An Extension of the Babel Protocol to Include Operating Cost: Providing Sustainability in Community Networks

Rodolfo B. S. Carvalho(✉), Carla Merkle Westphall, and Caciano Machado

Department of Informatics and Statistics Graduate Program in Computer Science - PPGCC, Federal University of Santa Catarina, Florianópolis, Brazil
rodolfo.carvalho@posgrad.ufsc.br, carla.merkle.westphall@ufsc.br, caciano.machado@ufrgs.br

Abstract. The expansion of networks worldwide and its benefits allowed the emergence and application of several technologies aimed at exchanging information in a decentralized manner, such as Blockchain, where there is no need for a reliable agent or third party for management. In this context, the emergence of various distributed wireless networks was possible, such as community networks, where large mesh networks composed of hundreds of nodes built by communities seek to solve digital inclusion problems. Wireless mesh networks still present some challenges in their growth. Even with specific protocols like Babel, which optimize its operation, there are problems such as reliability among network members and the correct distribution of resources to encourage its growth. These characteristics prevent wireless mesh networks from developing to reach areas of technology scarcity called the last mile. Thus, this work uses the optimization techniques for WMNs achieved by the Babel protocol and proposes the modification of the original Babel protocol to insert financial incentive mechanisms into the protocol. The article presents the proposed modifications and demonstrates, through simulation tests, the functioning and efficiency of the protocol extensions through the OMNeT++ platform combined with the INET Framework tool.

Keywords: Babel · Protocol · Routing · Incentive · Wireless · Mesh · Network

1 Introduction

Wireless mesh networks (WMNs) are networks capable of not only providing wireless connectivity to large areas (such as shopping malls and urban centers), but also taking such connectivity to remote locations [2]. There are several

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2022
O. Gervasi et al. (Eds.): ICCSA 2022, LNCS 13375, pp. 265–282, 2022.
https://doi.org/10.1007/978-3-031-10522-7_19

remote areas without Internet access due to the lack of economic interest from the large telephone operators. This fact motivates the construction of community networks [5,14], which use WMNs and affordable handsets, are relatively easy to deploy and help to solve the last mile problem. An example of this type of infrastructure is the Freifunk network in Germany [9].

The need to carry out many activities online, mainly due to the influence of the pandemic, has revealed shortcomings in making "last mile" connectivity widely accessible. It is necessary to meet the need, for example, 63% of school-age children who do not have access to the Internet [20]. The problems already identified in 2017 [7] continue to exist, and it is necessary: stable access to the network, accessible costs, and incentives for network maintenance and expansion.

Some studies have appeared in the literature in recent years that address the use of financial incentive mechanisms linked to the network [12,13] to guarantee the correct sustainability of the WMNs. The effort and quality of the work developed by the network nodes in incentive mechanisms can be measured with associated routing protocols present in the network layer.

There are several protocols in the literature that are directly associated with WMN environments [16]. Babel and B.A.T.M.A.N. are examples of such protocols that clearly stand out as shown in performance evaluations results [1,15]. This work adopts the Babel protocol due to its broad adoption for routing in WMNs [22], active development and concise documentation [8].

This work incorporates financial incentive metrics to encourage the expansion and operation of WMN infrastructure. The proposal analyzes the Babel protocol's efficiency, benefits, and costs when associated with incentive mechanisms. Tests were performed in laboratory mounted scenarios comparing, through the results obtained, the behavior of the protocol with financial incentive mechanisms with its version without the use of incentive mechanisms. The main aspects analyzed are related to the best selection of routes for traffic on the network, the message exchange mechanisms, and the state maintenance structure of the channels used for communication.

The remainder of this paper is organized as follows: Sect. 2 describes the basic concepts; in Sect. 3, related works are discussed; Sect. 4 presents the proposed solution; the experimental results and evaluation are described in Sect. 5 and, finally, Sect. 6 presents the conclusions of the paper.

2 Basic Concepts

WMNs (Wireless mesh networks) are considered Ad Hoc networks enhanced with several features present in mesh networks, allowing a self-organizing and decentralized communication between network participants, thus favoring communication in large areas and the extension of this connectivity to participants neighbors without the need for centralized control or cabling linking each node.

Although Ad Hoc networks have their structure of clients and network routers, mesh Networks incorporate specific structure characteristics to WMNs, basically leading to the existence of two types of devices, mesh clients and mesh

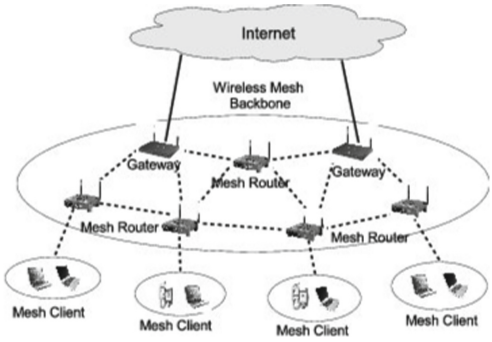

Fig. 1. WMN example [23].

routers (Fig. 1). While mesh clients can be both stationary and mobile, being able to receive packets or form a network among themselves and connected to other routers, mesh routers, in turn, have minimal and restricted mobility and are responsible for forming the backbone of WMNs. Arranged in a mesh topology where communication is performed wirelessly in a dynamically self-organizing and self-configuring environment, both mesh clients and mesh routers using the IEEE 802.11 standard, aimed at ensuring maximum stability, mainly due to constant state changes of the links and network connectivity that may occur [2].

The responsibility for managing the links and organizing the routing of packets rests with the protocols that run at the network layer and can be divided in two areas, based on reputation and based on credits. Reputation-based models seek, based on the behavior of network nodes, to punish network elements that act in a way that is harmful to the protocol. On the other hand, the credit-based models use a form of charging linked to the services provided by the elements of the network, providing or withdrawing credits according to harmful or beneficial behavior, respectively, which are identified by the protocol.

Routing protocols within WMNs have peculiar characteristics compared to conventional ones, mainly because they are dealing with *ad hoc* networks. Each existing node has partial or full mobility, being able to change the network topology with a certain frequency, which does not occur in wired connections, thus requiring better management in the definition of routes for the network layer.

2.1 Babel Protocol

The Babel protocol is considered a distance-vector routing protocol, and it uses the Bellman-Ford algorithm to discover the best path that each packet must take to reach its destination [10]. Designed to be robust and effective in unstable wireless networks, the Babel protocol adds some modifications to the general working dynamics of distance-vector protocols, which seek to avoid, through preventive refinements, the formation of loops in packet forwarding, and even that these do occur, undoing them in a timely manner and preventing them from forming again. Still, the protocol can also be used within fixed networks.

The protocol also measures the quality of the links. It can use several methods to calculate its routes, as needed by the network manager, and can be based on the packet loss rate or the shortest path to the desired destination. Within these and several other metrics existing in the protocol, the algorithm can adapt to different networks and devices, which, due to their respective limitations, such as a battery or signal strength or location, can take on different characteristics such as time interval between exchanges, that will be different between a mobile device and a desktop. That characteristic allows the protocol to support different types of wifi networks, knowing how to deal with heterogeneous environments, including networks with both IPv4 and IPv6.

The protocol also has some limitations, such as generating traffic to update the routing tables constantly, unlike other protocols such as OSPF and IS-IS that only generate updates when topology changes occur. Another limitation is the time for a participant to be reconnected to the network, when a node quickly disconnects and reconnects, a wait is required (about a few minutes) for it to be recognized again, which can become a limitation in mobile networks with automatic node inclusion.

3 Related Works

The related works identified were selected through bibliographic research, carried out and documented through a Systematic Literature Review Protocol, where a search string linked to the study topic was created and applied within 5 databases (IEEE, ACM, Wiley, Springer, Elsevier). A total of 390 studies were identified, which after exclusion by Title and Abstract, full reading of the texts and finally the application of the defined inclusion and exclusion criteria, 7 studies were selected, which cover the use of mechanisms to encourage WMNs and also the protocols most geared towards supporting such networks. At the end of the section, a comparative table of related works is shown about the proposal developed, seeking to combine the most suitable protocol with incentive mechanisms (Table 1).

The work of [4] seeks to explore viable and sustainable alternatives for access to the network that do not involve traditional private cabling companies, creating a sustainable and economically promising environment. Within the possible alternatives, the work focuses on community networks, specifically on one of the largest community networks in the world called Guifi.net. The paper describes how this WMN attaches economic incentives to the network, combined with infrastructure, implementation, and practices, which guarantee its sustainability. The case study shows many benefits of the association of a WMN to incentive mechanisms, association and benefits also applicable to the present paper, but the author of the work [4] does not use a specifically altered protocol to run at the network layer, and also does not perform comparative tests with traditional protocols for WMNs such as Babel.

The work of [17] proposes a new protocol named *Fair*, which seeks to ensure the economic management of the network in an automated way, contrary to the

work proposed by [18], where the financial adjustments are performed manually. The main idea of the protocol is based on the more devices a service provider has on the network, the higher the price per MB allocated to it. There is a certain limit to avoid network monopoly, leading one provider to own all nodes and creating possible disadvantages for users. The work adopts incentive mechanisms like the study presented in this paper, but it attributes the incentives for the choice of network bandwidth channels, while the study in this paper attributes the incentive for choosing the neighboring nodes that the packet will pass on routing.

Among the challenges found for the construction, maintenance, and use of WMNs, the work of [22] cites the logistic *last mile* problem, showing the difficulties of taking network connections to distant points in large cities, where for infrastructure, economic and logistical reasons, large operators and ISPs are not interested in taking their services. In order to enable the creation of a connected environment with low operational cost, adequate bandwidth, stable and capable of eliminating the traditional contracts manually made, the study proposes a network architecture called *Althea*. Althea is a network architecture based on distance-vector routing protocols, extending the Babel protocol. It associates the use of Ethereum cryptocurrencies to support its automated payment system, using a PoS-based blockchain (Proof-of-Stake), through the Cosmos platform. The work specifies modifications to the Babel protocol including mechanisms to encourage a functioning network, but does not present performance tests and comparisons with the original form of the Babel protocol or compare with other protocols currently focused on WMNs.

Another study on incentive mechanisms within WMNs [18] is focuses on ensuring the possibility of financial transactions, trust between participants, data immutability, and neutrality in data management. It adopts Blockchain technology as a solution linked to WMNs, using more specifically the structure of permissive Blockchains, which combine the benefits of Blockchain with mechanisms of identity and trust on users. The framework chosen by the article for implementation and testing was the Hyperledger Fabric (HLF) [3], which was evaluated both in production and in simulated laboratory testing environments.

The work of [19] addresses two problems found in multi-channel wireless ad hoc networks: a) the difficulty in correctly assigning channels to their respective interfaces, trying to align the stability of network connectivity to the maximum use of different channels; and b) the various interferences to which these channels are subject, reducing the efficiency of the network. The paper performs an analysis of cognitive mechanisms linked to the context of the network. This mechanism is used as the basis for the proposal of a multi-channel ad hoc network associated with hybrid channels. A responsible, fair rate control algorithm is applied for pricing each channel according to its availability as an incentive, ensuring a quick convergence in simulations carried out.

Within the related works, there are two comparative studies related to the efficiency of protocols aimed at WMNs: [16], and [21]. The work described in [16] test the five most mentioned protocols so far in the literature (AODV,

DYMO, HWMP, OLSR, BATMAN) in order to analyze and compare each one within four aspects: packet loss rate, packet delivery delay time, the average energy consumption of all network nodes and finally the number of collisions that occurred in the network. The study shows a comparison between proactive and reactive protocols, indicating that the proactive protocols, despite the high data overhead and higher energy consumption, have low latency in the delivery of packets and a low rate of packet loss, which is considered extremely positive for WMNs.

Finally, the article by [21] seeks to measure the performance of three routing protocols focused on WMNs (HWMP, BATMAN advanced, and Babel), in network deficiency/disaster environments caused by possible natural disasters, to which the network nodes need to respond quickly and in a coordinated way to restore the network. Both HWMP and BATMAN Advanced stood out within the static network scenario with similar performance. In contrast, only HWMP proved efficient in dealing with dynamic processes for the dynamic network scenario. For the scenario of large networks composed of up to one hundred routers, none of the protocols showed efficiency in dealing with large networks, except for the Babel protocol. New network architecture is proposed to deal with large networks and mitigate its problems. For the scenario of large networks composed of up to one hundred routers, none of the protocols showed efficiency in dealing with large networks. New network architecture is proposed to deal with large networks and mitigate its problems.

The Table 1 shows a summary of the related work compared to this paper, indicating possible gaps to be filled.

The first column of the table indicates the related works, with their respective references and year of publication. The second column identifies the works that added financial incentive mechanisms to the proposed models to sustain the network. The third column indicates the works that included/addressed the Babel and/or BATMAN protocols in their analysis. The fourth column indicates the works that performed virtual and/or real tests on the models proposed as a solution. Finally, the fifth and last column indicates the works that, after testing, showed clear comparisons with other solutions belonging to the same group/category of the study.

As the table shows, it is possible to identify several points that were not covered by related works proposals but aim to be included in this paper. Most of the related works include the application of incentive mechanisms for WMNs [4,17–19,22], but only one proposes changes to the protocol [17], creating a new protocol model to be used at the link layer level, but it doesn't include tests with the proposed model and it does not show comparisons with today traditional protocols for WMNs. Two other works [16,21] show comparisons between protocols for WMNs, the first work [16] evidence the efficiency of proactive protocols in the WMN environment and the second [21] highlighting the Babel protocol for environments of large networks that have suffered some type of disaster. Both solutions ended up not allying any type of incentive mechanism to the mentioned protocols.

Table 1. Related works comparison.

Work	Incentive mechanisms	Babel or BATMAN protocol	Virtual and/or real tests	Comparison group
[4], 2016	O			
[17], 2019	O	O		
[22], 2020	O			
[18], 2018	O		O	
[19], 2018	O			
[16], 2016		O	O	O
[21], 2017		O	O	O
This paper	O	O	O	O

This paper seeks to integrate such incentive mechanisms with the Babel protocol, combining a protocol aimed at WMN networks with the benefits brought by the incorporation of incentives to the network, demonstrated in related works.

4 Proposed Solution

The solution proposed is based on the inclusion of price cost metrics to calculate the selection of ETX (Expected Transmission Count) routes, using for this a fixed cost value to be assigned to each network node, called *tocost* (transmission operational cost), which will be passed on to neighbors through a TLV packet, at the time the IHU ("I Heard You") message exchanges occur.

Inside each TLV packet used, of the IHU type, a new Sub-TLV called OC (Operational Cost) will be added, which will be responsible for transporting the *tocost* value of its origin node to all neighbors so that the cost links is consistent among all nodes in the network.

The *tocost* value assigned to each participant, as it represents the operating cost that each node has to forward packets, will be determined by the user or person responsible for the host belonging and can be represented by any currency or token that can be freely chosen according to the needs of the network. Depending on the location of the node and the costs involved, considering hardware, maintenance, energy, and other expenses, the operating value of the node in a real network will always vary, so the cost is stipulated through a specified integer during node startup.

4.1 Routing Metric

The routing metric uses the ETX algorithm plus the cost variable called *tocost*, leading each network node to calculate the cost of a link based on four factors:

1. the *txcost* cost of receiving packets informed by a neighbor;
2. the transmission cost *rxcost* calculated by the node itself;
3. the estimated RTT (round-trip time) delay cost for the link, initially not present in the ETX algorithm but added to identify the best quality networks [11]; and,
4. the transmission operating cost *tocost* representing the incentive mechanism proposed in this paper.

The metric used is based on the sum of each cost variable, allowing the combination of the incentive strategy with others that are necessary for the network environment, without breaking basic rules of the Babel protocol [10], avoiding the possible formation of loops in the route paths and thus maintaining the integrity of the network. The basic rules of the protocol, considered for any change made, are based on three immutable and essential requirements for the operation of the protocol [11]. Starting from a function *M(c, m)*, which represents the Babel cost metric, where c is the calculation of the link's local cost, computed by the node itself, and m is the computed and advertised cost by the neighbor for the same link, by the except the following rules must be complied with:

- If c is infinite, then *M(c,m)* is also infinite.
- M is strictly monotonic:: M(c,m) > m.
- M meets the left distributive property: if $m <= m'$ then *M(c, m)* <= *M(c, m')*.

The last rule is important because it guarantees that the best global path will be found for the routes. However, the first two rules are responsible for avoiding the formation of routing loops, and their satisfaction is necessary to guarantee the integrity of the network.

The basic conditions cited can be easily met using additive metrics, recommended as the default for a wide variety of cost calculations [11]. All changes made to the code sought to meet these conditions, especially the changes made within the final calculation of the ETX algorithm, as can be seen in the code snippet presented, showing the summation structure of each metric adopted.

Require: Neighbor Object
Ensure: An integer, indicating the cost to send packets through Neighbor.
  if $txcost \geq infinity$ OR $rxcost \geq infinity$ **then**
    return $infinity$
  end if
  if $txcost \geq 256$ OR $rxcost \geq 256$ **then**
    $cost \leftarrow txcost$
  else
    $cost \leftarrow 256/(alpha * betha)$

$cost \leftarrow cost + rttcost$
$cost \leftarrow cost + tocost$
end if

Due to the modular structure of the Babel protocol, it is possible to use different techniques or algorithms for the route selection policy. In all of them, there is the possibility of using the OC operating cost metric, provided that the basic principles specified for the operation of the protocol, thus avoiding the creation of Loops in the routing paths and starvation problems associated with changing the conditions of network sustainability.

4.2 Message Exchange

The exchange of messages is carried out constantly by the protocol through the TLV packets, so in order to transmit the new cost variable *tocost*, a sub-TLV called OC (Operational Cost) was added to the end of the existing and standardized TLV IHU (Fig. 2).

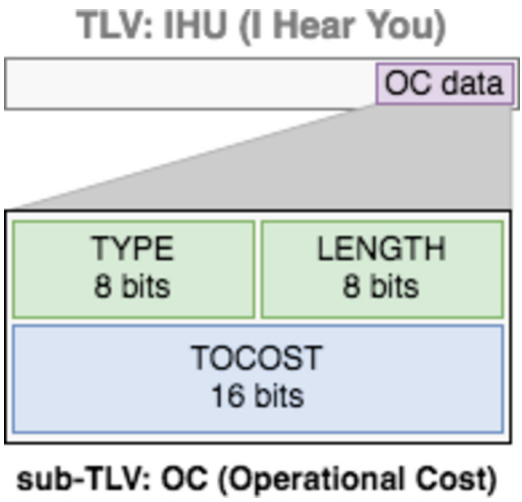

Fig. 2. Sub-TLV OC (Operational Cost).

The modular structure of the Babel protocol allows the inclusion of new sub-TLVs as long as they are in the same context as the parent TLV, that is, as both the OC sub-TLV and the IHU TLV are responsible for informing the cost and quality of links to the neighbors, they together allow to optimize the detection of changes in the topology and to reduce the overhead caused in the network, not being necessary the creation of a new TLV.

The sub-TLV OC has a size of 32 bits, which will be added to the end of the IHU message. The initial 16 bits make up its header structure, with 8 bits used for its type and 8 bits for the size. The rest of the 16 bits are used to store the cost variable *tocost* (Fig. 2). The header has fixed values linked to the sub-TLV structure, where the type established for the first 8 bits is defined by a constant with a fixed value of 4 for the extension performed. The size bits are assigned the value 16, referring to the *short* type of *tocost* included in the message body.

The sub-TLV also has the most significant bit of its typing set to zero, therefore considered a non-mandatory bit. The data inserted in the structure can be ignored if a network node does not recognize them, reading the remainder of the TLV, thus maintaining backward compatibility with the Babel protocol.

As a proactive protocol, all route tables seek to keep up-to-date with the best links in terms of QoS and its operating costs, which can be changed at any time through the exchange of IHU messages.

5 Experimental Results and Evaluation

We analyzed and compared the behavior of the original Babel protocol with the modified version of Babel [6], proposed in this paper, which includes the operating cost in its behavior. The following aspects were analyzed and compared: the choice of routing paths, throughput levels achieved, and the convergence time for choosing the best route. The implementation of the proposed extension of the Babel protocol was developed using the babeld module (version 1.10), implemented, and maintained by the author of the specifications. Babeld module was integrated with the INET framework tool (stable version 4.2.9) to execute the protocol within the Omnet++ software (stable version 5.7), a discrete event simulator based on the C++ language, using the Wireshark software (version 3.2.3) to record and analyze packets.

The first test environment simulate a small network composed of 5 mesh nodes interconnected through a ring topology (Fig. 3). The second test environment was designed to simulate a real network environment, and is composed of 60 mesh nodes arranged randomly in the virtual test environment, always keeping a minimum distance so that the wireless network reaches at least 2 other nodes.

Ring topology (Fig. 3) allows two paths to be tested between two ends of the network, the first path being shorter and of better quality, but 50% more expensive (red line), and the second path being longer and of lower quality, but at a lower cost. The second mesh topology allows the analysis to be more coherent with the large networks present in real environments, the costs are assigned to each node with the same proportion of values, leading some nodes to be 50% more expensive but that eventually can make part of a lower quality path.

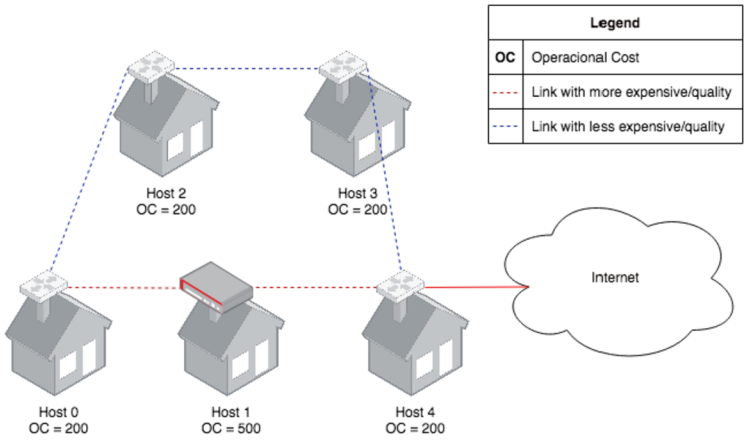

Fig. 3. Routing paths (Color figure online)

Packet traffic simulation in both test environments always occurs between two network nodes (Host0 and Host4), where Host4 makes a packet request to Host0 based on the following configuration within the OSI model (Fig. 4).

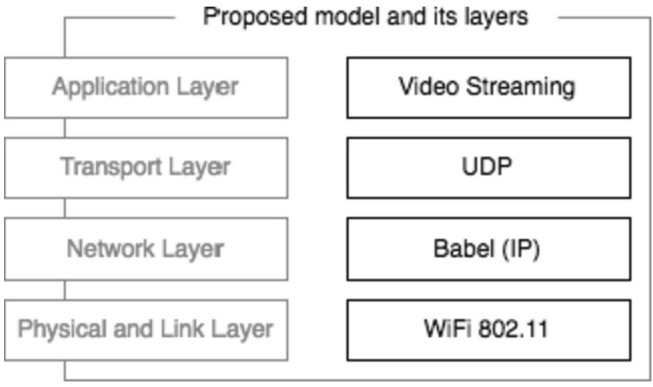

Fig. 4. Proposed layers model

The application layer simulates a Video Stream configured within INET through the "UdpBasic" packet. The transport layer is configured to use UDP, which does not guarantee the delivery of packets, with some analysis of throughput and packet loss rates being carried out. The network layer will consist of Babel, responsible for managing the routing and transfer of packets within the IP layer to reach their destination. Finally, the physical layer simulates data traffic through WiFi 802.11 radio signals.

The initialization of each node in the network is done through a call to babeld for each host:

```
Host0$ sudo ip netns exec host0 babeld -I babel0.pid -S
↪  babel-state0 -r -w -h 2 -M 0 -C 'reflect-kernel-metric true'
↪  -C 'interface tap0 channel 1 link-quality false' -Y 200

Host1$ sudo ip netns exec host1 babeld -I babel1.pid -S
↪  babel-state1 -r -w -h 2 -M 0 -C 'reflect-kernel-metric true'
↪  -C 'interface tap1 channel 1 link-quality false' -Y 700

Host2$ sudo ip netns exec host2 babeld -I babel2.pid -S
↪  babel-state2 -r -w -h 2 -M 0 -C 'reflect-kernel-metric true'
↪  -C 'interface tap2 channel 1 link-quality false' -Y 200

Host3$ sudo ip netns exec host3 babeld -I babel3.pid -S
↪  babel-state3 -r -w -h 2 -M 0 -C 'reflect-kernel-metric true'
↪  -C 'interface tap3 channel 1 link-quality false' -Y 200

Host4$ sudo ip netns exec host4 babeld -I babel4.pid -S
↪  babel-state4 -r -w -h 2 -M 0 -C 'reflect-kernel-metric true'
↪  -C 'interface tap4 channel 1 link-quality false' -Y 200
```

The configurations adopted in the execution of Babel was the following arguments: I specifies a file to register the process id; S specifies a file used to preserve long-term babeld information between each execution; r enables random id selection for each router; w disables optimizations for wired networks, assuming that all links are wireless; h specifies the interval in seconds between sending each packet *Hello*; M specifies the half-time in seconds of the exponential decay to smooth metrics during route selection; C specifies commands to be entered directly on the host's command line; and finally, as the last argument, the term Y was added referring to the cost of the node, which can be represented by a currency or any type of incentive to be adopted.

Within the tests performed, the values 200 were adopted for the cost of the longest path nodes and 700 for the shortest path node, as a way to verify the choice of the best routes, as by adding the cost of each host along the path, the longer one will cost 500, and the shortest path will cost 900.

The main aspects analyzed are related to the best selection of routes for network traffic, message exchange mechanisms, and the structure for maintaining the state of the communication channels. The correct routing and choice of the best paths must be maintained, whether due to the cost linked to the participants or the quality of the links.

5.1 Simulation Results

The simulation results were obtained by counting UDP packets that ran under the network and were successfully delivered to the destination host and are represented by the red line (Fig. 5), seeking to identify the number of received packets as a function of time. In order to observe the network execution in a mesh network scenario, two tests were carried out, the first simulating the streaming transfer with static participants, and the second simulating the transfer with a member leaving the network and getting back, that is initially used for the path (Host1), demonstrating the convergence time until a new route is defined.

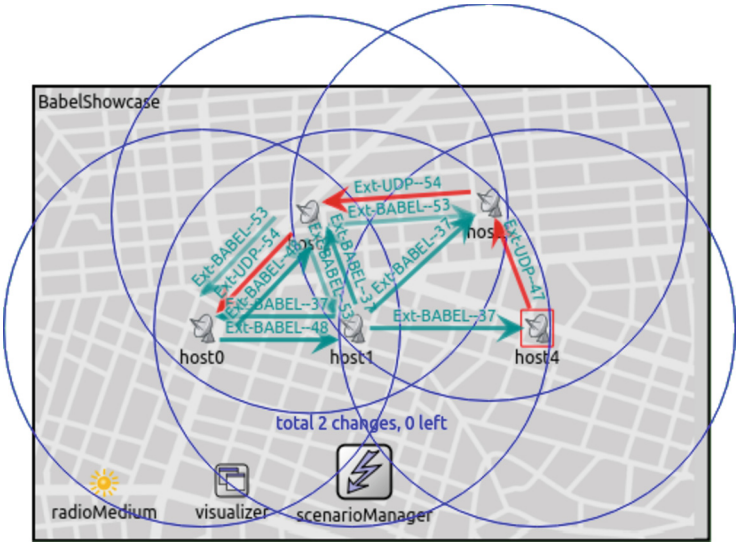

Fig. 5. Execution of inet framework. (Color figure online)

In the first analyzed test (Fig. 6), when the operating cost is added to the metric, the protocol achieves good stability in the choice of routes. The application layer starts streaming video at second 15 when UDP packets are sent, and the best route is selected to be used. The added weight (blue line) clarifies that the most interesting route is the longest, as its cost is lower. This guarantees that the protocol in its decisions will be more stable always maintaining the same route at each verification. In the long term it will reach a higher packet transmission rate (second 18 onwards). In its original version (red line), as there are some hops to other routes at times when the connection presents a less advantageous QoS, some transmission delays occur due to the instability of the transmission itself, resulting in a lower packet transmission rate.

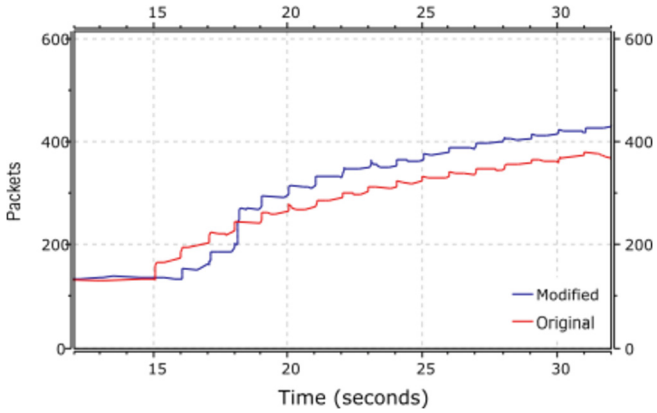

Fig. 6. Stable connection scenario 1 (Color figure online)

Within the second test analyzed (Fig. 7), taking into account the introduction of a cost value to calculate the best routing path, when the lowest cost node (Host1) in the network fails (second 14 onwards), there is the possibility of choosing not only the path with the best cost but also the choice based on the best Qos path at the time.

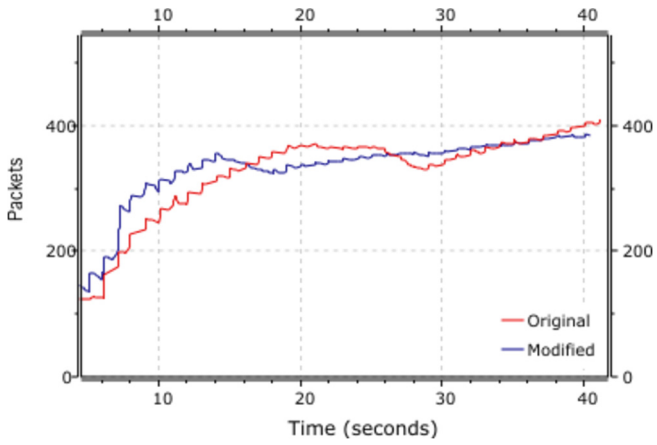

Fig. 7. Dropped connection scenario

However, when making a choice, the loss of packets that occurs due to the failure presented is not very significant in the long term, as the stability of the network when added the operating cost variable, leads it to avoid unnecessary hops by other routes at each cost verification.

The third test uses a large mesh network of 60 nodes (Fig. 8), where both the withdrawal of a participant within 15 s and its activation again in the network within 40 s are performed.

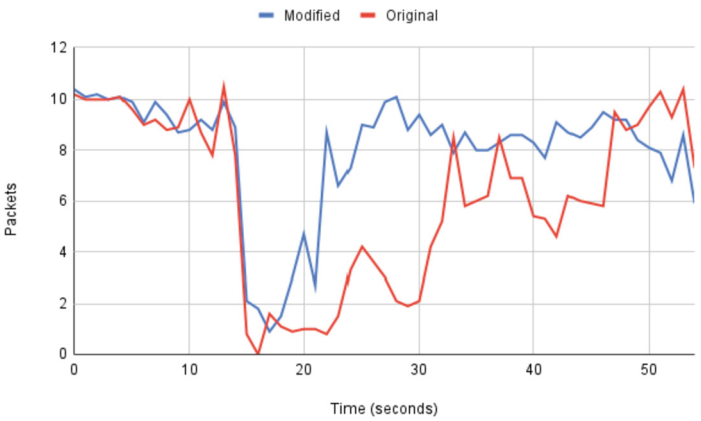

Fig. 8. Dropped connection scenario 2

As a node that participates in the route was removed (Fig. 8), the average of successfully transmitted packets drops quickly at 15 s, the network reconvergence mechanisms look for new neighbors to propagate the packet, and the version of modified Babel can return more quickly to the level of transmission prior to the modified crash, taking about 10 s for the packet traffic to normalize to the initial transmission level.

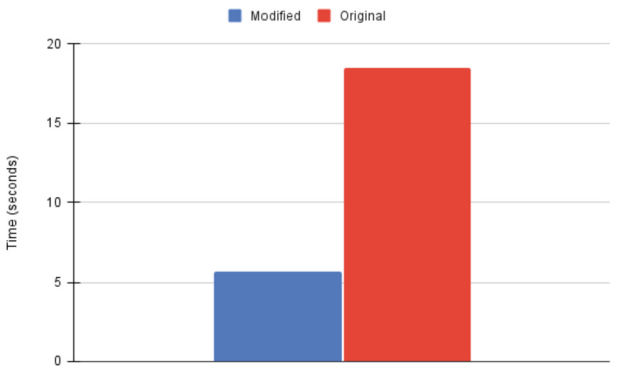

Fig. 9. Convergence time comparation

The network convergence time was also analyzed, taking into account the time between the participant leaving, and the time until packets start to be

transmitted again to the destination. The graph (Fig. 9) shows that the network with the addition of an incentive mechanism behaves 69% faster to establish a new traffic route, thus reducing interference from node exits or node failures.

6 Conclusions

In this work, a modification was presented within the Babel protocol, which allows the inclusion of the operational cost involved in each node, as a form of financial incentive for the network, so that it transmits a packet over the network, such cost is represented by the variable *tocost*.

Modifications were also included in the IHU response TLVs, appending to the end of them a new sub-TLV OC that carries the value *tocost* to neighbors. Neighbors include the variable received in the sub-TLV OC in the final cost of the ETX metric, already used as a standard in the Babel protocol for communication in WMNs.

Modifications carried out in the protocol were put under test and compared with tests carried out in the original protocol (unmodified) in order to analyze the effects on route calculation for a WMN network. The results showed that despite the increase in the size of the IHU messages, which cause a slight overhead, the connections showed greater stability and, consequently, greater throughput. This occurs because cheaper connections are chosen in most calculations, decreasing route changes as there is higher QoS.

In the changes made in the protocol, there are some limitations found. The first one is the overhead caused by the increase in the size of TLV IHU: this traffic overhead could be alleviated by sending the sub-TLV OC only in times of cost change. The second one is interoperability with routers that use the original Babel 1.10 protocol versus the previous ones, which did not implement OC in the metric: the choice of routes, in this case, would always privilege routers with protocols that do not implement OC, as this is not being added in the cost of a link, it considerably reduces the price of the link. The third and last limitation is the confidence in the veracity of the informed cost: for the case of routes without alternatives, the route participants could place abusive prices and still have to be chosen.

The main contribution of this work is the inclusion of an incentive mechanism for WMNs networks, which helps their expansion and maintenance, dividing operating costs among network users. The cost-sharing could take the form of a currency or credit, which could be converted into cash or other benefits, and used in conjunction with the Blockchain to ensure reliability and transparency in the final cost calculation processed by each node in the network. Including incentive mechanisms associated with the network layer through Babel protocol, new functionalities were added to the protocol that was not explored before by the related works [16,21], and through tests on simulated network environments, which also was not included by related works presented [4,17–19,22], it is possible to identify the performance of the modified version of Babel protocol.

For future works, it is possible to incorporate cost management mechanisms between nodes in a decentralized and transparent way, recording and accounting

all the resources supplied/consumed by the network, ensuring that costs are correctly distributed according to the work of each node, through a structure allied to the Blockchain. It would also be interesting to test in real environments of WMNs, such as community networks, to analyze and improve the proposal developed in real-use environments. Finally, the modifications to insert operating costs can also be applied in other protocols to guarantee the sustainability and development of the network.

References

1. Abolhasan, M., Hagelstein, B., Wang, J.C.P.: Real-world performance of current proactive multi-hop mesh protocols. In: 2009 15th Asia-Pacific Conference on Communications, pp. 44–47 (2009). https://doi.org/10.1109/APCC.2009.5375690
2. Akyildiz, I.F., Wang, X., Wang, W.: Wireless mesh networks: a survey. Comput. Netw. **47**(4), 445 – 487 (2005). https://doi.org/10.1016/j.comnet.2004.12.001, http://www.sciencedirect.com/science/article/pii/S1389128604003457
3. Androulaki, E., et al.: Hyperledger fabric: a distributed operating system for permissioned blockchains. In: Proceedings of the Thirteenth EuroSys Conference. EuroSys 2018, New York, NY, USA. Association for Computing Machinery (2018). https://doi.org/10.1145/3190508.3190538, https://doi.org/10.1145/3190508.3190538
4. Baig, R., Dalmau, L., Roca, R., Navarro, L., Freitag, F., Sathiaseelan, A.: Making community networks economically sustainable, the guifi.net experience. In: Proceedings of the 2016 Workshop on Global Access to the Internet for All. GAIA 2016, New York, NY, USA, pp. 31–36. Association for Computing Machinery (2016). https://doi.org/10.1145/2940157.2940163
5. Baig, R., Roca, R., Freitag, F., Navarro, L.: guifi.net, a crowdsourced network infrastructure held in common. Comput. Netw. **90**, 150–165 (2015). https://doi.org/10.1016/j.comnet.2015.07.009, http://www.sciencedirect.com/science/article/pii/S1389128615002327, crowdsourcing
6. Borges, R.: Babeld modified cost protocol (2022). https://www.gitlab.com/rodolfoCarvalho/babeld-cost
7. Brown, K.: 2017 internet society global internet report: Paths to our digital future (2017). Accessed 9 Jun 2018
8. Chroboczek, J.: Extension mechanism for the babel routing protocol (2015). https://tools.ietf.org/html/rfc7557
9. Freifunk.net: Freifunk network (2021). https://freifunk.net
10. Chroboczek, J., Schinazi, D.: The babel routing protocol (2021). https://datatracker.ietf.org/doc/html/rfc8966
11. Jonglez, B., Chroboczek, J.: Delay-based metric extension for the babel routing protocol (2019). https://datatracker.ietf.org/doc/html/draft-ietf-babel-rtt-extension-00
12. Machado, C., dos Santos, R.R.S., Westphall, C.M.: Hop-by-hop accounting and rewards for packet dispatching (2021)
13. Machado, C., Westphall, C.M.: Blockchain incentivized data forwarding in manets: Strategies and challenges. Ad Hoc Networks **110**, 102321 (2021). https://doi.org/10.1016/j.adhoc.2020.102321, https://www.sciencedirect.com/science/article/pii/S1570870520306752

14. Micholia, P., et al.: Community networks and sustainability: a survey of perceptions, practices, and proposed solutions. IEEE Commun. Surv. Tutor. **20**(4), 3581–3606 (2018). https://doi.org/10.1109/COMST.2018.2817686
15. Murray, D., Dixon, M., Koziniec, T.: An experimental comparison of routing protocols in multi hop ad hoc networks. In: 2010 Australasian Telecommunication Networks and Applications Conference, pp. 159–164 (2010). https://doi.org/10.1109/ATNAC.2010.5680190
16. Piechowiak, M., Zwierzykowski, P., Owczarek, P., Wasłowicz, M.: Comparative analysis of routing protocols for wireless mesh networks. In: 2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), pp. 1–5 (7 2016). https://doi.org/10.1109/CSNDSP.2016.7573902
17. San Miguel, E., Timmerman, R., Mosquera, S., Dimogerontakis, E., Freitag, F., Navarro, L.: Blockchain-enabled participatory incentives for crowdsourced mesh networks. In: Djemame, K., Altmann, J., Bañares, J.Á., Agmon Ben-Yehuda, O., Naldi, M. (eds.) GECON 2019. LNCS, vol. 11819, pp. 178–187. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-36027-6_15
18. Selimi, M., Kabbinale, A.R., Ali, A., Navarro, L., Sathiaseelan, A.: Towards blockchain-enabled wireless mesh networks. In: Proceedings of the 1st Workshop on Cryptocurrencies and Blockchains for Distributed Systems. CryBlock 2018, pp. 13–18, New York, NY, USA. Association for Computing Machinery (2018). https://doi.org/10.1145/3211933.3211936, https://doi.org/10.1145/3211933.3211936
19. Singh, M., Kim, S.: Trust bit: reward-based intelligent vehicle commination using blockchain paper. In: 2018 IEEE 4th World Forum on Internet of Things (WF-IoT), pp. 62–67 (2018)
20. Society, I.: 2020 impact report the internet is a lifeline (2020). https://www.internetsociety.org/impact-report/2020/
21. Tchinda, A.P., Frick, G., Trick, U., Lehmann, A., Tchinda, A.P., Ghita, B.: Performance analysis of wmn routing protocols for disaster networks. In: 2017 IEEE Symposium on Communications and Vehicular Technology (SCVT), pp. 1–6 (2017)
22. Tremback, J.: Althea white paper (2020). https://github.com/althea-net/althea-whitepaper/blob/master/whitepaper.pdf
23. Yang, J., Sakai, K., Kim, B., Okada, H., Sun, M.-T.: Cost-aware route selection in wireless mesh networks. In: Cao, J., Stojmenovic, I., Jia, X., Das, S.K. (eds.) MSN 2006. LNCS, vol. 4325, pp. 171–184. Springer, Heidelberg (2006). https://doi.org/10.1007/11943952_15