Routing in Large-scale Wireless Mesh Networks Using Temperature Fields

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Abstract— **Many wireless mesh networks are based on unicast routing protocols even though those protocols do not provide a particularly good fit for such scenarios. In this article, we report about an alternative routing paradigm, tailor-made for large multi-hop wireless mesh networks: field-based anycast routing. In particular, we present HEAT, a routing protocol based on this paradigm. In contrast to previous protocols, HEAT only requires communication between neighboring nodes. The underlying routing concept is a field similar to a temperature field in thermal physics. In extensive simulation experiments, we find that HEAT has excellent scalability properties due to the fully distributed implementation and provides much more robust routes than the unicast protocols AODV and OLSR. As a consequence, in large-scale mobile scenarios, the packet delivery ratio with HEAT is more than two times higher as compared to AODV or OLSR. These promising results indicate that HEAT is suitable for large-scale wireless mesh networks covering entire cities.**

I. INTRODUCTION

A large number of IEEE 802.11 or “WiFi” access points is deployed on a daily basis, and most major cities are already covered by a dense mesh of such devices. Wireless access points provide a bridge between wireless and wired networks, typically connecting wireless gear such as laptops or PDAs to the world-wide Internet. Even though some of these access points are installed as part of commercial wireless mesh networks, many access points are set up by private users and organizations striving for convenient Internet access. In the following, we refer to access points providing Internet access as *gateways* and to wireless devices demanding Internet access as *mesh nodes* or simply nodes. Since most privately-operated gateways are only lightly loaded, their excess capacity might be leveraged to offer Internet access to other nodes in range at negligible cost. Furthermore, the coverage of a gateway can be extended by having the nodes in range of the access point relay data on behalf of other wireless devices further away. Such a scenario, where data is relayed among nodes to and from gateways, is called a multi-hop wireless mesh network. A multi-hop wireless mesh network may be an extremely cost-effective means to provide Internet access to wireless devices in cities. However, since the mesh nodes are commodity notebooks, hand-helds, or similar devices carried and operated by humans, these nodes may move out of range or shut down at any time.

In general, mobile-to-mobile communication (i.e., communication among mobile devices) poses great challenges and routing in wireless mesh networks is much easier if every mesh node is in range of at least one gateway and thus only the last hop involves a human-operated device. In current wireless mesh networks, a dedicated wireless backbone network of a large number of stationary gateways provides this high level of coverage, albeit with a hefty price tag. We report about routing protocols for such networks in the next section. Fortunately, novel routing paradigms such as field-based anycast routing seem to make multi-hop wireless mesh networks feasible and we present such a routing protocol in Sections III–V. In Sections VI and VII, we report about our performance evaluation and in Section VIII, we conclude the article.

II. ROUTING IN WIRELESS MESH NETWORKS

Even though routing in wireless networks has undergone extensive study, most wireless mesh networks are based on routing protocols that were originally designed for ad hoc networks, i.e., small networks of mobile nodes that do not involve any infrastructure and where all nodes act both as routers and as end systems. Nordström et al. propose to use source routing based on the ad hoc routing protocol DSR (dynamic source routing) [1]. Another popular ad hoc routing protocol, OLSR (optimized link state routing) [2] provides for interoperation with other networks by injecting external route information into the OLSR network. Since these protocols construct and maintain an individual unicast route from every mesh node to one of the gateways, the state information to be maintained increases with the number of nodes as well as the number of gateways in the mesh network, and their scalability is limited.

The task group for mesh networking of the IEEE 802.11 working group also considers similar routing methods. In its first draft [3], they propose to implement routing at the MAC layer. According to [4], their target size of an IEEE 802.11s WLAN mesh network is up to 32 static mesh gateways. In particular, the 802.11s task group specifies a default mandatory routing protocol called HWMP (hybrid wireless mesh protocol) that is inspired by a combination of the ad hoc routing protocol AODV (ad hoc on-demand distance vector) [5] and tree-based routing. In addition, the draft allows further standardized or vendor-specific path selection protocols. Up to now, the only alternative protocol described in the draft is RA-OLSR (radio aware optimized link state routing protocol).

Mosko et al. [6], propose to establish multiple non-disjoint paths. While this may enhance the resilience against topology changes, this multi-path unicast routing protocol is even less scalable than single-path unicast routing protocols discussed before. In [7], scalability to the number of nodes is improved based on geographical information; however, such information is often not available.

One challenging problem, alas, is that the scalability to the number of nodes of the described unicast routing protocols is limited. As we will see in the next section, the mesh network scenario lends itself well to anycast routing.

A. *Anycast Routing*

Anycast routing is aimed at networks where some client nodes require a route to any member from a certain group of service nodes. In the context of wireless mesh networks, the mesh nodes are the clients and the gateways are the service nodes. Anycast routing was first proposed for IP networks; protocol implementations followed for wireless ad hoc networks [8]. However, these IP anycast routing protocols are still based on *unicast* routing techniques such as link-state or distance vector routing, and as a consequence they inherit the scalability problems of these protocols. IP anycast in general scales poorly to the number of groups since IP anycast addresses can not be aggregated into subnets. In mesh networks however, one anycast group representing the gateways to the Internet is typically sufficient and scalability to the number of groups is not a concern.

To summarize, no established routing protocol tailor-made for large wireless mesh networks is readily available today. A routing protocol for wireless mesh networks should take advantage of the specific topology and traffic pattern of such networks. It needs to be scalable to the number of nodes as well as to the number of gateways.

In the remainder of the article we focus on multi-hop wireless mesh networks. While the majority of our elaboration applies to all mesh networks that involve mobile nodes, some of the characteristics are more accentuated in multi-hop mesh networks. In particular, multi-hop wireless mesh networks involve mobile-to-mobile communication and it is imperative that the routing protocol be robust to node mobility. An important feature of routing protocols for multi-hop wireless mesh networks is thus robustness against frequent changes in the topology of the network incurred by node mobility.

III. HEAT: FIELD-BASED ANYCAST ROUTING

The field-based or gradient-based routing paradigm in general has properties that are desirable in dynamic networks as it opens a greater design space than the traditional distance-vector or link-state routing paradigms. Lenders et al. proposed a model for anycast routing based on potential fields in [9] that uses flooding to establish the field. In this article, we have a closer look at *HEAT* [10], a protocol aiming to satisfy the requirements mentioned in the previous section. HEAT is a proactive field-based anycast routing protocol and shares with other field-based protocols the general forwarding principle. HEAT differs in how it establishes the field that defines the routes: its method to establish and maintain the field mimics heat dissipation in solids and is quite unique as it does not require flooding. Rather, nodes calculate their field value based solely on information from their immediate neighbors.

In multi-hop wireless mesh networks, multiple paths are typically available between a node and one or more gateways. It is the task of the anycast routing protocol to select a path according to a certain optimization goal. HEAT aims to select among the available paths the one that provides the maximal robustness against changes of the topology. Such topology changes may be induced by node mobility, or temporary or permanent node failures. Furthermore, environmental influences also have a severe impact on the availability and lifetime of the wireless links between the nodes and the gateways.

HEAT is inspired by the physical laws that describe heat conduction. Similar to heat sources and surrounding particles, gateways and nodes define a field in the network. Gateways represent heat sources; nodes are assigned a temperature and conduct heat from the gateways to each other. The higher the temperature of a node, the closer it is to a gateway and the greater is the diversity of paths to this gateway. Based on this temperature field, a route is then defined as the path that follows the steepest gradient; in other words, packets are always forwarded to the neighboring node with the highest temperature and thus eventually reach a gateway. HEAT establishes the temperature field in the network based on purely local information, i.e., every node calculates its own temperature by evaluating solely the temperature of its immediate neighbors. Since HEAT is an anycast protocol and only requires communication between immediate neighbors, it is well suited for large-scale applications, as it is scalable to the number of nodes and the number of gateways.

IV. THE CONCEPT OF HEAT

HEAT has two distinguishing features. First, it considers in the routing decision both the *length* and the *robustness* of the available paths. Second, the field construction and maintenance mechanism of HEAT scales to the number of nodes and the number of gateways since it only requires communication among *neighboring* nodes. These two features are tightly linked to the underlying routing concept that is inspired by temperature fields. In brief, HEAT assigns a temperature value to every node in the mesh network. New nodes are assigned a value of zero; gateway nodes are assigned a well-defined maximum value. The temperature of nodes is determined based on a simple yet effective algorithm that incorporates into the calculation both (i) the distances to available gateways and (ii) the robustness of the paths toward these gateways. That is, a path providing multiple alternative delivery opportunities along its way is preferred to a path over which packets cannot be naturally re-routed to an alternative path to one of the gateways. An example is depicted in Fig. 1. Note that there are many partly disjoint paths available leading to the gateway on the right-hand side, whereas only one path is available to the left-hand gateway. The temperature gradient as determined by HEAT is steeper toward the gateway on the right, and packets are routed in this direction, even if the network distance to the left gateway is shorter (measured in the number of hops). Only the packets from the two leftmost nodes are routed to the left-hand gateway.

A. *Physical Analogy*

A temperature field assigns a single scalar value to every particle in space. The temperature is higher in the vicinity of heat sources and then decreases with distance.

In a solid, heat is transferred by conduction. On a microscopic scale, conduction presents itself as hot, rapidly moving or vibrating atoms and molecules. By interactions among neighboring atoms and molecules, heat is transferred. The physical parameter *thermal conductivity,* κ, indicates its ability to conduct heat. The conduction of heat is governed by *Fourier's Law*. In essence, this law demands that the temperature of the field always decrease away from sources,

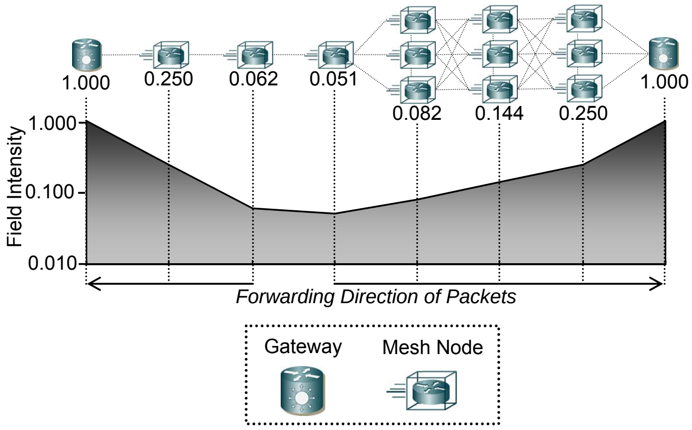


Fig. 1. Example of a temperature field with a conductivity value of $\kappa = 1/4$ and areas of different link redundancies. The packets of the node with temperature value 0.051 are forwarded to the right, across an area of high redundancy instead of to the closest gateway at the left.

resulting in a temperature gradient whose maxima are at the sources.

In order to map the properties of temperature fields to a given network topology, nodes in the mesh network are considered as particles and gateways as heat sources. In [9], Lenders et al. show that under the assumption that there are no local maxima in the field, following the path defined by the steepest gradient always leads to a gateway; and that there are no loops in this path. However, not all policies for assigning scalars to nodes guarantee that there are no local maxima in the potential field. HEAT guarantees the absence of local maxima by adhering to the following policy: For every node, only neighbors with a higher temperature may contribute to the node's own temperature. This policy guarantees monotonicity of the field and thus ensures that there are no local maxima (cf. [10]).

V. THE HEAT ANYCAST ROUTING PROTOCOL

According to the concept described before, the gateways act as the heat sources of a temperature field and the mesh nodes are assigned temperature values such that the optimal route towards any gateway is defined by the steepest gradient of the temperature field. In order to construct the temperature field starting from the initial temperature values of the gateways, the temperature values of neighbors are periodically exchanged between the gateways and neighboring mesh nodes through HEAT beacon messages. Based on these messages, every mesh node calculates its own temperature using the field calculation function.

Once the field is constructed, routing packets from the mesh nodes to the gateways is straightforward and implemented on a hop-by-hop basis: A packet is always forwarded to the neighbor with the highest temperature, resulting in steepest-gradient routing. Routing back from the gateways to the mesh nodes is implemented as source routing from the gateways. All packets sent towards gateways record their route. The source route for packets towards mesh nodes is then constructed from the inverse of the path recorded by the last packet received from the destination node. A more thorough discussion of the backward path can be found in [11].

A. Field Construction and Maintenance

As mentioned before, the sources of the temperature field are the gateways. Therefore, each gateway initializes its temperature with a certain maximum value. For the heat propagation, every node (including the gateway nodes) periodically broadcasts its temperature value to its neighbors at a given HEAT beacon time interval. Based on these messages, all nodes build and maintain a data structure called neighbor table, which contains an entry for every known neighbor. Neighbor entries comprise the address, the last reported temperature, and a timestamp value of the corresponding node. Whenever an entry is added, removed, or changed, the temperature value is re-computed. In essence, we have to differentiate among three cases:

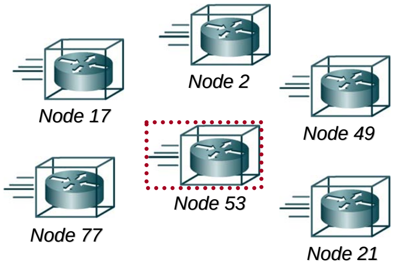
1) **New neighbor:** If a beacon from an unknown neighbor is received, a corresponding entry is added to the neighbor table.
2) **Maintain neighbor:** If the reported temperature value of a known neighbor changes, the node re-calculates its temperature value.
3) **Missing neighbor:** If no beacon is received from a neighbor for a certain period, its entry is removed and the temperature value is re-computed.

The detailed algorithm is described in Alg. 1. The algorithm calculates the temperature t_{final} of a node as follows: In a first step, the node sorts its neighbors based on their temperatures $\theta_i, i \in \{0, ..., n\}$ in ascending order (line 1) into an array a. Then, it iterates over a accumulating the temperature of the next neighbor to the sum of the temperatures of the previous neighbors t_j until the temperature of the next neighbor is less than the accumulated temperature (line 4). In each step j, the value t_{j+1} is calculated as follows (line 5): The difference between the temperature of the currently considered neighbor, denoted by $a[j]$, and the temperature accumulated so far, t_j, is calculated. Then, this difference is multiplied by the conductivity parameter κ, and the result is added to the temperature accumulated so far, denoted by t_j.

Algorithm 1 Temperature field calculation function.

```
1: $a = sort_{ascending}(\theta_0, ..., \theta_n)$
2: $j = 0$
3: $t_j = 0$
4: while $t_j < a[j]$ do
5:     $t_{j+1} = t_j + (a[j] - t_j) \cdot \kappa$
6:     $j = j + 1$
7: end while
8: $t_{final} = t_j$
```

As a result, nodes which have many neighbors that can reach one or more gateways obtain higher temperatures than nodes with only a small number of such neighbors. This effect is more pronounced the smaller the parameter κ is chosen. Figure 1 illustrates an example temperature field with a rather small value of $\kappa = 1/4$. At this low κ, the greater link diversity in the right-hand side of the network has a considerable impact on the steepness of the temperature gradient. A step-by-step example of the field calculation function is given in Fig. 2 for $\kappa = 1/4$.



Step 1		Step 2		Step 3		Step 4		Step 5	
NBR	FI	NBR	FI	NBR	FI	NBR	FI	NBR	FI
2	0.800	2	0.800	2	0.800	2	0.800	2	0.800
21	0.600	21	0.600	21	0.600	21	0.600	21	0.600
49	0.500	49	0.500	49	0.500	49	0.500	49	0.500
77	0.300	77	0.300	77	0.300	77	0.300	77	0.300
17	0.040	17	0.040	17	0.040	17	0.040	17	0.040
t_0: 0.000		t_0: 0.000		t_1: 0.200		t_2: 0.300		t_3: 0.350	

t_1=(0.800-0)/4+0

t_2=(0.600-0.200)/4+0.200

t_3=(0.500-0.300)/4+0.300

t_3 ≥= 0.300

Fig. 2. Example of the temperature field calculation with a conductivity value of $\kappa = 1/4$ for node 53: step 1, sort neighbors (nbr) by temperature value; step 2-5 iterate down the table until the given temperature value of the node is higher or equal to the next neighbor; node 71 and 17 do not contribute to the temperature value of node 53: they will increase their values after the next HEAT beacon message of node 53 (node 77: 0.313 and node 17: 0.118)

B. Expediting Convergence

A new node joining the network simply assigns itself a temperature of zero, broadcasts a HEAT beacon and then waits for a beacon from one of its neighbors. The very first arriving HEAT beacon already provides the new node with a route to the Internet. As more beacons arrive, the node adjusts its temperature until the temperature converges to its final value.

A node that disappears, for instance by moving out of range, in most cases only has a local impact on the temperature field. As soon as a node detects that the neighbor with the highest temperature is no longer available, it selects among the remaining neighbors the one with the highest temperature.

In rare cases, the disappearance of a node may cause network partitioning and individual gateways may become unreachable. During the time it takes the temperature field to reconverge, some nodes may not be able to reach any gateways. In order to expedite convergence in such cases, HEAT uses so-called *early HEAT beacons*. When a node detects that a neighbor has disappeared and that this disappearance has a significant impact on its temperature, the node broadcasts an early HEAT beacon. To limit the overhead caused by early HEAT beacons, nodes that receive an early HEAT beacon wait for a short period (e.g., a few broadcast intervals) before forwarding it, allowing multiple messages triggered by the same event to be aggregated.

C. Load Balancing

Under the HEAT protocol, every gateway is assigned the maximal temperature at the beginning, but this value may be adjusted according to the load level of the gateway. This enables the gateway to avoid congestion among the mesh nodes in its vicinity and also to adjust the total traffic to the bandwidth of its Internet access link. Note that in the evaluation we present in the next section, we do not change the temperature values of the gateway as such dynamic adaptation may not be feasible in some scenarios.

VI. EVALUATION METHODOLOGY

To evaluate the performance of HEAT, we have run an extensive simulation study with Glomosim, a network simulator for wireless networks. We compare the performance of HEAT with the popular AODV and OLSR ad hoc routing protocols in versions that were extended such that they can be used in multi-hop mesh networks, as described next. Note that in the highly dynamic scenarios we consider, the link lifetimes are too short for advanced routing metrics such as ETX to be useful.

All simulations have a duration of at least 10000 seconds; the reported values are averaged over at least 20 simulation runs with different random seeds.

A. Extended AODV

As a first reference for the performance of HEAT, we use an extended version of AODV. AODV is a reactive routing protocol and establishes a route to a destination only on demand. A node that needs a route broadcasts a route request to its neighbors, which forward this message, and record the node that they received it from. This creates a number of temporary routes back to the requesting node. As soon as a node that already has a route to the destination node receives the route request, this node sends back a message through the temporary route to the node that requested the route, which then selects among the received replies the route with the least number of hops. In order to enable the use of AODV in the mesh scenario, we extended the standard implementation of AODV included in Glomosim according to [12] to support gateway discovery in mesh networks. As proposed in the cited paper, all gateways are connected to a dedicated router that acts as a proxy to the Internet. This router has two tasks: (i) on the forward path, it sends route replies on behalf of hosts in the Internet; (ii) on the backward path, it initiates route requests for nodes in the wireless mesh network. Thus AODV does not have to distinguish between the different gateways and only a common route to the Internet has to be maintained, the route to the dedicated router.

B. OLSR

Second, we compare HEAT with the OLSR implementation from the University of Niigata. OLSR is a proactive link-state routing protocol, which means that it floods a complete topology description across the network and every node locally computes the optimal forwarding paths. OLSR allows to redistribute routing information from so-called "Non OLSR Interfaces" as the gateway uplink interface to the Internet. Using simulation experiments, we have found that the performance of OLSR drops quickly with increasing mobility. We assume that this is in part due to the long hello interval of 2 seconds. In order to achieve a fair comparison with HEAT, which has a beacon interval of 1 second, we adjusted the hello interval of OLSR also to 1 second. With this adjustment, the performance of OLSR improves by roughly 10% and we use this setting for all experiments presented in this article.

C. Simulation Settings

The simulation experiments are based on a WiFi network. All nodes are equipped with an IEEE 802.11b radio with a nominal bandwidth of 11 Mbps and a maximum range of 250 m. As MAC layer protocol we use the 802.11 DFWMAC-DCF with RTS/CTS handshake. As the radio propagation model, we use the two-ray ground model.

D. Mobility Model

Since simple mobility models such as the random waypoint or the random walk mobility models are often reported to lack realism, we use our own, more realistic mobility model [10]. This model only allows nodes to move along roads defined by a road map of a real city. We extract these road maps from the Swiss geographic information system as this database includes vectorized building and road maps that are accurate within less than one meter. Furthermore, this database also provides speed limit information for all roads.

The actual node movement is modeled according to the steady-state random trip mobility model [13] on the road maps. That is, a node chooses a random destination in the city and moves to this position at a constant speed along the fastest path. Note that we deliberately do not introduce any pausing of the nodes, and a node therefore begins to move to a new destination as soon as it arrives at the target position. The city mobility model is applied for pedestrians as well as cars since the movements of both are constrained by the available roads. Cars are further restricted by the speed limits on all roads.

E. Traffic Pattern

Wireless mesh networks are mostly used for Internet applications like web browsing, messaging, chatting, etc. and we use an Internet traffic model consisting of a mix of streaming and web browsing traffic, as described in [10]. All traffic in the simulations is between nodes in the wireless mesh network and hosts in the Internet and there is no communication among the mesh nodes.

VII. EVALUATION RESULTS

We use the following metrics to compare the performance and scalability of HEAT with OLSR and AODV.

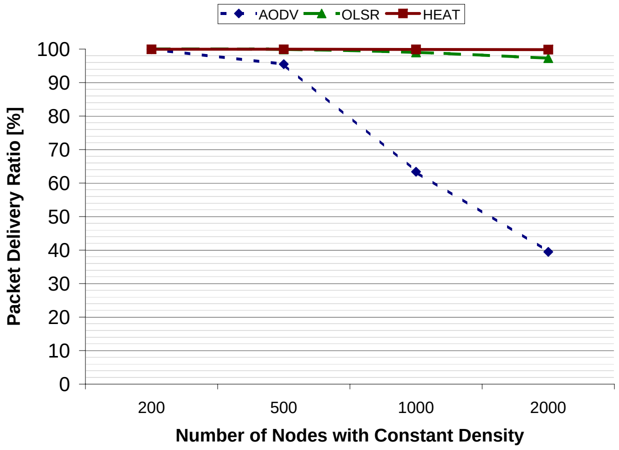
- The *packet delivery ratio* denotes the ratio between the number of packets that are successfully received and the total number of packets sent. This metric comprises the data packets sent from the mesh nodes to the gateways as well as packets from the gateways back to the mesh nodes.
- The *routing overhead* refers to the average number of routing control messages sent per node and per second.

A. Scalability to the Network Size

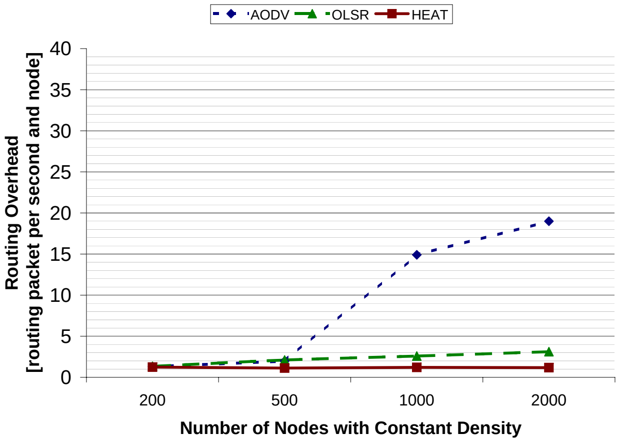
In a first experiment, we evaluate, how the performance is affected by increasing the network size at a constant average node degree. The node degree is kept constant by increasing the simulation area (the section of the maps we consider) in parallel with the number of nodes. The results for a *static* scenario are shown in Fig. 3. The nodes are placed randomly, 100 of the nodes are active, i.e., they generate traffic, and 5 Internet gateways are available. The average node degree is approximately 6. The upper part of this figure shows the delivery ratio. With HEAT, this ratio remains constant at almost 100% even as the network size increases to 2000 nodes. With OLSR, the delivery ratio decreases, but only marginally. With AODV, the delivery ratio drops significantly at network sizes greater than 500 nodes. The routing overhead, as shown in the bottom plot of Fig. 3, indicates that the reason for the performance degradation of AODV is related to this metric. As the network size increases, the average distance between the data sources and the Internet gateways also becomes longer. This increase in the length of the shortest available path forces AODV to increase the scope of its route discovery procedure [5] and it ends up using the network capacity mostly for the flooding of control messages. The overhead under OLSR increases slightly because—being a link-state routing protocol—OLSR requires complete knowledge about the whole topology to calculate the shortest path. This result shows that the hierarchical flooding mechanism used by OLSR mitigates the scalability problem as compared to AODV. HEAT achieves the best result with a constant overhead per node, independent of the network size.

B. Effect of Node Mobility

In this second experiment, we investigate how node mobility affects the routing performance. We consider two scenarios: (i)



(a) Packet delivery ratio.



(b) Routing overhead.

Fig. 3. Impact of the Network Size.

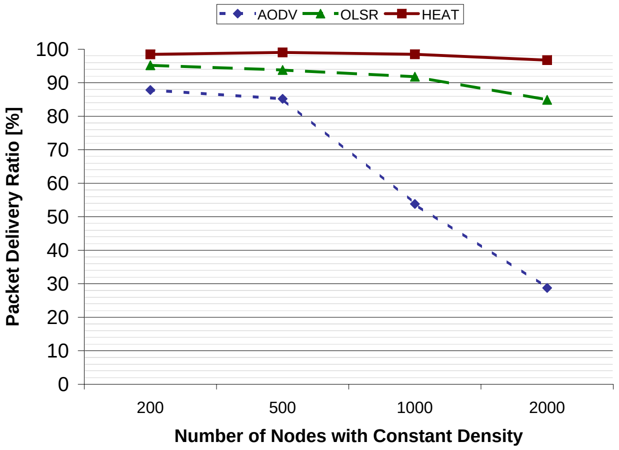
a scenario with mobile nodes moving at pedestrian speeds (i.e., node speeds that are uniformly distributed between 0.5 m/s and 3 m/s), and (ii) a scenario including nodes moving at car speeds in a city (i.e., node speeds between 10 m/s and 20 m/s).

The results for the pedestrian scenario with a simulation area of 5 km by 5 km, 5 gateways placed at strategic positions, and 100 active nodes are given in Fig. 4. At this rather low node speed, the packet delivery ratio of HEAT is almost as high as in the static scenario (shown previously in Fig. 3), but the routing overhead is slightly higher. The increasing overhead originates from the early HEAT beacons. The results of OLSR reveal that its packet delivery ratio decreases slightly for nodes moving at pedestrian speed, particularly in larger networks with longer routes. AODV is most affected by the node mobility and its delivery ratio drops sharply already at 1000 nodes.

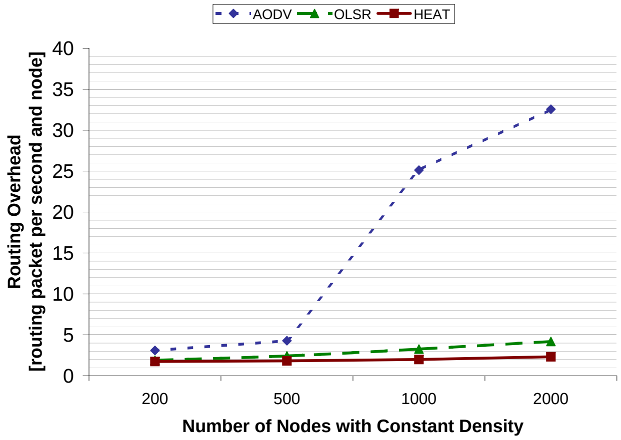
Figure 5 shows the performance at car speeds using the same settings. At these node speeds, the performance of all three protocols is lower than at pedestrian speeds. The packet delivery ratio of HEAT remains above 70% for all network sizes we evaluate. OLSR as well as AODV suffer much more and at a network size of 2000 nodes, neither of them delivers more than 50% of the packets. OLSR is affected heavily by mobility because it has to propagate information about link state changes through the whole network. HEAT, in contrast, only requires local information exchange and the early HEAT beacon mechanism accelerates the convergence of the temperature field. Again, AODV performs worst of the three, assumably due to the high overhead of route discovery broadcast messages.

C. Effect of the Number of Gateways

To conclude our evaluation, we look at the effect of the number of gateways in the mesh network. In Fig. 6, the packet delivery ratio and the routing overhead are plotted for the pedestrian scenario with 1000 nodes, 100 of which generate traffic. A total of 1 to 30 gateways are placed randomly over the entire simulated area of 5 km by 5 km. The packet delivery ratio rises with the number of gateways. This is mainly because the average distance between mesh nodes and gateways becomes shorter if the number of gateways is increased. Therefore, the average path length is shorter and the paths are less prone to link failures caused by mobility. Furthermore, when the number of gateways is too small (e.g., only one gateway), the capacity of the radio interface at the gateway(s) becomes a limiting factor. In other words, the available capacity of the gateway(s) is not sufficient to support all the traffic generated by the mesh nodes.

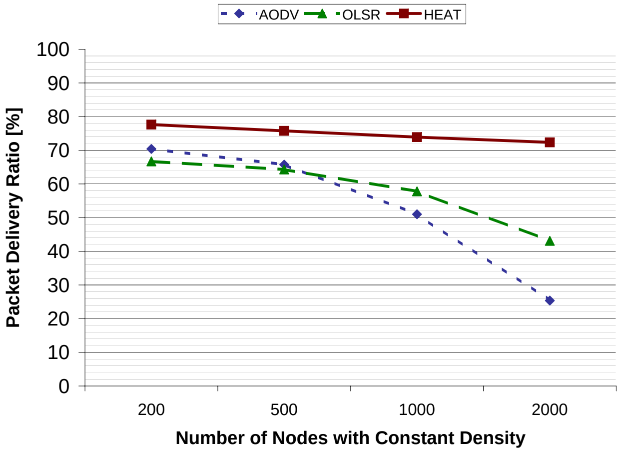


(a) Packet delivery ratio.

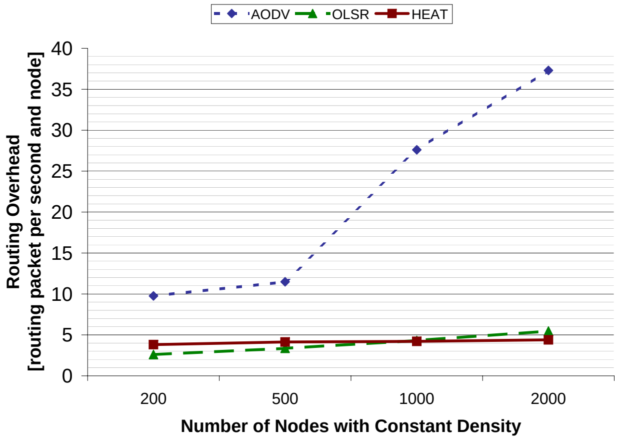


(b) Routing overhead.

Fig. 4. Mobile scenario at pedestrian speeds.



(a) Packet delivery ratio.



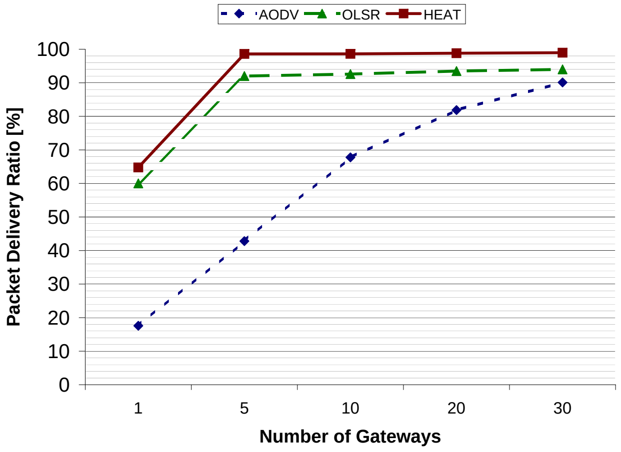
(b) Routing overhead.

Fig. 5. Mobile scenario at car speeds.

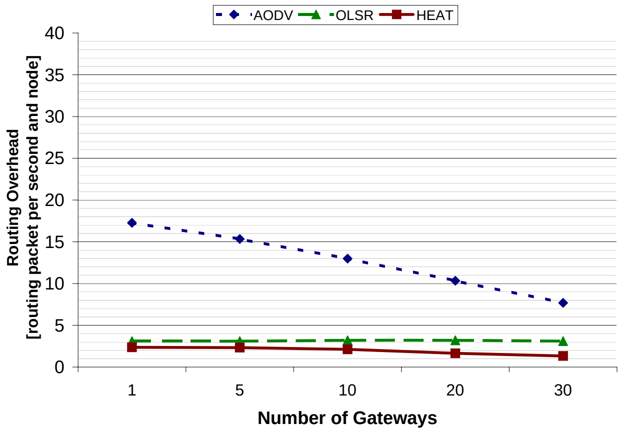
Considering the number of gateways required for an average packet delivery ratio of at least 99%, we find that with HEAT, 5 gateways are sufficient. OLSR only achieves a packet delivery ratio of 91% with this number of gateways; adding more gateways only slightly helps because the limiting factor of OLSR in mobile scenarios is that routes fail frequently and it does not discover and replace invalid routes quickly enough. With only 5 gateways, AODV achieves a delivery ratio of less than 50%; increasing the number to 30 gateways brings the delivery ratio to a still rather low 90%. We conclude from this experiment that in mobile scenarios, OLSR and AODV require many more gateways than HEAT to achieve a delivery ratio close to 99%. Thus, HEAT appears particularly suitable for deployments where the number of gateways is a crucial figure.

VIII. CONCLUSION

In this article, we report about established and novel ways to route data in wireless mesh networks. We discuss the state of the art and then go on to report about a recently published routing protocol for multi-hop wireless mesh networks called HEAT. In contrast to established routing protocols, HEAT uses the field-based anycast routing paradigm. Using anycast makes HEAT particularly scalable and suitable for very large and dense mesh networks. The field-based routing algorithm of HEAT provides for robust routes even with mobile nodes moving at car speeds.



(a) Packet delivery ratio.



(b) Routing overhead.

Fig. 6. The effect of the number of gateways (mobile scenario at pedestrian speeds).

We compare the performance of HEAT with AODV and OLSR through extensive simulation experiments. In a large static mesh network scenario with 1000 nodes covering an area of 5 km by 5 km, we find that both HEAT and OLSR achieve packet delivery ratios above 95% whereas AODV does not reach more than 30 %. In order to evaluate the performance in mobile scenarios, we use a realistic mobility model based on road maps from real cities. With nodes moving at car speed, HEAT outperforms both AODV and OLSR in terms of packet delivery ratio by more than a factor of two. Since the number of gateways determines to a large extent the cost of a mesh network, we evaluate, how many gateways are necessary to achieve a packet delivery ratio of at least 99%. Under HEAT, this delivery ratio is reached with 5 gateways. OLSR only achieves a delivery ratio of 91% with 5 gateways, and with 30 gateways, it is still below 95%. AODV only delivers 42% of the packets with 5 gateways, 30 gateways raise the delivery ratio to 90%.

We conclude that novel routing paradigms such as the field-based anycast routing concept employed by HEAT may contribute to more affordable wireless mesh networks in the near future. To what extent the results of our simulation experiments are applicable to real-world networks is difficult to determine because large-scale mobile testbeds are not available yet.

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