A Hierarchical Routing Algorithm for Small World Wireless Networks

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***Abstract*—Embedded devices are tomorrow working in dynamic wireless networks, which requires novel solutions for routing because of heterogeneity, long communication paths, long delays and weak performance. As a contribution of this research, a hierarchical routing algorithm called as, *Hi-Search*, is provided. The algorithm relies on the wireless short-cut based solution for small world wireless networks and hierarchical neighbor discovery. The provided hierarchical search algorithm is based on graph theoretical system model and network search tree analysis both on overlay and physical levels. The efficiency of the *Hi-Search* algorithm is analytically evaluated in terms of search path depths, number of control messages, and delay of the search, which are compared against the flat physical routing approach. 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. In addition, the number of control message send actions and search delays are lower compared with physical routing.**

Keywords-dynamic wireless networks; small world; routing.

I. INTRODUCTION

The number of wirelessly communicating embedded devices has continuously been increasing in recent years. It is expected that the networks consisting of such devices will be highly dynamic wireless networks. Therefore, it is here assumed that dynamic self-configurable (ad hoc) routing solutions are required. The ad hoc networking protocols, such as, e.g., Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [1], Ad hoc On-Demand Distance Vector (AODV) [2], and Dynamic MANET On-demand (DYMO) [3] 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. A possible solution approach for these challenges is overlay networking [4, 5]. Delay-Tolerant Networks (DTN) and opportunistic networking [6, 7, 8] solutions enable communication also when the source and destination nodes not necessarily reachable at the time of communication need. However, the *heterogeneity* of nodes, radio links, and dynamic topologies still triggers challenges for them.

The selected approach in this research for solving the heterogeneity problem is application small world paradigm for wireless networks [9, 10, and 11]. By adding a few short-cut links, path length of wireless networks can be reduced drastically. Our previously published simulations have indicated that increasing the number of referred wireless short-cuts lowers the end to end delays, and makes the physical routes shorter, and also improves throughput [12]. In addition, the key enabling mechanisms for neighbor discovery are provided in [13] to solve the elementary challenges related to multilevel routing and creation of wireless short-cuts. Relying on these solutions, we have provided here, a hierarchical search algorithm, called as *Hi-Search*. The provided hierarchical search algorithm is based on graph theoretical system model and network search tree analysis both on overlay and physical level. The efficiency of the *Hi-Search* algorithm is evaluated in terms of search path depths, number of control messages, and delay of the search, which are compared against the flat physical routing approach. In physical routing, the neighboring nodes have always only direct physical communication links between each other, and in overlay routing there can also be logical communication links between logically neighboring nodes, which are not necessarily physically adjacent.

Related research is shortly analyzed in the following. The hierarchical routing schemes with distributed hash tables (DHT) are discussed in [14]. The essential difference compared with our solution is that DHT based hierarchical routing schemes do not take into consideration of physical route discovery at all. Small world based routing, called as SWER, dedicated to supporting sink mobility and small transfers have been provided in [15]. 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 difference compared with our solution, is that the weak sensor nodes and radio links are still applied in realizing the short-cut. Strategies for adding long-ranged links to centrally placed gateway node in wireless mesh networks are provided in [16]. Based on the strategies, 43% of reduction in average path length was reported. Hierarchical routing based on clustering using adaptive routing using clusters (ARC) protocol is provided in [17]. They represent a new algorithm for cluster leader revocation to eliminate the ripple effect caused by leadership changes. Other examples of related routing solutions are a contact-based architecture for resource discovery [18], Mobile router nodes used as data mules [19], and P2P-based SWOP protocol [20]. There are also quite a many solutions for neighbor discovery such as [21, 22]. However, route discovery is usually executed in flat manner, e.g., [23]. The problem in such a search is that the search queries are forwarded also into the deep leafs of the

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search trees. Our approach is different in the sense that only the nearest logical overlay nodes are searched in the physical route level, and the network can be optimized by removing non-optimal radio links and physical routers from the path acting as a wireless short-cut.

The system mode, reasoning and the hierarchical search algorithm is described in section II. The efficiency of the hierarchical search is evaluated in section III. Finally, in section IV, conclusions are provided.

II. Hierarchical Search Algorithm

A. Hierarchical System Model

The network consists of different types of nodes such as *U* node, which is a user interface (UI) node, which is able to host the network, set of services and it may visualize the services 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 be a sensor (*Ts*), actuator (*Ta*) or camera (*Tc*). Each of the referred nodes may not be always on and they may be mobile and can apply whatever wireless/wired access means for communication with the neighbor nodes. An example system is shown in the form of graph in Figure 1. In the example physical network graph (G_{PN}), vertice ($V_{PN}=0$) i.e. node (0) represent the User node. Each vertise 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, e.g., distance (*D*) and delay (Δt), $E_{PN}.\{D, \Delta t\}$. In the example the overlay network graph (G_{ON}) are established by the U, and S vertices (V_{ON}). The dotted red lines represent the edges of the overlay network (E_{ON}). The overlay network graph is here said to be *virtual* graph of the physical network graph (G_{ON} c G_{PN}). Respectively, we can define 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}) shown in Figure 2. Such 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.

Respectively, G_{ON} can be represented in the form of a tree (T_{ON}) shown in Figure 3. It is easy to see that the height of the overlay network tree is smaller than the height of the physical network tree. It means that the overlay network path from source to the destination usually contains smaller amount of hops.

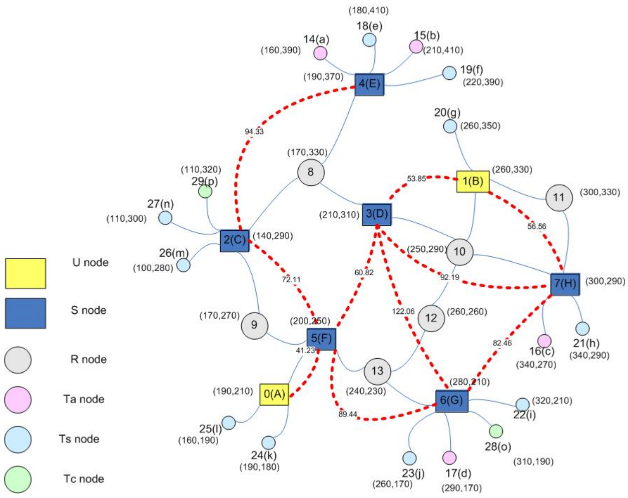

Figure 1. Example System Graph (G_{PN} and G_{ON}).

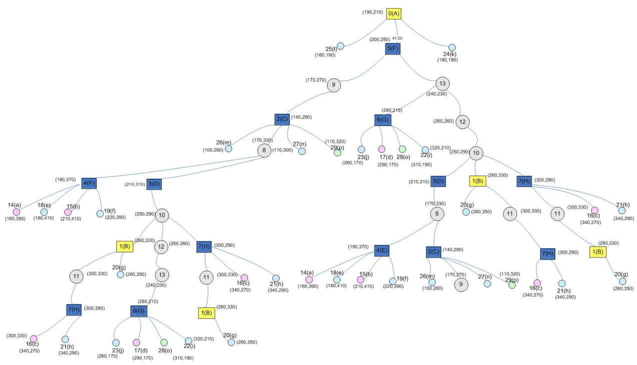

Figure 2. Example System physical network Tree (T_{PN}).

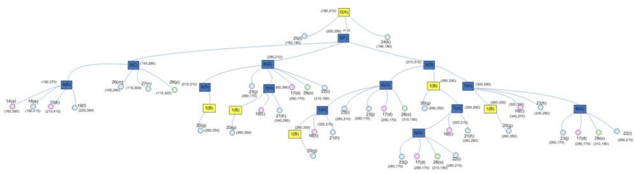

Figure 3. Example System Overlay Network Tree (T_{ON}).

B. Reasoning

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

- Each edge in the search path means additional communication delay for the search. Therefore, the amount of levels in the search tree needs to be minimized. For example, if the search proceed into deep sub trees, which does not have the destination, the search unnecessarily disturbs the vertices and consumes the radio bandwidth in the area of the leaf sub tree.
- Each vertice in the search tree processes the search, and it adds processing delay (Δt_p) for the search. Therefore,

the amount of vertices in the search path needs to be minimized. It can be claimed that the search unnecessarily disturb all vertices in the search path, if the node is not the destination. Unnecessary disturbing any node should be minimized.

- Let us call the minimization of the search tree levels, minimization of the amount of vertices in the search path and minimization of vertice disturbing as *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 means that the hierarchical search is executed in T_{ON} (Figure 3.) and in the split sub trees of T_{PN} visualized in Figure 4. In this way, the physical level search results a local optimum physical path 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 the others, e.g., they can have good power sources and good computing platform while the 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) shall 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 lowers the total communication delay (Δt_c) of the search. Let's call here the removal process as *network optimization*.
- The network optimization process is focused into the split sub trees of T_{PN}, see Figure 4. Because, the R nodes are assumed to be the bottleneck nodes, the S/U nodes actively tries to remove them from the local physical communication paths, and create a shortcut between the neighboring S/U nodes. As a result from the successful network optimization, the search tree is like T_{ON} visualized in Figure 3.
- Summarizing, the hierarchical search with search tree minimization and network optimization processes results a situation, where the search path consist only powerful and well-connected S/U nodes and not any bottleneck nodes

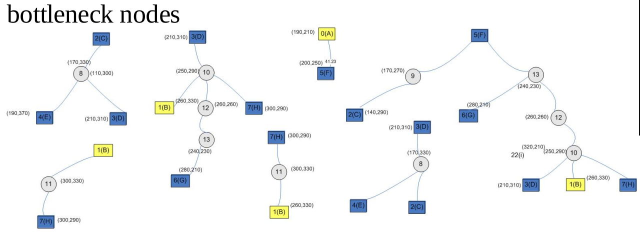

Figure 4. Split sub trees of T_{PN}.

C. Hierarchical Search Algorithm

The hierarchical search algorithm is represented in the Figure 5. 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 the key contents of it and replies with *DiscoverRep*, which is sent in 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 of the *DiscoveRep* triggers searching for the physical route between the neighboring overlay nodes, e.g., using AODV RREQ/RREP procedure. After the original source receives *DiscoverRep* via the discovered physical route, the system is ready to provide messaging services for applications.

When an *ApplicationMsg* is received from the upper layer and the overlay route is known, it is forwarded towards the intended destination. Otherwise, an overlay route is searched first, and then the message is forwarded towards it.

```
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
applicationMsg
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 5. Hierarchical Search Algorithm.

In this manner, the ApplicationMsg has been delivered to the destination using hierarchical search with minimized search tree. At any time after system is ready, the network optimization procedure can be initiated. In the network optimization, direct wireless communication links for the neighboring overlay nodes are created as communication short-cuts in the cases where it is physically possible with the available radio access technologies of the overlay nodeswhich mean lower search paths.

III. EFFICIENCY OF THE HIERARCHICAL SEARCH

The depths of the search paths, for the example graph shown in Figure 1. are visualized in Figure 6. There are 37 possible search paths for both physical and overlay networks, see Figure 2. and Figure 3. respectively. Each search path is shown in the x-axis, and the depth of the search path is shown in the y-axis in the Figure 6. For example, for the search path number 11, the depth of 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 provided *Hi-Search* algorithm applies overlay route search, which mean lower search paths.

The physical search path depths of overlay hops are shown in Figure 7. (see also Figure 4.). The y-axis shows the physical search path depths, and x-axis shows the number of their required searches in Figure 1. in physical routing situation. For example, the physical search path 5-9-2, which depth is 2, happens 17 times in physical routing situation. The referred physical search paths seem generally happen multiple times in the example network in physical routing situation. This is not very efficient, and therefore the proposal is that the network optimization creates shortcuts between the neighboring overlay vertices. Then there is need to execute referred physical search paths only once for the network, and optimization can be based on it. The referred action is initiated in the row 22 of the *Hi-Search* algorithm.

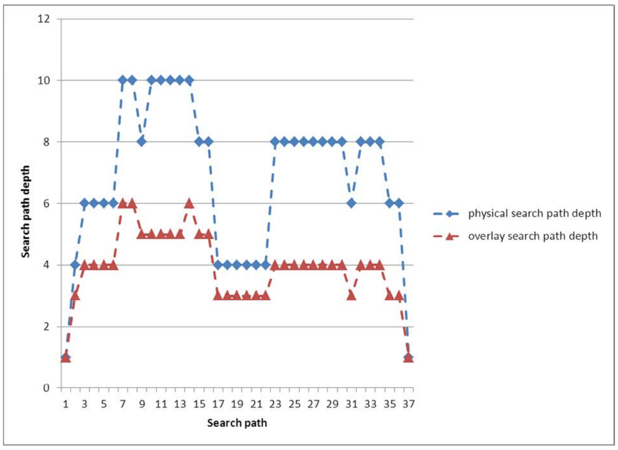

Figure 6. Search path depths.

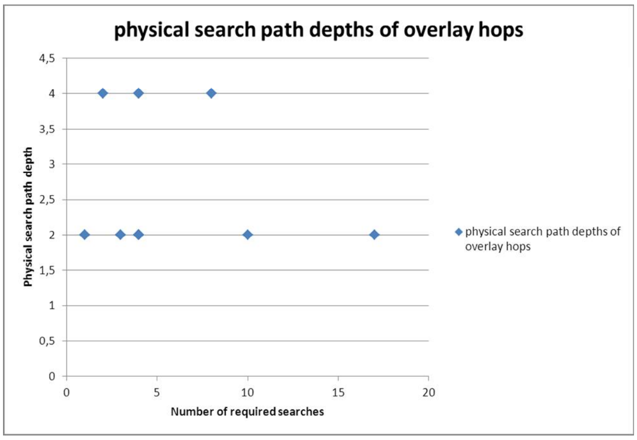

Figure 7. Physical search path depths of overlay hops.

The number of control message sending actions is shown in y-axis of Figure 8. When the physical route between neighbouring overlay nodes are searched initially and optimised, the number of control message send actions are about the same level as in physical routing (x=7). However, after the optimisation has been executed, then the number of control message send actions lowers significantly, because there isn't need to repeat optimisation. It can be seen that the number of control message send actions is lower when applying *Hi-Search* algorithm compared with physical routing.

The total delay of the search is shown in y-axis of Figure 9. It is here assumed that the delay in each physical hop, i.e. radio link, is 10ms, the optimization happen in 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 the optimization, the delays are in lower level. As a result, it is seen that the *Hi-Search* algorithm is better because it has lower search delays than physical routing.

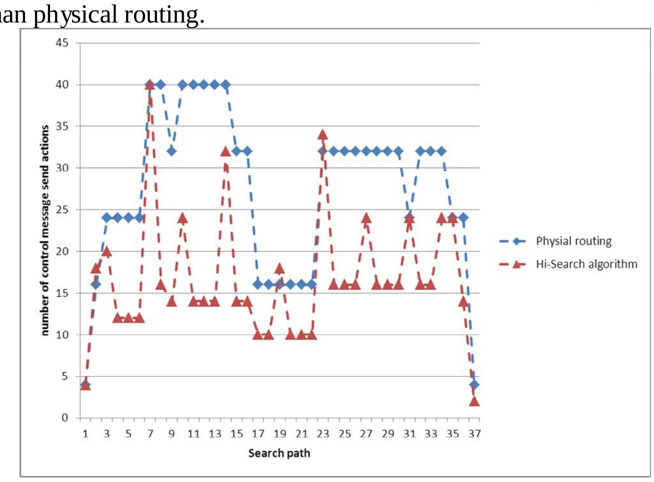

Figure 8. The number of control message sending.

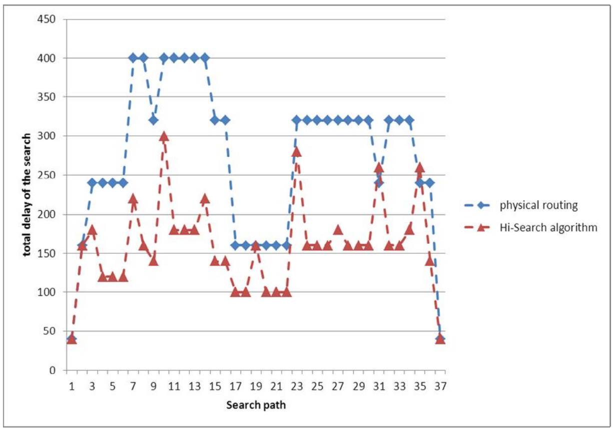

Figure 9. Delay of the search.

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 bigger than what is shown in Figure 9. In addition, the processing delay of each vertise is usually bigger than zero. When applying *Hi-Search* algorithm, the number of intermediate hops in the path is minimized in such a manner that weak vertices are removed from the path. Therefore, in practical situation the delay difference between physical search and *Hi-Search* algorithm is even bigger than what is shown in Figure 9.

IV. CONCLUSIONS

As a contribution of this research, the hierarchical routing algorithm called as, *Hi-Search*, is provided. The algorithm relies on the wireless short-cut based solution for small world wireless networks and for the key enablers for hierarchical neighbor and route discovery, network optimization and service discovery. The provided hierarchical search algorithm is based on graph theoretical system model and network search tree analysis both on overlay and physical level. The efficiency of the *Hi-Search* algorithm is evaluated in terms of search path depths, number of control messages, and delay of the search, which are compared against the flat physical routing approach.

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 physical routes between logically neighbouring vertices are searched only once, and then the network optimization creates shortcuts between them. It can be seen that the number of control message send actions is lower when applying *Hi-Search* algorithm compared with physical routing. In addition, it has lower search delays than physical routing. When the physical characteristics including the radio specific delays of each edge, and processing delay of each vertice in the path is taken into concern, then the delay difference between *Hi-Search* and physical routing is even bigger. This is because; network optimization removes high delay edges, and weak vertices from the path.

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