19.                               send ON-RouteRep
20.                             ELSE forward ON-RouteReq
21.                   CASE Timeout (Net-Opt)
22.                             optimize (network)
23.                             start (timer, Net-Opt)
24.         ENDSWITCH
25. ENDWAIT
```

Figure 7. Hierarchical Search Algorithm.

D. Procedure of the Hierarchical Search

The basic procedure of the hierarchical search algorithm is shown in Figure 8. First, after power on, each overlay node initiates the logical neighbor discovery procedure by sending *DiscoveryReq* messages to indicate their presence to their neighbors . Based on these broadcast messages, the physical routers in the chain can add the information about their physical neighbors into their routing tables. These messages are forwarded by all the nodes until an overlay node receives them. When an overlay node receives the *DiscoverReq*, unicast sending of *DiscoverRep* to the source of the *DiscoverReq* is activated. This activates searching of physical routes between the overlay node, and neighboring source overlay node.

The network may consist of different routing clusters, clouds in Figure 8. , which may apply different physical routing protocols. For example, in cluster 1, the AODV route discovery will be executed, and as a result, a physical route between A and C can be discovered. The other clusters may use any other routing protocol for route discovery. When the physical route has been discovered, then the *DiscoverRep* is sent to the source overlay node. As a result of the logical neighbor discovery procedure, the overlay nodes know their physical and logical overlay neighbors and the *logical short-cut* has been established between the overlay neighbors. The physical routes between logical neighbors are stored in the physical level routing tables. After this phase, network optimization may be activated.

When an application message (*APP-msg*) is received from upper layers, it triggers searching of the overlay route by sending *ON-RouteReq* towards the logical neighbors. Each intermediate overlay node forwards the *ON-RouteReq* until the destination is discovered. The destination node then replies with *ON-RouteRep* message, which is sent via the same route, which the *ON-ReouteReq* used. The nodes in the path update the routing tables accordingly to enable smooth forwarding of the *APP-msg* from source to destination i.e., from A to E.

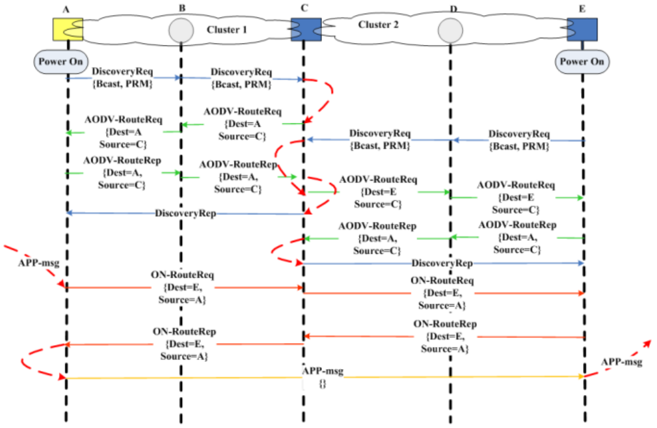

Figure 8. Hierarchical routing procedure.

E. Network Optimization

In the network optimization, direct wireless communication links between the neighboring overlay nodes are created (See Figure 7. row 22, and dotted red links in Figure 3.). These links are called *physical short-cuts*, and they can be created in the cases when the overlay nodes can apply larger transmit power or use a longer distance radio access method to communication with the neighboring overlay node(s) directly.

Because of these physical short-cuts, the physical route can skip some of the physical routers, which makes the path shorter compared with a communication without them. For example, the physical communication path without the physical short cuts between B and D can consist of 3 intermediate physical hops via physical routers numbered 4, 6 and 7 (see Figure 3.). In that case, the logical short-cut between B and D is available via the referred intermediate hops, and it can be used to make long -distance routing more efficient. However, enabling also a physical short-cut link could enable node B to reach node D via a direct radio link without any intermediate physical routers by using, for example, a somewhat larger transmit power or other radio access system.

It is here assumed that the overlay node is a higher capability node, which usually has more power capabilities and can also have several different radio access technologies to be used for communication. Therefore, such nodes are able to create referred physical short-cuts. In addition, it is assumed that such nodes are able to act as cluster heads in the network topology. Therefore, the number of overlay nodes can be used as a measure of *clustering level* in the system. If there is smaller number of cluster heads, i.e. overlay nodes, then there are not many clusters in the network. If there are more cluster heads, then there are more clusters in the network.

Let us define low degree *(D_L)* to indicate the number of nodes, which have a small (0-2) number of neighbors. Usually, these kinds of nodes are other than overlay nodes, because those nodes usually have a limited number of radio accesses and power capabilities. Respectively, high degree (D_H*)* indicates the number of nodes, which a have higher (> 2) number of neighbors. Usually, these kinds of nodes are overlay nodes i.e., cluster heads. The degree of clustering (D) is here defined as a function (1) depending on the number of low and high degree nodes, and it is used to indicate the level of clustering in a specific topology (*T*) in a specific moment of time (t).

$$\Delta\ (T,\ \tau) = \Delta_H(T,\ \tau)\ /\ \Delta_\Lambda(T,\ \tau). \quad (1)$$

The degree of clustering (1) is larger when the number of high degree nodes increases, and smaller when there are fewer high degree nodes. When the number of low degree nodes is significantly larger than the number of high degree nodes, the system represents a scale-free network. Then a majority of nodes have very few neighbors, and only a few nodes have many neighbors. Usually, the heterogeneous wireless network represents this kind of scale-free phenomenon. Because the degree of clustering depends on the topology and time, the effect of physical short-cuts for the path lengths and performance are in this work studied by means of simulations .

V. EVALUATION

Evaluation of the hierarchical search algorithm, network optimization and related procedures is provided in this chapter.

A. *Evaluation of Hi-Search Algorithm*

The depths of the search paths for the example graph shown in Figure 3. are shown in Figure 9. There are 37 possible search paths for both physical and overlay networks, see Figures 4 and 5 respectively. Each search path is shown in the x-axis, and the depth of the search path is shown in the y-axis in Figure 9. For example, for search path number 11, the depth of the physical search path is 10 and the depth of the overlay search path is 5. In general, the search path depths for the overlay routes are lower than the search path depths for the end-to-end physical routes. The *Hi-Search* algorithm provided applies overlay route search, which means lower search paths.

The physical search path depths of overlay hops are shown in Figure 10. (See also Figure 5.). The y-axis shows the physical search path depths, and the x-axis shows the number of their required searches in Figure 3. in a physical routing situation. For example, the physical search path 5-9-2, whose depth is 2, happens 17 times in a physical routing situation. The referred physical search paths seem generally to happen multiple times in the example network in a physical routing situation. This is not very efficient, and therefore the algorithm creates logical short-cuts between the neighboring overlay nodes. Then there is a need to execute referred physical search paths only once for the network, and network optimization can be based on it. The referred network optimization action is initiated in row 22 of the *Hi-Search* algorithm to check and create possible physical short-cut link between the neighboring overlay nodes.

The number of control message sending actions is shown in the y-axis of Figure 11. When the physical route between neighboring overlay nodes is searched initially and optimized, the number of control message send actions is at about the same level as in physical routing (x=7). However, after the optimization has been executed, then the number of control message send actions drops significantly, because there is no need to repeat optimization. It can be seen that the number of control message send actions is lower when applying the *Hi-Search* algorithm compared with physical routing.

The total delay in the search is shown in the y-axis of Figure 12. It is assumed here that the delay in each physical hop, i.e. the radio link, is 10ms, the optimization happens in a parallel manner and the processing delay in each node is zero. The peaks of the delay for the *Hi-Search* algorithm are related to optimization of the network. After optimization, the delays are at a lower level. As a result, it is seen that the *Hi-Search* algorithm is better because it has lower search delays than physical routing.

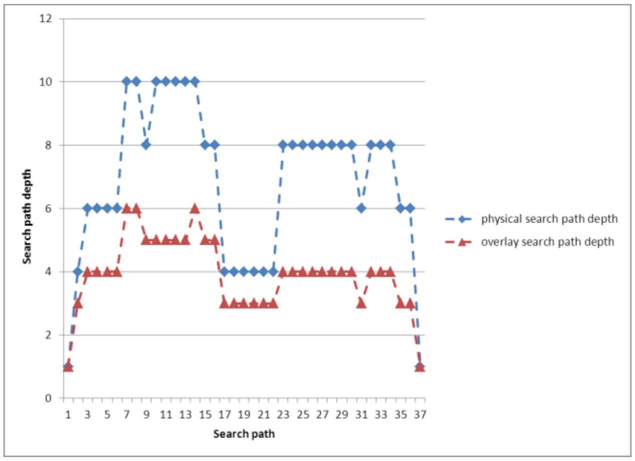

Figure 9. Search path depths.

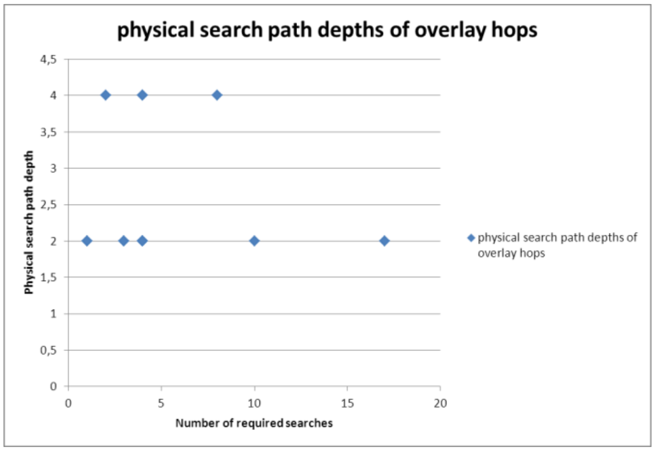

Figure 10. Physical search path depths of overlay hops.

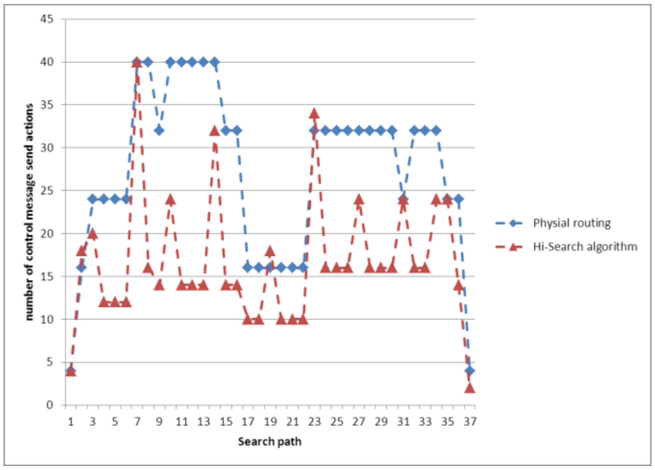

Figure 11. The number of control message sending.

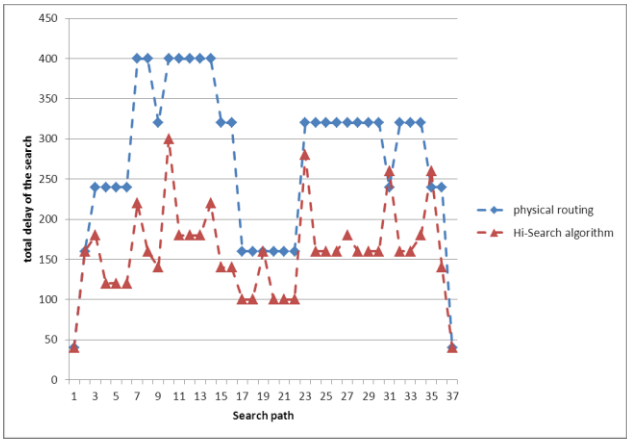

Figure 12. Delay the search.

In practical situations, the physical characteristics including the delay in each edge vary according to applied radio access technology. The network optimization removes weak and high delay edges from the path, which may make the delay difference between physical search and *Hi-Search* algorithm even larger than what is shown in Figure 12. In addition, the processing delay of each vertex is usually bigger than zero. When applying the *Hi-Search* algorithm, the number of intermediate hops in the path is minimized in such a manner that weak nodes are removed from the path by network optimization. Therefore, in a practical situation the delay difference between physical search and *Hi-Search* algorithm is even larger than what is shown in Figure 12.

B. Evaluation of network optimization

The evaluation of network optimization has been carried out with NS-2 simulations to evaluate its effects to the end-to-end delays, physical route lengths and throughput. In addition, the effects of degree of clustering, i.e. the number of physical short-cuts to these, have been studied. Mobility is not allowed in the simulations, and the comparison is carried out in such a manner that the only changing factors are the number of physical short-cuts and the transmission power. In this way, it is expected that the effect is seen in pure manner.

Four different topologies have been simulated, each of which have a different number of nodes: 61, 100, 150 and 200. The applied simulation parameters are shown in Figure 13. The physical level routing solution is called eAODV, and the overlay level solution is called eORCP.

Delay in sending a packet between source and destination as a function of the number of nodes is shown in Figure 14. The blue line represents eAODV routing in the network, in which all the nodes have transmission power Pt_ 0.002818, which means 2.818 mW and ca. 50m transmission range. In this case, there are no overlay nodes, which means that all the nodes are in the same cluster. The other lines represent eORCP with a different number of overlay nodes (2, 4, and 6) added into the same network topology. The overlay nodes have transmission power Pt_ 0.2818, which means 281.8 mW and approx. 150m transmission range. Therefore, the overlay nodes can be connected with neighbor nodes in a larger neighborhood area. In the simulations, the end-to-end delay is an average of 50 measured round trip end-to-end delays. According to the simulation results, the end-to-end delay is shorter when the number of overlay nodes increases. The differences in the delays of eAODV and eORCP-* cases are not very big, however; the simulations give a clear indication that the larger number of physical short-cuts makes the end-to-end delay shorter.

```
set val(chan)    Channel/WirelessChannel              ;# channel type
set val(prop)   Propagation/TwoRayGround  ;#radio-propagation model
set val(netif)  Phy/WirelessPhy            ;          # wireless
set val(mac)    Mac/802_11                            ;# MAC type
set val(ifq)    Queue/DropTail/PriQueue               ;# queue type
set val(ll)     LL                                    ;# Link layer type
set val(ant)    Antenna/OmniAntenna                   ;# antenna type
        ….
# SharedMedia interface with parameters to make
# it works like the 914MHz Lucent WaveLAN DSSS radio interface

Phy/WirelessPhy set CPThresh_ 10.0
Phy/WirelessPhy set CSThresh_ 1.559e-11
Phy/WirelessPhy set RXThresh_ 3.652e-10
Phy/WirelessPhy set Rb_ 2*1e6

#the range is about 50 meters

Phy/WirelessPhy set Pt_ 0.002818
Phy/WirelessPhy set freq_ 914e+6
Phy/WirelessPhy set L_ 1.0
```

Figure 13. Simulation parameters.

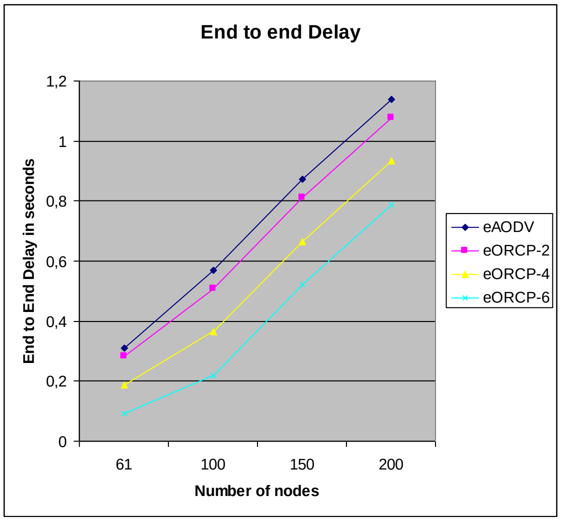

Figure 14. End-to-End Delay.

The reason for the shorter end-to end-delay can be seen from Figure 15. Because the overlay nodes use larger transmits power when implementing the wireless short-cuts, they enable a shorter physical route to the destination. Because there is some delay in each of the wireless links, the end-to-end delay is shorter when the number of hops is fewer. For example, in 61 node network, the end-to-endroute for the pure physical router network (eAODV) consist of 55 hops, and when applying 6 overlay nodes, the physical route consist of 15 hops. This gives a clear indication that the larger number of physical short-cuts reduces the number of intermediate hops, i.e. the path of a route is shorter. However, it is obvious that the absolute quantity of reduction in the delay and the number of intermediate hops in the route depends on the topology.

Throughput in delivering a large number of packets between source and destination as a function of number of nodes is shown in Figure 16. In the measurement, the applied packet size has been 512 Bytes. As can be seen, the system with eAODV solution has a somewhat lower throughput compared with, for example, eORCP-2, eORCP-4 and eORCP-6. This means that the performance improves when the number of overlay nodes increases independent of the number of nodes attached into the system. Thus, the simulations give a clear indication that increasing the number of physical short cuts in the system improves system performance. The improvement is not very big, however. It is seen that this improvement is generic, even if it is obvious that the absolute quantity of the performance improvement depends on the topology.

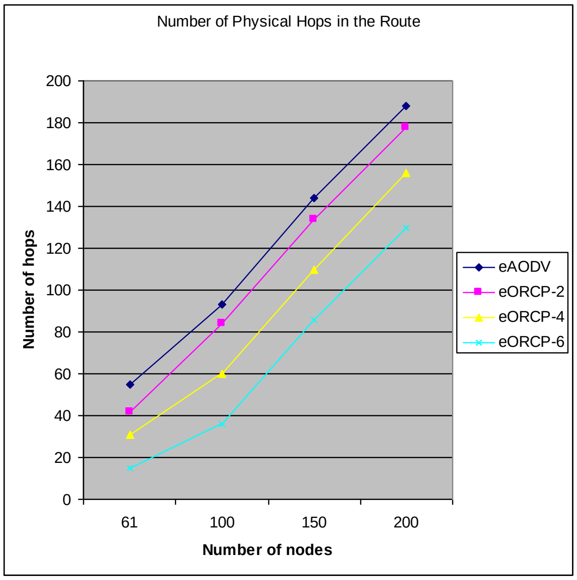

Figure 15. The number of physical hops in the route.

The degree is here used to indicate the level of clustering in a specific topology and moment of time. In addition, the number of overlay nodes is used to indicate the level of clustering, as described earlier. In our simulation cases, the overlay nodes have larger transmission power (Pt_ 0.2818, ~ 150m range); and it enable them to have more than 2 neighbors in the communication range in the simulated topologies. Instead, the physical router nodes have lower power (Pt_ 0.002818, ~50m range), and therefore they can have only 0-2 neighbors. In the simulation cases, the number of overlay nodes (D_H: 0, 2, 4, 6) has been significantly smaller than the number of physical router nodes (D_L: 61, 100, 150 and 200). Therefore, the simulated topologies represent scale-free networks, because the majority of nodes have very few neighbors (D_L is big), and only a few nodes have many neighbors (D_H is small).

The discovered physical route lengths are shown in Figure 17. The simulation of 4 topologies all indicate that when the degree of clustering increases, the number of hops in the discovered physical route decreases. This result indicates typical small world phenomena, where the high clustering means shorter physical routes between nodes.

Throughputs of 4 topologies as functions of degree of clustering are shown in Figure 18. As can be seen, throughput increases when clustering increases. This means that the degree of clustering has a positive effect on the throughput. The system can be claimed to scale better because, when the clustering is higher, throughput is better and delay lower.

The simulation results indicate clearly that when increasing the number of physical short-cuts in the system, the end to end delays and the physical routes become shorter, and throughput improves. Thus, when the degree of clustering increases, the physical routes become shorter and the performance of the system improves. Simultaneously, the system scalability is improved, because when the clustering is higher, throughput is better and delay lower. These improvements seem to be generic; however, it is obvious that the absolute quantity of the improvement depends on the topology.

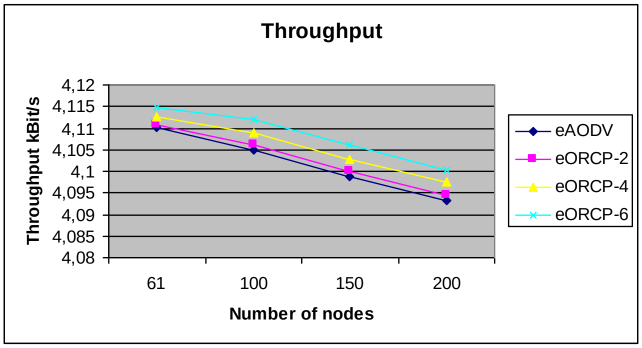

Figure 16. Throughput.

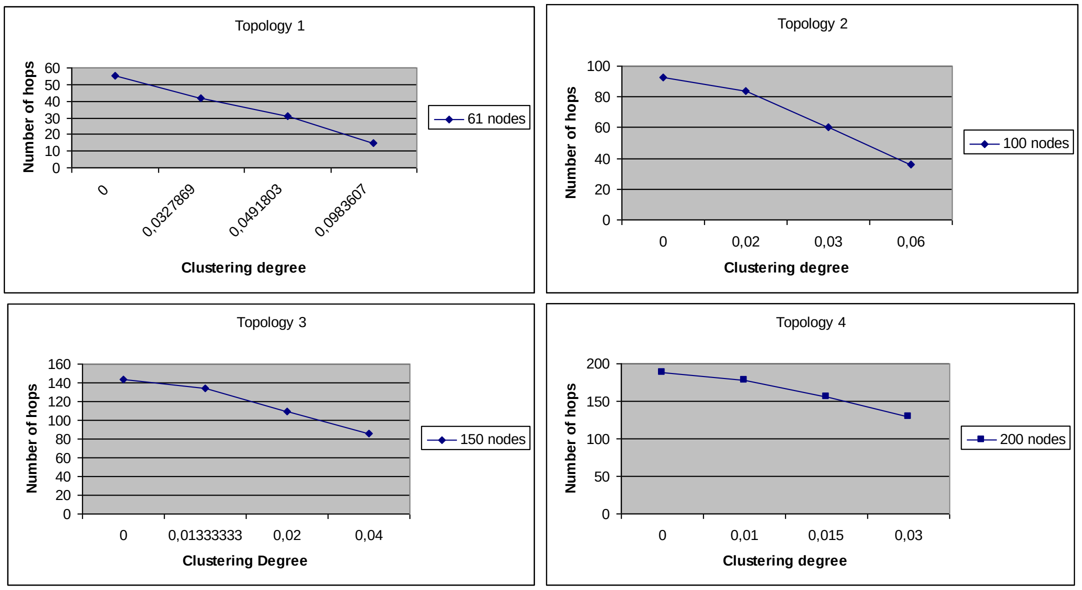

Figure 17. Route length as a function of degree of clustering.

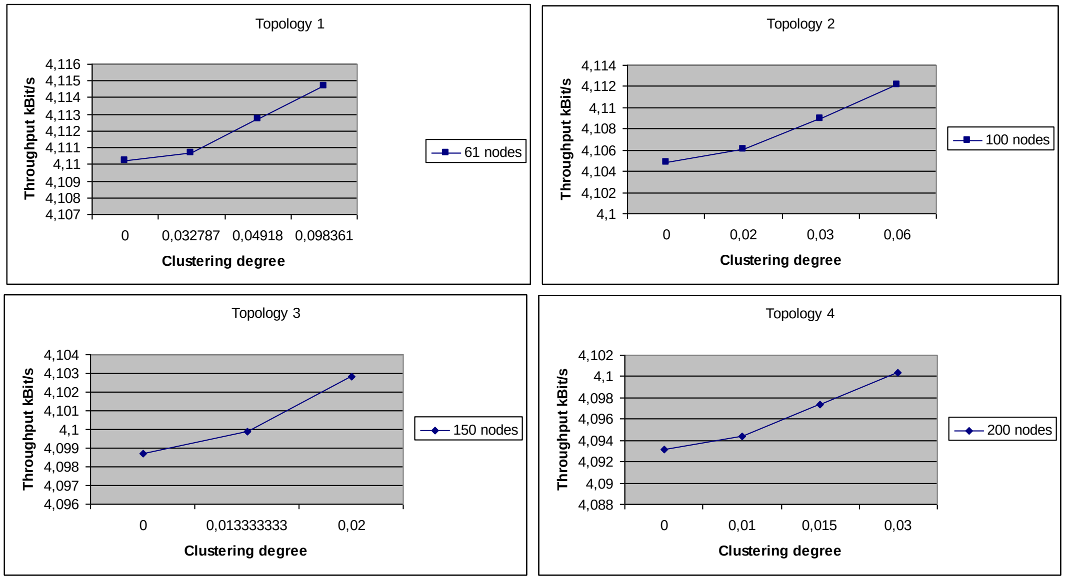

Figure 18. Throughput as a function of degree of clustering.

C. *Evaluation of Procedures*

The topology of the simulated network is shown in Figure 3. The simulated network consist of two U nodes, six S nodes, six R nodes, ten sensor nodes (Ts), four actuator nodes (Ta) and two camera nodes (Tc). The blue lines represents physical routes, and the dotted lines shows overlay neighbor connections. The numbers represent the physical addresses of nodes, and letters of the alphabet represent overlay addresses. In this example, all the nodes have both physical address (1…30) and the service nodes (U, S, Ts, Ta and Tc) have a logical address (A … H, a … p). The numbers in parenthesis indicate the location of the nodes. The simulation parameters of the radio links are shown in Figure 19.

The procedure for simulation is described briefly in the following:

- *Initialization and startup of the nodes and their services*: During this process, all the layers of the nodes are started including the services of the nodes. The services include virtualized M2M services such as overlay router (P2P router), switch, heating regulator, temperature sensor, and surveillance camera.
- *Hierarchical Neighbor Discovery:* During this procedure, the physical router inside the nodes detects physical neighbors, and the logical overlay router inside some nodes becomes aware of its logical neighbors. The length of the logical short-cut, i.e. the intermediate wireless hops between the path of neighboring overlay nodes, and the delay between logical neighbors have a significant contribution to the efficiency of the neighbor discovery process.
- *Network optimization:* During this procedure, the network creates the physical shortcut. In the simulations, the capabilities of the creation of physical short-cut are analyzed and evaluated in a functional sense.
- *Service Discovery:* During this procedure, the user is searching via the U node for all the services, which are available to him/her at the time of the search. The list of all the available services is shown as a result of the search. The number of discovered services and the waiting time of the search have an essential meaning for the user.
- *Service use:* During service use, service level payloads are transferred from the service node to the user node. Measuring the end-to-end delay, the number of physical intermediate hops in the route and throughput is used in the evaluations.

The measured delays in hierarchical neighbor discovery are shown in Figure 20. The delay values are shown on the Y axis in seconds as a function of intermediate physical hop numbers. In the simulated topology, there were only 1, 2 or 4 physical hop routes between the overlay neighbors. The delays represent time from the sending of NeighborHelloReq (DiscoveryReq in step 2 of Figure 7.) to receiving NeighborHelloRsp (DiscoverRep in step 4 of Figure 7.), i.e. the creation of logical short-cuts. The delay includes discovery of the physical route to the logical neighbor, and delivery of the related messages using the route. The measurements indicate that the number of physical hops increases the average delay in the hierarchical neighbor discovery. However, the variance in the measured delays in the hierarchical neighbor discovery is quite a high. The reason for this is assumed to be the loss of messages in the simulated radio channel (Propagation/TwoRayGround) or message drops in the physical router queue (Queue/DropTail/PriQueue).

```
set val(chan) Channel/WirelessChannel       ;# channel type
set val(prop) Propagation/TwoRayGround      ;# radio propagation model
set val(netif) Phy/WirelessPhy              ;# wireless
set val(mac) Mac/802_11                     ;# MAC type
set val(ifq)  Queue/DropTail/PriQueue       ;# queue type
set val(ll)   LL                            ;# link layer type
set val(ant) Antenna/OmniAntenna            ;# antenna type
…
# unity gain, omni-directional antennas
# set up the antennas to be centered in the node and 1 meter above it
Antenna/OmniAntenna set X_ 0
Antenna/OmniAntenna set Y_ 0
Antenna/OmniAntenna set Z_ 0.95
Antenna/OmniAntenna set Gt_ 1.0
Antenna/OmniAntenna set Gr_ 1.0

# Initialize the SharedMedia interface with parameters to make
# it work like the 914MHz Lucent WaveLAN DSSS radio interface
Phy/WirelessPhy set CPThresh_ 10.0
Phy/WirelessPhy set CSThresh_ 1.559e-11
Phy/WirelessPhy set RXThresh_ 3.652e-10
Phy/WirelessPhy set Rb_ 2*1e6

# Transmitter power is divided by 100 for the smaller nodes.
# The range is about 50 meters
Phy/WirelessPhy set Pt_ 0.002818
Phy/WirelessPhy set freq_ 914e+6
set val(chan) Channel/WirelessChannel       ;# channel type
set val(prop) Propagation/TwoRayGround      ;# radio propagation model
set val(netif) Phy/WirelessPhy              ;# wireless
set val(mac) Mac/802_11                     ;# MAC type
set val(ifq)  Queue/DropTail/PriQueue       ;# queue type
set val(ll)   LL                            ;# link layer type
set val(ant) Antenna/OmniAntenna            ;# antenna type
…
# unity gain, omni-directional antennas
# set up the antennas to be centered in the node and 1 meter above it

Antenna/OmniAntenna set X_ 0
Antenna/OmniAntenna set Y_ 0
Antenna/OmniAntenna set Z_ 0.95
Antenna/OmniAntenna set Gt_ 1.0
Antenna/OmniAntenna set Gr_ 1.0

# Initialize the SharedMedia interface with parameters to make
# it work like the 914MHz Lucent WaveLAN DSSS radio interface

Phy/WirelessPhy set CPThresh_ 10.0
Phy/WirelessPhy set CSThresh_ 1.559e-11
Phy/WirelessPhy set RXThresh_ 3.652e-10
Phy/WirelessPhy set Rb_ 2*1e6

# Transmitter power is divided by 100 for the smaller nodes.
# The range is about 50 meters

Phy/WirelessPhy set Pt_ 0.002818
Phy/WirelessPhy set freq_ 914e+6
Phy/WirelessPhy set L_ 1.0
```

Figure 19. The simulation parameters.

The number of discovered services and the waiting time of the search have an essential meaning for the user. The discovered services are shown as printed output from the U nodes *0* and *1* in a simulation execution in Figure 21. In the example simulation execution, 6 services were discovered out of 16 possible. The service reply messages from the P2P router C and D and sensor nodes j, h and g were dropped in the simulated radio channel, and therefore the services behind them were not discovered. The measured waiting time of the service discovery results was on average 0.4573 sec. The example service discovery simulation case indicates that loss of messages in the wireless channels causes undiscovered services unless reliable delivery services are not provided by the communication layer for the services layer.

During service use, service level payloads are transferred from the service node to the user node. The measured performance of simulated service use is shown in Tab I. When increasing the sending power, the number of intermediate hops decreases. For example, in our topology visualized in Fig. 6, the number of intermediate nodes between *U*-nodes *0* and *1* was reduced from *5* to *3*. As a result of this, the end-to-end delay was decreased from *30.2 ms* to *17.9 ms*. In addition; throughput is also improved somewhat, from *4.1268 kbit/s* to *4.1272 kbit/s*. The measured performance of simulated service use indicates that the establishment of wireless short-cuts can be very useful, because it reduces the number of intermediate hops, makes end-to-end delay shorter and improves throughput.

Simulation of *dynamic* network optimization proved to be very challenging with the *NS-2* simulator, because it did not seem to be possible to change the transmission power or applied radio technology dynamically after the node had been created in the simulator.

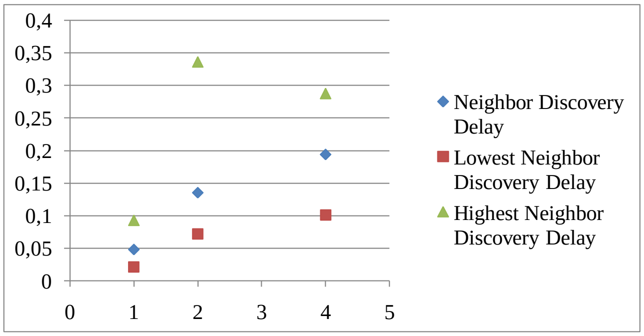

Figure 20. Average delays in seconds in hierarchical neighbor discovery.

```
**************** Node 0's Services at 200.00 ****************
 -- Location / Updated / Service --
 --     l  /  98.22  / H_sensor_A2  --
 --     k  /  96.21  / T_sensor_A1  --
 --     F  /  150.12  / P2P_Router4  --
 --     G  /  150.40  / P2P_Router5  --
 --     d  /  150.40  / H_Regul_G1  --
 --     i  /  150.40  / T_sensor_G2  --
 --     o  /  150.40  / S_camera_G4  --
 --     H  /  150.44  / P2P_Router6  --
 --     c  /  150.44  / H_Regul_H1  --
 --     D  /  150.45  / P2P_Router2  --
 *********************************************************
 **************** Node 1's Services at 200.00 ****************
 -- Location / Updated / Service --
 --     g  /  88.17  / A_sensor_B1  --
 *********************************************************
```

Figure 21. The discovered services in the U – nodes.

TABLE I. MEASURED PERFORMANCE OF SIMULATED SERVICE USE

Sending power Pt_	**Number of intermediate hops**	**End to end delay ms**	**Throughput kbit/s**
0.009818	3	17.9	4.1272
0.002818	5	30.2	4.1268

D. Discussion

The problem in flat route discovery is that search queries are also forwarded in the deep leaves of the search trees. This problem is solved in the hierarchical routing in the sense that only the nearest logical overlay nodes are initially searched at the physical route level. The result of this step is discovered physical routes between neighboring overlay nodes. After this phase, the network can be optimized by removing non-optimal radio links and physical routers from the referred local physical path. The result of this step can be direct connection between neighboring overlay nodes, which may be most optimal for local communication. When an application message needs to be sent, then searching of the end-to-end route is triggered. If network optimization has been successful, then the search paths depths are as in overlay search, i.e. significantly lower than the search path depths for the end-to-end physical routes. The evaluations also indicate that then the number of control message send actions and delay of the search are also lower. In addition, the search queries do not unnecessarily disturb the nodes, which are in the deep leaves of the search trees.

The measurements of hierarchical neighbor discovery simulations indicate that the number of physical hops increases the average delay in the hierarchical neighbor discovery, but the variance is quite high because of message losses in the communication channel. The loss of messages also causes undiscovered services when no reliable communication is provided by communication layer to the services layer. The measured performance of simulated service use indicates that the establishment of wireless short-cuts can be useful, because it decreases the number of intermediate hops, makes end-to-end delay shorter and improves throughput.

The evaluations of the hierarchical routing have been carried out in multiple steps: theoretical evaluation of the Hi-Search algorithm, simulation of the network optimization and simulation of the procedures. The theoretical evaluation is limited in the sense that only one example network has been represented; however, the aim is to enlarge and generalize the graph theoretical evaluation in the next step. Limitations of the NS-2 environment cause serious challenges in simulation-based evaluation of network optimization and procedures. This is because it is not possible to simulate properly the features of dynamic wireless networks, such as, for example, changing the transmission power, changing applied radio technology dynamically after the node has been created, and having more than one different radio and network interfaces for a single node. Therefore, evaluation of the network optimization and procedures was limited here to quite simple topologies without any mobility. The aim in the next step is to simulate more complicated dynamic networks, more complex topologies, mobility and advanced features of hierarchical network with NS-3, and also to evaluate in a real experimental case.

VI. CONCLUSIONS

The evaluation indicates that the search path depths for the *Hi-Search* algorithm are lower than the search path depths for the end-to-end physical routes. The logical short-cuts, i.e. the physical routes between logically neighboring vertices, are searched only once, which reduces the number of required control message send actions. The search delays are lower compared with physical routing. The network optimization removes weak and high delay edges and vertices from the path, which may make the delay difference between physical search and *Hi-Search* algorithm even greater. The evaluation of network optimization indicates that increasing the number of referred physical short-cuts reduces the end-to-end delays, makes the physical routes shorter, and also improves throughput. When the degree of clustering increases, the physical routes become shorter and the performance of the system improves. The detected evaluation results of the network optimization with physical short-cuts conforms quite well to the phenomenon of small world and scale-free networks. The evaluation of procedures indicates that the average delays in neighbor discovery are increased by the number of physical hops. In addition, message losses in the radio channel increases variance in the neighbor discovery delays. Generally speaking, the service discovery delays were at a feasible level in the simulated topology. However, loss of messages in the wireless channels causes undiscovered services. The measured performance of simulated service use indicates that the establishment of physical short-cuts can be useful, because it reduces the number of intermediate hops, makes end to end delay shorter and improves throughput.

Summarizing, the evaluation results indicate that the *Hi-Search* algorithm with network optimization is able to lower search delays, make the physical routes shorter, and also improve throughput. In addition, solving the complexity and heterogeneity problems is made possible by localizing route search and abstracting communication to two different routing layers. However, because of practical limitations with the applied simulation platform, it was not possible to simulate properly dynamic features of different topologies and mobility. Therefore, the aim in the next step is to work with more complicated dynamic networks, more complex topologies, mobility and advanced features of the hierarchical network with NS-3, and also to evaluate hierarchical routing in a real experimental platform.

ACKNOWLEDGMENT

We would like to thank Tekes and VTT for funding this work.

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