Wireless Mesh Networking Protocol for Sustained Throughput in Edge Computing

Josiah Burchard*, Dmitrii Chemodanov†, John Gillis†, and Prasad Calyam†
*Department of Computer Science, Southeast Missouri State University, Email: josiah@jburchard.com
†University of Missouri, Email: {calyamp, gillisj}@missouri.edu, dycbt4@mail.missouri.edu

***Abstract*—It is critical to provide sustained data throughput in edge computing, where several sensor devices generate information that needs to be fused and used for decision making in e.g., disaster incident scenes. To this end, we compare the effectiveness of two protocols, Hybrid Wireless Mesh Protocol (HWMP) and Greedy Perimeter Stateless Routing (GPSR), based upon their ability to stream data in a mesh network. We model the two protocols using three topologies consisting of a sender, receiver and multiple Mesh Points to relay the data. We perform experiments varying the density, scale and failure rates of the topology. Finally, we evaluate the effectiveness of both protocols by comparing the total throughput from sender to receiver in each experiment. We show that geographic routing algorithms such as GPSR, given their potential for statelessness, can be more effective in delivering sustained data throughput than the 802.11s standard HWMP in high failure and large scale topology cases.**

***Index Terms*—mesh network; hybrid wireless mesh protocol; geographic routing; greedy perimeter stateless routing; edge computing; sustained throughput; Internet of Things**

I. Introduction

Mesh networking, consisting of a sender, receiver and multiple mesh points has recently become an important area of study with the advent of the Internet of Things (IoT), and related edge computing paradigms. IoT requires high, sustained throughput across large areas that may not have wireless or even wired connectivity. An example IoT application may involve e.g., multiple incident disaster triage involving first responders combing through a disaster scene with the help of IoT devices to stream data to an incident commander for analysis. A mesh network can quickly provide a wireless connection over a large area to facilitate the data flow between the edge, gateway and the cloud as shown in Fig. 1.

In a mesh network where a sender is out of range of the receiver, the sender will route packets through intermediate mesh points until it reaches its destination. Routing decisions throughout these mesh points are gravely important when considering the efficiency and viability of a mesh network. High, sustained throughput is necessary for demanding applications such as live video streaming and mission critical data analysis, which have large computation and data handling requirements.

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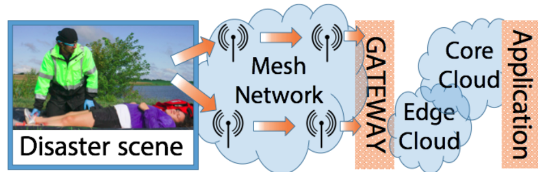

Fig. 1. Edge to Gateway to Cloud to App

The industry standard for mesh networks is defined by 802.11s as the Hybrid Wireless Mesh Protocol (HWMP) [1]. HWMP learns the network topology in real time to make routing decisions. While this allows for an easily configured network, it has the overhead to learn the current state of the network. This will congest the network and degrade the overall throughput. This effect is compounded each time the network topology changes, and is magnified as the network scales. Additionally, mesh networks often have a high rate of failure as devices are added/removed, moved out of range or become malfunctioning. Hence, topology learning is not an efficient solution to make routing decisions in a mesh network.

Geographic routing is a technique that uses the knowledge of the mesh points' locations for routing decisions. It implements a 'Stateless' protocol that eliminates overhead by avoiding learning the network topology [2]. Stateless in this context is meant to include only the minimum necessary state required to make any forwarding decisions, which only includes immediate one-hop neighbors of a mesh point. There are many geographic routing protocols suggested in literature ([3], [4], [5]), including Greedy Perimeter Stateless Routing (GPSR) [2]. GPSR is a well known implementation of geographic routing and has been selected for study in this work based upon its simplicity and establishment as a classical example in mesh networking literature. GPSR provides a higher, sustained throughput than HWMP because of its fault tolerance and low overhead provided by stateless routing.

In this paper, we compare the effectiveness of HWMP and GPSR protocols and compare their ability to stream data in a mesh network at sustained throughput levels in edge computing scenarios involving e.g., disaster incidents. We model the two protocols using three topologies consisting of a sender, receiver and multiple Mesh Points to relay the data. These topologies include the 'Joplin Area' (affected severely in 2011 by a tornado disaster) and 'Full Grid' scenarios that were created based on real-life scenarios for disaster triage using the Panacea's Cloud platform [6]. We perform experiments varying the density, scale and failure rates of the topology. Finally, we evaluate the effectiveness of both protocols by comparing their total throughput, as well as the throughput distribution from sender to receiver in each experiment. We discover that geographic routing, implemented through GPSR, dramatically increases the quality of application (QoA) and corresponding quality of experience (QoE).

The remainder of the paper is organized as follows: Section II provides an overview of the HWMP and GPSR protocols. Section III lists related works that have compared these two protocols. Section IV describes our experiment setup. Section V describes our experiment results along with a detailed discussion of the findings. Section VI concludes the paper.

II. Wireless Mesh Network Routing Protocols

A. HWMP

HWMP uses a blend of reactive and proactive methods to perform path selection with updated metrics on the current topology. A proactive tree-based routing scheme is implemented as well as an adaptation of Ad hoc On Demand Distance Vector (AODV) using up to date metrics on the network [1], [7].

The proactive portion of HWMP sends control messages throughout the network to build a tree-based location table. These control messages all have a time to live (TTL) field, a destination sequence number (DSN) and a metric field. The metric is specifically implemented as Airtime Link and gathers information about the quality of the route to later use in path selection. To construct the location table, a Path Request (PREQ) message containing a destination MAC address is first broadcasted through the network to each available mesh point. As each mesh point receives the PREQ, it checks the DSN and metric fields and updates its reverse path information if the path of the PREQ has a greater DSN or if it has a better metric. Then it will construct and append new metric data into the PREQ considering the link between the previous mesh point and itself and rebroadcast the message for other mesh points to receive. When the destination receives the PREQ, it will unicast a Path Reply (PREP) message back towards the sender using the path provided by the PREQ metrics. Each intermediate mesh point will update its forward path (between the mesh point and the sender of the PREP) with newly created metrics and forward the message along. When the PREP message reaches the destination, there is now a valid route with up to date metrics from the source to the destination. This process can be repeated until there are multiple paths between the source and destination.

The reactive portion of HWMP uses Radio Metric Ad hoc On Demand Distance Vector (RM-AODV). This is an extension of AODV which makes use of Airtime Link metric for path selection. When the sender begins to send a message, it will check its location table for the possible paths to the destination and then use RM-AODV to select the best path to the destination. The path selection always happens at transmission time to make use of the most up-to-date metrics.

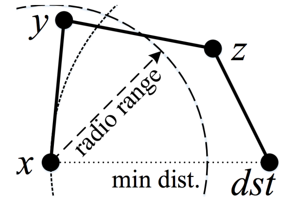

Fig. 2. Local minimum problem illustration: x faces the local minimum problem locating closer to dst than all its neighbors; as a result, it cannot forward packets further although a valid path through y exists

B. GPSR

GPSR implements a greedy forwarding algorithm in which a mesh point will always forward packets to the node that is closest to the destination and within range of the forwarding mesh point. This technique provides a straightforward method of efficient path guessing from source to destination. By utilizing greedy forwarding, each mesh point only needs to know the state of its current one-hop neighbors. Additionally, each mesh point only requires this information at transmission time. This implies no overhead in the network since control messages do not need to be transmitted throughout the network. By using a purely reactive method of path selection, forwarding information is always fresh. This makes greedy forwarding extremely fault tolerant since a failure in any mesh point does not increase any overhead on the network [2].

There are classic examples of where greedy forwarding fails. The Local Minimum problem shown in Fig. 2 describes a situation where a path exists from a mesh point to a destination, but the next mesh point in the path sequence is farther away than the current mesh point. When there is no possible path in greedy forwarding mode, GPSR switches to recovery mode which uses perimeter routing.

Perimeter routing instructs packet forwarding to route around the void following the right hand rule. Perimeter mode continues operation until the packet is closer to the destination than when perimeter mode had been started. At this point greedy forwarding mode continues.

III. Related Work

Many recent works have studied performance comparisons between popular routing protocols such as HWMP [8], [9], [10], [11], [12], GPSR [13], [14], [15] and many others. These studies generally focus on end-to-end throughput and latency as their performance metrics. Many applications such as live streaming and real time applications for disaster incident response that involve large-scale computing requirements depend on sustained throughput. A large variance in throughput, even when resulting in overall higher throughput, is undesirable in these applications.

This work focuses on two mesh network protocols, GPSR and HWMP, in their ability to support high, sustained throughput given large scale and failures. We examine end-to-end throughput as a whole, as well as the cumulative distribution to show the presence of a large variance. This work also makes use of real-life scenarios such as the Joplin Area and Full Grid topologies that are common to the Panacea's Cloud platform use case of disaster triaging. A mesh network solution, as implemented in the Panacea's Cloud platform [6] has to reliably collect and transfer rich multimedia video streams from aerial cameras or hand-help smart phones available close to a disaster incident site. In addition, the Panacea's Cloud platform is expected to constantly scale up the number of mesh points required and experiences particularly large failure rates compared to routine networking scenarios because of the highly volatile environment of disaster triaging. We simulate these conditions by measuring throughput against variations of scale and failure rates.

IV. Experiment Setup

A. Simulation Parameters

Our simulation was implemented using the industry standard Network Simulator 3 (NS-3). HWMP implementation was provided by the core NS-3 library and our GPSR implementation was based upon [16]. Each experiment contained a sender, receiver and multiple mesh points. The sender streamed 5 Mbps of data to the receiver from a one second starting delay to the end of the experiment. Each node has an approximate range of 250 m, but the number of neighbors to each node depends on the trial. A full list of the simulation parameters is shown in Table I.

TABLE I
Global Simulation Parameters

Data rate	5 Mbps
Packet Size	512 b
Frequency	2.4 Ghz
Radio Type	802.11g
Receiver Moving Speed	2.8 m/s
Simulation Time	400 s

1) Mobility Scenes: Three mobility scenes were selected for experimentation. First is a full grid, with NxM nodes spaced evenly apart. The sender was positioned within the grid in the top left corner. The receiver originated outside the right edge of the grid, moved at a slanted angle into the grid, stopped for 60 seconds, then continued through the bottom edge outside the grid and remained there until the end of the simulation. In this scene, there are several paths to route data through the mesh and the shortest path consequently changes throughout the experiment.

The second scene is entitled Joplin disaster area as shown in Fig. 3, modeled after a city block in Missouri that had been destroyed by a tornado in 2011 and consequently searched for survivors. This scene contains mesh points lining the perimeter of a near square city block. The sender and receiver move in a similar fashion to the full grid scene.

The third scene is a straight line. The sender is positioned on the left, then each mesh point consecutively and ending with the receiver on the right end. This experiment was included to compare throughput when path selection and topology changes are minimal.

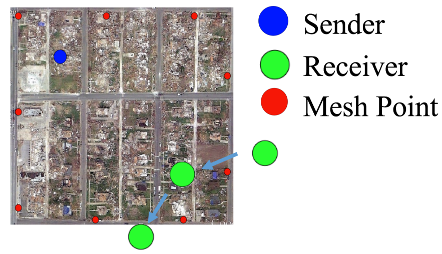

Fig. 3. Joplin Area Mobility Scene

2) Scale and Failure Rate Levels: Six scale and failure experiments were performed with each protocol and mobility scene set for a total of 2 * 3 * 2 * 6 = 72 experiments. The scale experiments had a zero percent failure rate and an increasing number of mesh points from four to twenty. The failure experiments had nine mesh points and increased in the probability of failure from 10-60%. To implement failure in the experiment, every 30 seconds N% of mesh points are moved to an isolated area very far away from the experiment and are returned after 30 seconds.

Each experiment described above was performed 50 times with varying topology densities up to twice as dense. For example, the spacing between mesh points in the full grid mobility scene is varied between 50 and 100 m.

B. Case Study: Panacea's Cloud

A direct application of this research is to select a mesh protocol for high, sustained throughput for the Panacea's Cloud platform [6]. Panacea's Cloud is a disaster triage management system consisting of various IoT edge devices, an offline mesh network and a server with intelligent edge computing. Mesh devices that include virtual beacons, wearable heads-up displays and other video capture sources (e.g., aerial drone video or smart phone cameras) will move about the scene while collecting and transmitting data which will change the network topology at a human timescale. The mesh network will have to accommodate these changes in topology and provide high, sustained throughput. The data transmitted from the edge devices may consist of priority data regarding the disaster scene that requires immediate processing by an edge server, and/or transfer to a gateway that will forward the data to a cloud application in a remote site. Another application could simply consist of a live video stream that should be viewed smoothly by another edge device or the server application itself, and this remote observation may need high frame rates.

C. Selected Mobility Scenes

The Full Grid and Joplin Area mobility scenes were selected because of their relevance to the Panacea's Cloud platform. These mobility scenes represent common topologies that would be used by Panacea's Cloud in disaster triaging. The Straight Line mobility scene was selected purely for the experimental purposes of comparing sustainable throughput between protocols as this is not a practical topology for disaster triage management.

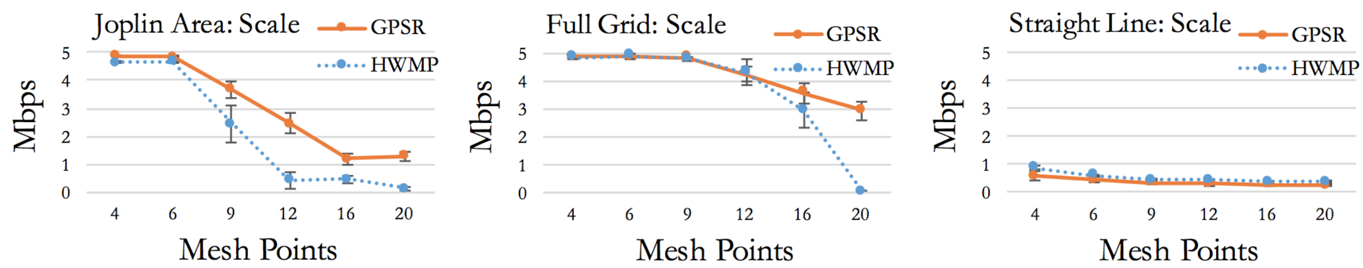

Fig. 4. Mean throughput results over increasing number of mesh points. In Joplin Area and Full Grid where there are multiple possible routing decisions, GPSR shows higher throughput

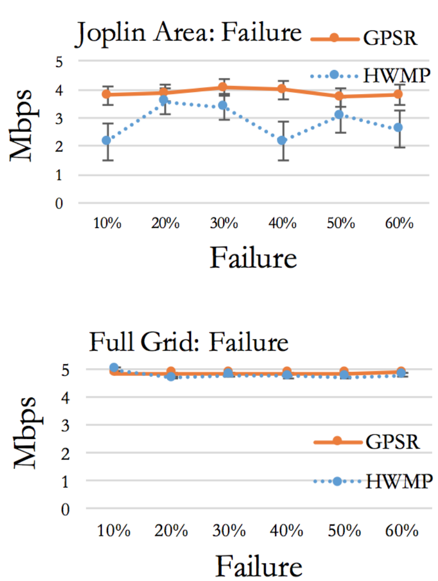

Fig. 5. Results showing GPSR performs better or near equivalent to HWMP even over increasing levels of failure in the mesh points

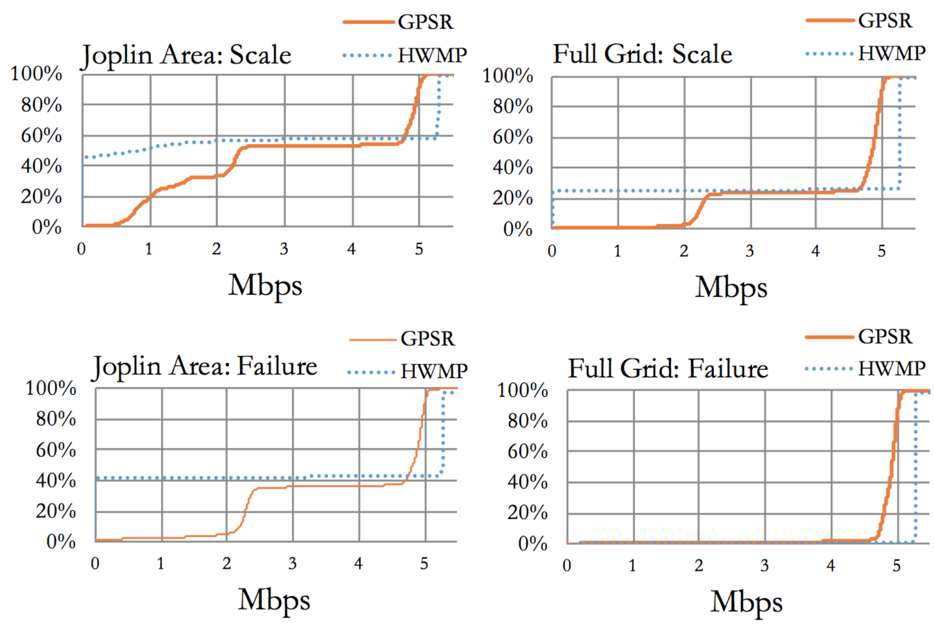

Fig. 6. In every experiment, GPSR exhibits more sustained throughput than HWMP as shown by their cumulative distribution functions

V. Simulation Results

A. Results

In Full Grid and Joplin Area mobility scenes, GPSR presented significantly higher throughput in all experiments as shown in Fig. 4. As the scale increased, GPSR throughput slowly declined while HWMP throughput rapidly decreased. Additionally as shown in Fig. 4, as the mesh points scale beyond 16 in Joplin Area and 20 in Full Grid, HWMP throughput degrades to near zero Mbps while GPSR only presents minimal degradation. Fig. 5 further details the impact of failure rates on throughput in the two protocols. The throughput of both GPSR and HWMP are not largely hindered by increasing levels of failures in mesh points.

The most interesting property is the sustained throughput as shown in Fig. 6, where cumulative distribution plots of throughput are shown across every trial and variation for each experiment. This is measured as total end to end throughput from client to server per second. With GPSR, the throughput is sustained with a distribution lying largely between .5 and 6 Mbps. However, HWMP does not share this property as its throughput distribution includes large quantities near zero. In the Joplin Area simulations, HWMP had about 48 and 58% of its total throughput ranging between 1 and 6 Mbps for scale and failure experiments respectively. Under the same conditions, GPSR possessed about 80 and 97% total throughput within the 1 and 6 Mbps range.

B. Discussion

The Panacea's Cloud platform relies on live data streamed through a mesh network. At a minimum, at least .5 Mbps of throughput is desired to stream sensor data through the mesh network to the edge cloud for computing. As seen from Fig. 6, the Joplin Area simulation shows near 98% of the total throughput above .5 Mbps for GPSR and only about 55% above .5 Mbps for HWMP. This leads to poor QoA and related QoE presented by repeated delays of information that could be intolerable during real time data processing.

Another feature of the Panacea's Cloud platform is to perform a live video stream for a wearable device in the mesh network to an administrator on the edge cloud which requires at least 2 Mbps of throughput for standard definition video. Again in Fig. 6 and the Joplin Area experiments, GPSR possessed about 93 and 65% throughput above 2 Mbps with failure and scale variations respectively. In the same conditions HWMP possessed about 58 and 44% throughput respectively. GPSR would dramatically increase the QoA and related QoE of this application.

While these results plainly show that GPSR presents a better solution for mesh routing in simulation, it is not necessarily a practical candidate in real environments. GPSR relies on the unit graph assumption, detailing that each mesh point is always connected to every other mesh point within its fixed radio range. In practice, even in static environments, radios frequently violate this rule as small conditions change in the environment [17]. There are suggestions to combat the reality of dynamic radio range such as Cross-Link Detection Protocol in [17], however this will add small additional overhead to GPSR that was not accounted for in this simulation.

A larger burden in the physical implementation of geographic routing is that each mesh point relies on accurate location information to make forwarding decisions. This location could at best increase the price per mesh point and at worse be completely unavailable. In environments where GPS is not viable (e.g., under ground, inside large buildings) and no other location information can be obtained, GPSR or any other geographic routing solution is not available. While GPSR only shows marginally higher throughput at small scale (below nine mesh points), it presents a more sustained throughput in every experiment and thus is suitable particularly for applications with real-time computation requirements.

VI. Conclusion

Using real-life scenarios including the Joplin Area and full grid topologies and variations of density, scale and failures, we have shown that GPSR with the benefit of stateless routing can achieve higher and more sustainable throughput than HWMP. We have also shown that GPSR scales with less degradation than HWMP with topologies greater than about 16 mesh points. By analyzing the throughput distribution, we see that GPSR possesses a much more sustained throughput which increases the QoA and related QoE for real time applications such as the Panacea's Cloud platform to aid disaster response.

In the case of Panacea's Cloud, location information provided by IoT devices give the necessary information for geographic routing to the mesh points at little cost and the network scale must increase far beyond 16 mesh points. Therefore these results show that GPSR is a practical, optimal protocol for high, sustained throughput in edge computing.

A part of our future work, we want to verify our simulation results through implementation of GPSR on physical routers. A good starting place would be to add geographic capabilities to a router running OpenWRT [18] and implement GPSR as a new routing package on the device.

References

[1] G. Hiertz, D. Denteneer, S. Max, R. Taori, J. Cardona, L. Berlemann, B. Walke, "IEEE 802.11s: the WLAN mesh standard", *IEEE Wireless Communications*, 2010.

[2] B. Karp, H.T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks", *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking*, 2000.

[3] P. Bose, P. Morin, I. Stojmenovi, J. Urrutia, "Routing with guaranteed delivery in ad hoc wireless networks", *Wireless networks*, 2001.

[4] M. Mauve, H. Fler, J. Widmer, T. Lang, "Position-based multicast routing for mobile ad-hoc networks", *ACM SIGMOBILE Mobile Computing and Communications Review*, 2003.

[5] A. Cvetkovski, M. Crovella, "Hyperbolic embedding and routing for dynamic graphs", *Proceedings of IEEE INFOCOM*, 2009.

[6] J. Gillis, P. Calyam, A. Bartels, M. Popescu, S. Barnes, J. Doty, D. Higbee, S. Ahmad, "Panacea's Glass: Mobile Cloud Framework for Communication in Mass Casualty Disaster Triage", *Proceedings of IEEE Mobile Cloud Computing, Services, and Engineering (MobileCloud)*, 2015.

[7] J. Ben-Othman, L. Mokdad, M.O. Cheikh, "Q-HWMP: improving end-to-end QoS for 802.11 s based mesh networks", *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM)*, 2010.

[8] S.M.S. Bari, F. Anwar, M.H. Masud, "Performance study of hybrid wireless mesh protocol (hwmp) for ieee 802.11 s wlan mesh networks", *Proceedings of International Conference on Computer and Communication Engineering (ICCCE)*, 2012.

[9] A. Ksentini, O. Abassi, "A comparison of VoIP performance over three routing protocols for IEEE 802.11s-based wireless mesh networks (wlan mesh)", *Proceedings of the 6th ACM International Symposium on Mobility Management and Wireless Access*, 2008.

[10] J.C.P. Wang, B. Hagelstein, M. Abolhasan, "Experimental evaluation of IEEE 802.11 s path selection protocols in a mesh testbed", *Proceedings of International Conference on Signal Processing and Communication Systems (ICSPCS)*, 2010.

[11] S. Ghannay, S.M. Gammar, F. Kamoun, "Comparison of proposed path selection protocols for IEEE 802.11 s WLAN mesh networks", *Springer Wireless and Mobile Networking*, 2008.

[12] A. Zakaria, H. Mohamad, N. Ramli, M. Ismail, "Performance evaluation of routing protocols in wireless mesh network", *Proceedings of International Conference on Advanced Communication Technology (ICACT)*, 2013.

[13] V. Naumov, R. Baumann, T. Gross, "An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces", *Proceedings of the 7th ACM International Symposium on Mobile Ad hoc Networking and Computing*, 2006.

[14] W. Wang, F. Xie, M. Chatterjee, "An integrated study on mobility models and scalable routing protocols in VANETs", *Proceedings of Mobile Networking for Vehicular Environments*, 2007.

[15] M.A. Zayene, N. Tabbane, R. Elidoudi, "Performance evaluation of greedy perimeter stateless routing protocol in ad hoc networks", *Proceedings of International Conference on Computer Sciences and Convergence Information Technology (ICCIT)*, 2009.

[16] A. Fonseca, A. Cames, T. Vazo, "Geographical routing implementation in NS3", *Proceedings of the 5th International ICST Conference on Simulation Tools and Techniques*, 2012.

[17] Y.J. Kim, R. Govindan, B. Karp, S. Shenker, "Geographic routing made practical", *Proceedings of the 2nd conference on Symposium on Networked Systems Design & Implementation*, 2015.

[18] F. Fainelli, "The OpenWrt embedded development framework", *Proceedings of the Free and Open Source Software Developers European Meeting*, 2008.