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A Genetic Algorithm Based System for Wireless Mesh Networks: Analysis of System Data Considering Different Routing Protocols and Architectures

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Abstract Wireless Mesh Networks (WMNs) are attracting a lot of attention from wireless network researchers. Node placement problems have been investigated for a long time in the optimization field due to numerous applications in location science. In our previous work, we evaluated WMN-GA system which is based on Genetic Algorithms (GAs) to find an optimal location assignment for mesh routers. In this paper, we evaluate the performance of four different distributions of mesh clients for two WMN architectures considering throughput, delay and energy metrics. For simulations, we used ns-3, Optimized Link State Routing (OLSR) and Hybrid Wireless Mesh Protocols (HWMP). We compare the performance for Normal, Uniform, Exponential and Weibull distributions of mesh clients by sending multiple Constant Bit Rate (CBR) flows in the network. The simulation results show that for HWM protocol the throughput of Uniform distribution is higher than other distributions. However, for OLSR protocol the throughput of Exponential distribution is better than other distributions. For both protocols, the delay and remaining energy is better for Weibull distribution.

Keywords Wireless Mesh Networks · Genetic Algorithms · ns-3 · OLSR · HWMP · Giant Component · User Coverage

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1 Introduction

Wireless Mesh Networks (WMNs) can be seen as a special type of wireless ad-hoc networks. WMNs are based on mesh topology, in which every node (representing a server) is connected through wireless links to one or more nodes, enabling thus the information transmission in more than one path. The path redundancy is a robust feature of mesh topology. Compared to other topologies, mesh topology does not need a central node, allowing networks based on it to be self-healing. These characteristics of networks with mesh topology make them very reliable and robust networks to potential server node failures.

There are a number of application scenarios for which the use of WMNs is a very good alternative to offer connectivity at a low cost. It should also mentioned that there are applications of WMNs which are not supported directly by other types of wireless networks such as cellular networks Barolli (2007), ad hoc networks Palmieri and Castiglione (2012), Palmieri (2013), wireless sensor and actor networks Kulla et al. (2014)

and standard IEEE 802.11 networks. There are many applications of WMNs in Neighboring Community Networks, Corporative Networks, Metropolitan Area Networks, Automatic Control Buildings, Medical and Health Systems, Transportation Systems, Surveillance and so on.

In WMNs, the mesh routers provide network connectivity services to mesh client nodes. The good performance and operability of WMNs largely depends on placement of mesh routers nodes in the geographical deployment area to achieve network connectivity, stability and client coverage.

In our previous work Oda et al. (2013), Ikeda et al. (2012), Oda et al. (2014), we considered the version of the mesh router nodes placement problem in which we are given a grid area where to deploy a number of mesh router nodes and a number of mesh client nodes of fixed positions (of an arbitrary distribution) in the grid area. We used mesh router nodes placement system that is based on Genetic Algorithms (GAs) to find an optimal location assignment for mesh routers in the grid area in order to maximize the network connectivity.

In this work, we use the topology generated by WMN-GA system and evaluate by simulations the performance of four different distributions of mesh clients considering two architectures of WMNs by sending multiple Constant Bit Rate (CBR) flows in the network. For simulations, we used ns-3, Optimized Link State Routing (OLSR) and Hybrid Wireless Mesh Protocols (HWMP). As evaluation metrics we considered throughput, delay and residual energy. We compare the performance for Normal, Uniform, Exponential and Weibull distributions of mesh clients by sending multiple Constant Bit Rate (CBR) flows in the network. The simulation results show that for HWM protocol the throughput of Uniform distribution is higher than other distributions. However, for OLSR protocol the throughput of Exponential distribution is better than other distributions. For both protocols, the delay and remaining energy is better for Weibull distribution.

The structure of the paper is as follows. In Section 2, we discuss the related work. In Section 3, we explain architectures of WMNs. In Section 4, we present an overview of HWMP and OLSR routing protocol. In Section 5, we give a short description of NS-3. In Section 6, we present the implemented WMN-GA simulation system. In Section 7, we show the description and design of the simulation system. In Section 8, we discuss the simulation results. Finally, conclusions and future work are given in Section 9.

2 Related Work

Until now, many researchers performed valuable research in the area of multi-hop wireless networks by computer simulations and experiments Nordstrom (2002). Most of them are focused on throughput improvement and they do not consider mobility Draves et al. (2004).

WMNs are attracting a lot of attention from wireless research. Node placement problems have been investigated for a long time in the optimization field due to numerous applications in location science (facility location, logistics, services, etc.).

The main issue of WMNs is to achieve network connectivity and stability as well as QoS in terms of user coverage. Several heuristic approaches are found in the literature for node placement problems in WMNs Muthaiah and Rosenberg (2008), Tang (2009), Franklin and Murthy (2007), Vanhatupa et al. (2007). As node placement problems are known to be computationally hard to solve for most of the formulations Lim et al. (2005), Wang et al. (2007), GAs have been recently investigated as effective resolution methods. However, GAs require the user to provide values for a number of parameters and a set of genetic operators to achieve the best GA performance for the problem Yao (1993), Denzinger and Kidney (2006), Odetayo (1997), Xhafa et al. (2008), Xhafa et al. (2007).

3 Architectures of WMNs

In this section, we describe the architectures of WMN. The architecture of the nodes in WMNs Xhafa et al. (2009) can be classified according to the functionalities they offer as follows:

Infrastructure/Backbone WMNs: This type of architecture (also known as infrastructure meshing) is the most used and consists of a grid of mesh routers which are connected to different clients. Moreover, routers have gateway functionality thus allowing Internet access for clients. This architecture enables integration with other existing wireless networks and is widely used in neighboring communities.

Client WMNs: Client meshing architecture provides a communications network based on peer-to-peer over client devices (the role of mesh router is not need). In this case we have a network of mesh nodes which provide routing functionality and configuration as well as end-user applications, so that when a packet is sent from one node to another, the packet will jump from node to node in the mesh of nodes to reach the destination.

Hybrid WMNs: This architecture combines the two previous ones, so that mesh clients are able to access the network through mesh routers as well as through direct connection with other mesh clients. Benefiting from the advantages of the two architectures, Hybrid WMNs can connect to other networks (Internet, Wi-Fi, and sensor networks) and enhance the connectivity and coverage due to the fact that mesh clients can act as mesh routers.

4 Overview of HWMP and OLSR Routing Protocol

4.1 HWM Protocol

Hybrid Wireless Mesh Protocol (HWMP) defined in IEEE 802.11s, is a basic routing protocol for a wireless mesh network. It is based on AODV Perkins et al. (2003) and tree-based routing. It relies on peer link management protocol by which each mesh point discovers and tracks neighboring nodes. If any of these are connected to a wired backhaul, there is no need for HWMP, which selects paths from those assembled by compiling all mesh point peers into one composite map.

HWMP is hybrid, because it supports two kinds of path selection protocols. Although these protocols are very similar to routing protocols, but bear in mind, that in case of IEEE 802.11s these use MAC addresses for "routing", instead of IP addresses. Therefore, we use the term "path" instead of "route" and thus "path selection" instead of "routing".

HWMP is intended to displace proprietary protocols used by vendors like Meraki for the same purpose, permitting peer participation by open source router firmware.

4.2 OLSR Protocol

The OLSR protocol Clausen and Jacquet (2003) is a pro-active routing protocol, which builds up a route for data transmission by maintaining a routing table inside every node of the network. The routing table is computed upon the knowledge of topology information, which is exchanged by means of Topology Control (TC) packets.

OLSR makes use of HELLO messages to find its one hop neighbours and its two hop neighbours through their responses. The sender can then select its Multi Point Relays (MPR) based on the one hop node which offer the best routes to the two hop nodes. By this way, the amount of control traffic can be reduced. Each node has also an MPR selector set which enumerates nodes that have selected it as an MPR node. OLSR uses TC messages along with MPR forwarding to disseminate neighbour information throughout the network. Host Network Address (HNA) messages are used by OLSR to disseminate network route advertisements in the same way TC messages advertise host routes.

5 NS-3

The ns-3 simulator is developed and distributed completely in the C++ programming language, because it better facilitated the inclusion of C-based implementation code. The ns-3 architecture is similar to Linux computers, with internal interface and application interfaces such as network interfaces, device drivers and sockets. The goals of ns-3 are set very high: to create a new network simulator aligned with modern research needs and develop it in an open source community. Users of ns-3 are free to write their simulation scripts as either *C++ main()* programs or *Python* programs. The ns-3's low-level API is oriented towards the power-user but more accessible "helper" APIs are overlaid on top of the low-level API.

In order to achieve scalability of a very large number of simulated network elements, the ns-3 simulation tools also support distributed simulation. The ns-3 support standardized output formats for trace data, such as the pcap format used by network packet analyzing tools such as tcpdump, and a standardized input format such as importing mobility trace files from ns-2.

The ns-3 simulator is equipped with *Pyviz* visualizer, which has been integrated into mainline ns-3, starting with version 3.10. It can be most useful for debugging purposes, i.e. to figure out if mobility models are what you expect, where packets are being dropped. It is mostly written in Python and it works both with Python and pure C++ simulations. The function of ns-3 visualizer is more powerful than network animator (*nam*) of ns-2 simulator.

The ns-3 simulator has models for all network elements that comprise a computer network. For example, network devices represent the physical device that connects a node to the communication channel. This might be a simple Ethernet network interface card or a more complex wireless IEEE 802.11 device.

The ns-3 is intended as an eventual replacement for popular ns-2 simulator. The ns-3's wifi models a wireless network interface controller based on the IEEE 802.11 standard IEEE (2007). The ns-3 provides models for these aspects of 802.11:

1. Basic 802.11 DCF with infrastructure and ad hoc modes.
2. 802.11a, 802.11b, 802.11g and 802.11s physical layers.

3. QoS-based EDCA and queueing extensions of 802.11e.
4. Various propagation loss models including Nakagami, Rayleigh, Friis, LogDistance, FixedRss, and so on.
5. Two propagation delay models, a distance-based and random model.
6. Various rate control algorithms including Aarf, Arf, Cara, Onoe, Rraa, ConstantRate, and Minstrel.

6 Implemented WMN-GA Simulation System

In this section, we present the implemented WMN-GA System. First, we introduce the GA and then present the GUI of the WMN-GA System.

6.1 Genetic Algorithms

GAs have shown their usefulness for the resolution of many computationally combinatorial optimization problems. For the purpose of this work we have used the *template* given in Algorithm 1.

Algorithm 1 Genetic Algorithm Template

```
Generate the initial population P^0 of size μ;
Evaluate P^0;
while not termination-condition do
  Select the parental pool T^t of size λ; T^t := Select(P^t);
  Perform crossover procedure on pairs of individuals in
  T^t with probability p_c; P_c^t := Cross(T^t);
  Perform mutation procedure on individuals in P_c^t with
  probability p_m; P_m^t := Mutate(P_c^t);
  Evaluate P_m^t ;
  Create a new population P^{t+1} of size μ from individuals
  in P^t and/or P_m^t ;
  P^{t+1} := Replace(P^t; P_m^t)
  t := t + 1;
end while
return Best found individual as solution;
```

We present next the particularization of GAs for the mesh router nodes placement in WMNs.

6.1.1 Encoding

The encoding of individuals (also known as chromosome encoding) is fundamental to the implementation of GAs in order to efficiently transmit the genetic information from parents to offsprings.

In the case of the mesh router nodes placement problem, a solution (individual of the population) contains the information on the current location of routers in the grid area as well as information on links to other mesh router nodes and mesh client nodes. This information is kept in data structures, namely, `pos_routers` for positions of mesh router nodes, `routers_links` for link information among mesh routers and `client_router_link` for link information among mesh routers and mesh clients (matrices of the same size as the grid area are used). Based on these data structures, the size of the giant component and the number of covered mesh clients are computed for the solution.

It should be also noted that mesh routers are assumed to have different radio coverage, therefore to any router could be linked to a number of mesh clients and other mesh routers. Obviously, whenever a mesh router is moved to another cell of the grid area, the information on links to both other mesh routers and mesh clients must be computed again and links are re-established.

6.1.2 Selection Operators

In the evolutionary computing literature we can find a variety of selection operators, which are in charge of selecting individuals for the pool mate. The operators considered in this work are those based on *Implicit Fitness Re-mapping* technique. It should be noted that selection operators are generic ones and do not depend on the encoding of individuals.

– *Random Selection*: This operator chooses the individuals uniformly at random. The problem is that a simple strategy does not consider even the fitness value of individuals and this may lead to a slow convergence of the algorithm.
– *Best Selection*: This operator selects the individuals in the population having higher fitness value. The main drawback of this operator is that by always choosing the best fitted individuals of the population, the GA converges prematurely.
– *Linear Ranking Selection*: This operator follows the strategy of selecting the individuals in the population with a probability directly proportional to its fitness value. This operator clearly benefits the selection of best endowed individuals, which have larger chances of being selected.
– *Exponential Ranking Selection*: This operator is similar to Linear Ranking but the probabilities of ranked individuals are weighted according to an exponential distribution.
– *Tournament Selection*: This operator selects the individuals based on the result of a tournament among individuals. Usually winning solutions are the ones of better fitness value but individuals of worse fitness value could be chosen as well, contributing thus to avoiding premature convergence. Particular cases of this operator are the *Binary Tournament* and $N-$*Tournament Selection*, for different values of N.

6.1.3 Crossover Operators

The crossover operator selects individuals from the parents generation and interchanging their *genes*, thus new individuals (descendants) are obtained. The aim is to obtain descendants of better quality that will feed the next generation and enable the search to explore new regions of solution space not explored yet.

There exist many types of crossover operators explored in the evolutionary computing literature. It is very important to stress that crossover operators depend on the chromosome representation. This observation is especially important for the mesh router nodes problem, since in our case, instead of having strings we have a grid of nodes located in a certain positions. The crossover operator should thus take into account the specifics of mesh router nodes encoding. We have considered the following crossover operator, called *intersection operator* (denoted `CrossRegion`, hereafter), which take in input two individuals and produce in output two new individuals.

6.1.4 Mutation Operators

Mutation operator is one of the GA ingredients. Unlike crossover operators, which achieve to transmit genetic information from parents to offsprings, mutation operators usually make some small local perturbation of the individuals, having thus less impact on newly generated individuals.

Crossover is "a must" operator in GA and is usually applied with high probability, while mutation operators when implemented are applied with small probability. The rationale is that a large mutation rate would make the GA search to resemble a random search. Due to this, mutation operator is usually considered as a secondary operator.

In the case of mesh routers node placement, the matrix representation is chosen for the individuals of the population, in order to keep the information on mesh router nodes positions, mesh client positions, links among routers and links among routers and clients. The definition of the mutation operators is therefore specific to matrix-based encoding of the individuals of the population. Several specific mutation operators were considered in this study, which are move-based and swap-based operators.

- *SingleMutate*: This is a move-based operator. It selects a mesh router node in the grid area and moves it to another cell of the grid area.
- *RectangleMutate*: This is a swap-based operator. In this version, the operator selects two "small" rectangles at random in the grid area, and swaps the mesh routers nodes in them.
- *SmallMutate*: This is a move-based operator. In this case, the operator chooses randomly a router and moves it a small (*a priori* fixed) number of cells in one of the four directions: up, down, left or right in the grid. This operator could be used a number of times to achieve the effect of SingleMutate operator.
- *SmallRectangleMutate*: This is a move-based operator. The operator selects first at random a rectangle and then all routers inside the rectangle are moved with a small (*a priori* fixed) numbers of cells in one of the four directions: up, down, left or right in the grid.

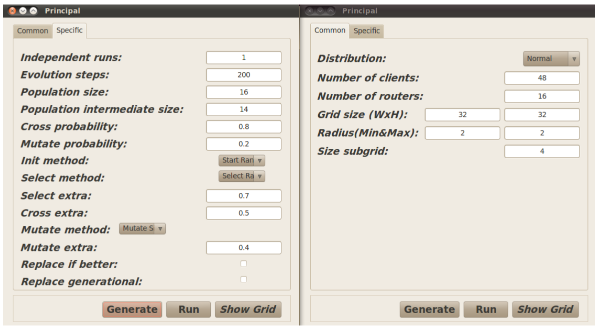


Fig. 1 GUI tool for WMN-GA system.

6.2 GUI of WMN-GA System

The WMN-GA system can generate instances of the problem using different distributions of client and mesh routers.

The GUI interface of WMN-GA is shown in Fig. 1. The left site of the interface shows the GA parameters configuration and on the right side are shown the network configuration parameters.

For the network configuration, we use: distribution of mesh clients, number of mesh clients, number of mesh routers, grid size, radius of transmission distance and the size of subgrid.

For the GA parameter configuration, we use: number of independent runs, number of generations, population size, select methods, mutate methods, crossover probability, mutation probability, initial mesh router placement methods.

7 Simulation Description and Design

7.1 Positioning of mesh routers by WMN-GA system

We use WMN-GA system for node placement problem in WMNs. A bi-objective optimization is used to solve

Table 1 Input parameters of WMN-GA system.

Parameters	Values
Number of clients	48
Number of routers	16, 20, 24, 28, 32
Grid width	32 [units]
Grid height	32 [units]
Independent runs	10
Number of generations	200
Population size	64
Selection method	Linear Ranking
Crossover rate	80 [%]
Mutate method	Single
Mutate rate	20 [%]
Distribution of mesh clients	N, U, E, W

this problem by first maximizing the number of connected mesh routers in the network and then the mesh client coverage. The input parameters of WMN-GA system are shown in Table 1. In Fig. 2, Fig. 3, Fig. 4 and Fig. 5, we show the location of mesh routers and mesh clients for first generations and the optimized topologies generated by WMN-GA system for Normal (N), Uniform (U), Exponential (E) and Weibull (W) distributions, respectively.

In Fig. 6, Fig. 7, Fig. 8 and Fig. 9 are shown the simulation results of Size of Giant Component (SGC) vs. number of generations. After few generations, all mesh routers are connected with each other.

Then, we optimize the position of mesh routers in order to cover as many mesh clients as possible. We consider Normal and Uniform distributions of mesh clients, which are similar with nodes concentrated in event-site environment, while Exponential and Weibull distributions of mesh clients, which are similar with mesh clients concentrated in hot-spot environment. The simulation results of SGC and Number of Covered Mesh Clients (NCM) are shown in Table. 2.

7.2 Simulation Description

We conduct simulations using ns-3 simulator. The simulations in ns-3 are done for number of generations 1 and 200. The area size is considered 640m×640m (or 32 units×32 units) and the number of mesh routers is from 16 to 32. We used HWMP and OLSR routing protocols and sent multiple CBR flows over UDP. The pairs source-destination are the same for all simulation scenarios. Log-distance path loss model and constant speed delay model are used for the simulation and other parameters are shown in Table 3.

Table 3 Simulation parameters for ns-3.

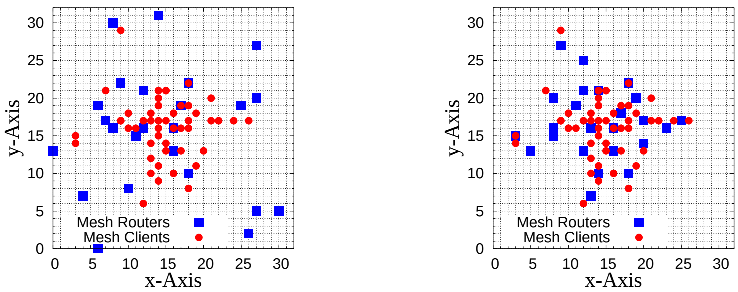
Parameters	Values
Area Size	640m×640m
Number of mesh routers	24, 32
Distributions of mesh clients	N, U, E, W
Number of mesh clients	48
Propagation loss model	Log-distance Path Loss Model
Propagation delay model	Constant Speed Model
Routing protocol	HWMP, OLSR
Transport protocol	UDP
Application type	CBR
Packet size	1024 [Bytes]
Number of source nodes	10
Number of destination nodes	1
Transmission energy	17.4 [mA]
Receiving energy	19.7 [mA]
Simulation time	60 [sec]

8 Discussion of Simulation Results

We used the throughput, delay and energy metrics to evaluate the performance of WMNs using HWMP and OLSR protocols for Normal, Uniform, Exponential and Weibull distributions and I/B WMN and Hybrid WMN architectures. In Fig. 10, we show the simulation results of HWM protocol throughput for Normal, Uniform, Exponential and Weibull distributions, respectively. For Normal and Exponential distributions, the throughput of I/B WMN is a little bit higher than Hybrid architecture. For Weibull distribution the throughput is almost the same for both WMN architectures. However, for Uniform distribution the throughput of Hybrid WMN is higher than I/B WMN. This is because for Normal and Exponential distributions, the mesh routers are concentrated in the grid area, thus there are many collisions and the network becomes congested.

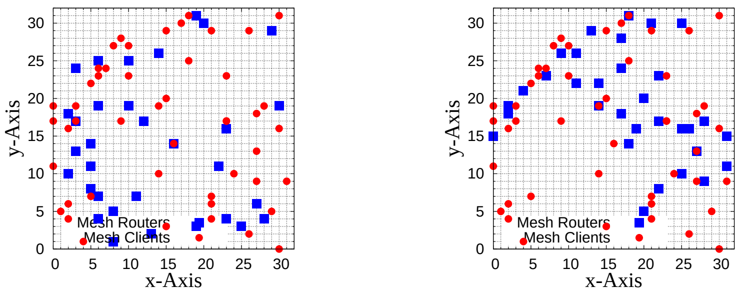
In Fig. 11, we show the delay for four distributions considering HWM protocol. For Normal and Weibull distributions (see Fig. 11(a) and Fig. 11(d)), the delay is almost the same. However, for Uniform distribution the delay of Hybrid WMN is lower than I/B WMN as shown in Fig. 11(b). This is because in Hybrid WMN also the mesh client communicate between each other. But, for Exponential distribution (see Fig. 11(c)) the delay of I/B WMN is low compared with Hybrid WMN.

In Fig. 12, we show the remaining energy of HWM protocol for both WMN architectures and four distributions, respectively. For Normal and Exponential distributions, the energy decreases sharply, because the mesh routers are concentrated in the grid area and many packets collide with each other. For Weibull distribution, the energy decrease almost the same for both WMN architectures. For Uniform distribution, the remaining energy of I/B WMN is higher than Hybrid WMN. This is because in Hybrid WMN, there are three communications: mesh client to mesh client, mesh router to mesh router and mesh client to mesh router.



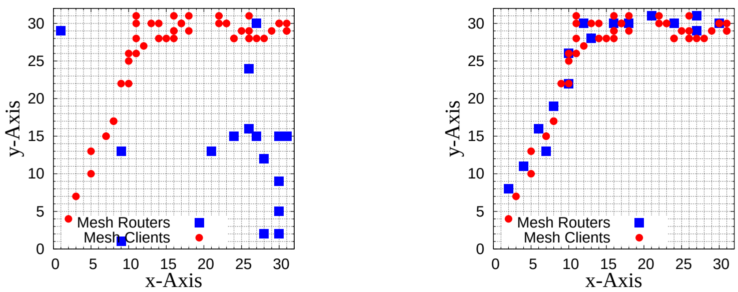
(a) Number of generations: 1 (8, 12)   (b) Number of generations: 200 (24, 47)

Fig. 2 Location of mesh routers by WMN-GA system, (m, n): m is number of connected mesh routers, n is number of covered mesh clients of normal distribution.



(a) Number of generations: 1 (15, 18)   (b) Number of generations: 200 (32, 35)

Fig. 3 Location of mesh routers by WMN-GA system, (m, n): m is number of connected mesh routers n is number of covered mesh clients of uniform distribution.



(a) Number of generations: 1 (12, 11)   (b) Number of generations: 200 (16, 47)

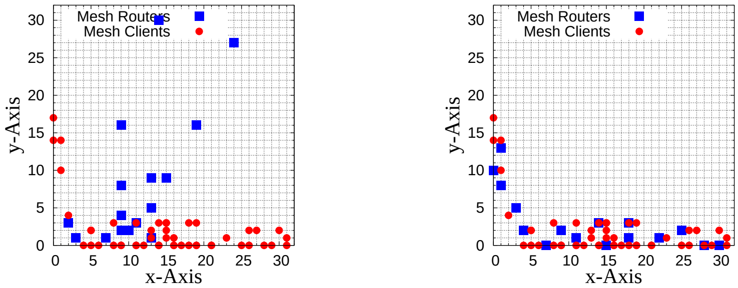
Fig. 4 Optimized location of mesh routers by WMN-GA, (m, n): m is number of connected mesh routers, n is number of covered mesh clients (Exponential distribution).

From the simulation results, we conclude that for HWM protocol the throughput of Uniform distribution is higher than other distributions. But, the delay and remaining energy is better for Weibull distribution.

In Fig. 13, we show the simulation results of OLSR protocol throughput for Normal, Uniform, Exponential and Weibull distributions, respectively. For Normal and Uniform distributions, the throughput of Hybrid WMN is higher than I/B WMN architecture. But, for Exponential distribution, the throughput of I/B WMN is higher than Hybrid WMN architecture. For Weibull distribution, the throughput is almost the same for both WMN architectures.

In Fig. 14, we show the delay for four distributions considering OLSR protocol. In Fig. 14(a) and Fig. 14(b), the delay of Hybrid WMN is a lower compared with I/B WMN. For Exponential and Weibull distributions (see Fig. 14(c) and Fig. 14(c)), the delay is almost the same for both distributions. However, the delay of Weibull distribution is lower than other distributions.

In Fig. 15, we show the remaining energy of OLSR protocol for Normal, Uniform, Exponential and Weibull distributions. For Normal distribution, the remaining



(a) Number of generations: 1 (12, 17) (b) Number of generations: 200 (16, 47)

Fig. 5 Optimized location of mesh routers by WMN-GA, (m, n): m is number of connected mesh routers, n is number of covered mesh clients (Weibull distribution).

Table 2 Evaluation results of WMN-GA system.

Number of mesh routers	Normal Distribution SGM	NCN	Uniform Distribution SGC	NCM	Exponential Distribution SGM	NCN	Weibull Distribution SGC	NCM
16	16	44	16	21	16	47	16	47
20	20	46	20	22	20	48	20	48
24	24	47	24	27	24	48	24	48
28	28	48	28	33	28	48	28	48
32	32	48	32	35	32	48	32	48

energy of Hybrid WMN is higher than I/B WMN. While for Exponential distribution, the remaining energy of I/B WMN is higher than Hybrid WMN. For Uniform and Weibull distributions, the energy decrease is almost the same for both WMN architectures. Also, for Uniform and Weibull distributions, the remaining energy is higher compared with Normal and Exponential distributions.

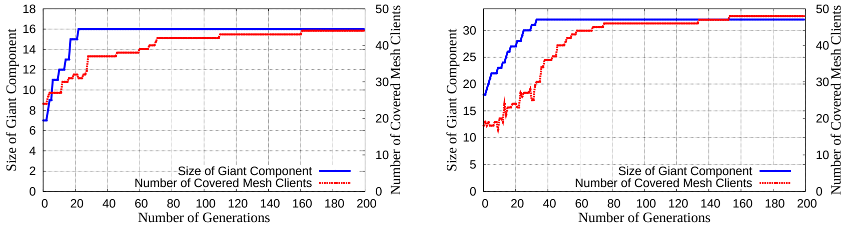
From the simulation results, we conclude that the throughput of Exponential distribution for OLSR protocol is better than other distributions. But, the delay and remaining energy is better for Weibull distribution.

9 Conclusions

In this paper, we evaluated by simulations the performance of WMNs considering throughput, delay and energy metrics. We used two architectures of WMNs. The topologies of WMNs are generated using WMN-GA system with area size 640m×640m. The mesh clients are distributed in the grid area using Normal, Uniform, Exponential and Weibull distributions.

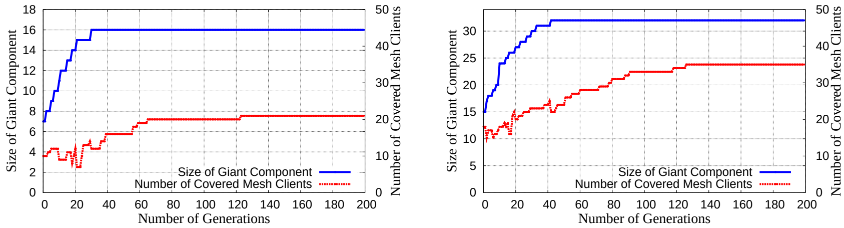
We carried out the simulations using ns-3 simulator. We transmitted multiple CBR flows over UDP. For simulations, we considered HWMP and OLSR protocol, log-distance path loss model and constant speed delay model. From simulations, we found the following results.

– For Normal and Exponential distributions, the throughput of I/B WMN is a little bit higher than Hybrid architecture. For Weibull distribution the throughput is almost the same for both WMN architectures. However, for Uniform distribution the throughput of Hybrid WMN is higher than I/B WMN. This is because for Normal and Exponential distributions, the mesh routers are concentrated in the grid area, thus there are many collisions and the network becomes congested.
– Considering HWM protocol, for Normal and Weibull distributions, the delay is almost the same. However, for Uniform distribution the delay of Hybrid WMN is lower than I/B WMN. This is because in Hybrid WMN also the mesh client communicate between each other. But, for Exponential distribution the delay of I/B WMN is low compared with Hybrid WMN.
– For HWM protocol and Normal and Exponential distributions, the energy decreases sharply, because the mesh routers are concentrated in the grid area and many packets collide with each other. For Weibull distribution, the energy decrease almost the same for both WMN architectures. For Uniform distribution, the remaining energy of I/B WMN is higher than Hybrid WMN. This is because in Hybrid WMN, there are three communications: mesh client to mesh client, mesh router to mesh router and mesh client to mesh router.
– For HWM protocol the throughput of Uniform distribution is higher than other distributions. But, the delay and remaining energy is better for Weibull distribution.



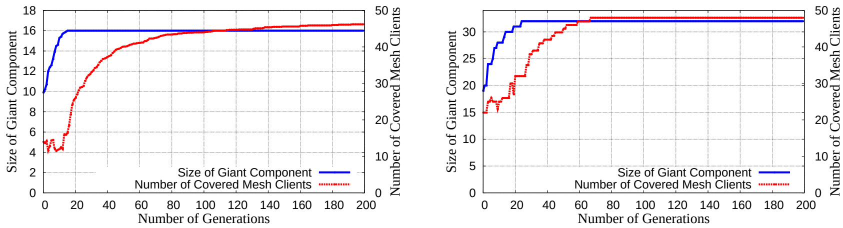
(a) Number of mesh routers: 16 (b) Number of mesh routers: 32

Fig. 6 SGC and NCM vs. number of generations for Normal Distribution.



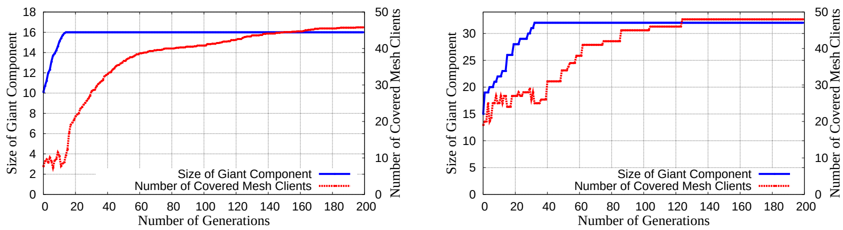
(a) Number of mesh routers: 16 (b) Number of mesh routers: 32

Fig. 7 SGC and NCM vs. number of generations for Uniform Distribution.



(a) Number of mesh routers: 16 (b) Number of mesh routers: 32

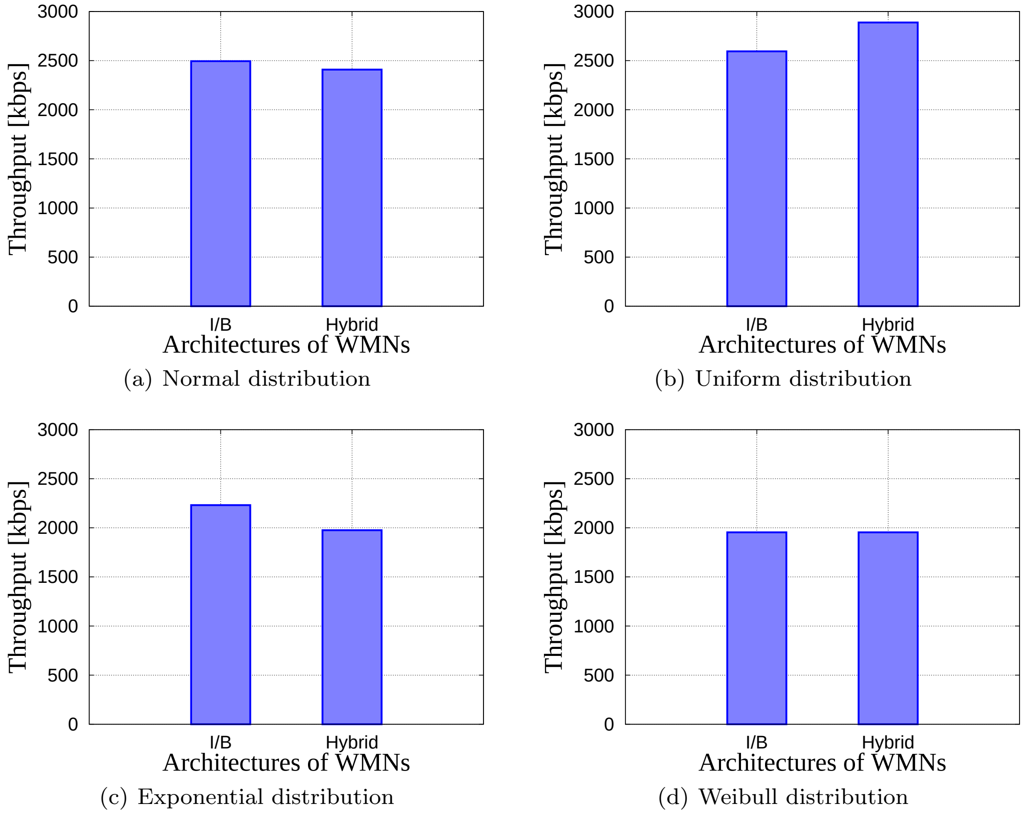
Fig. 8 SGC and NCM vs. number of generations for Exponential Distribution.



(a) Number of mesh routers: 16 (b) Number of mesh routers: 32

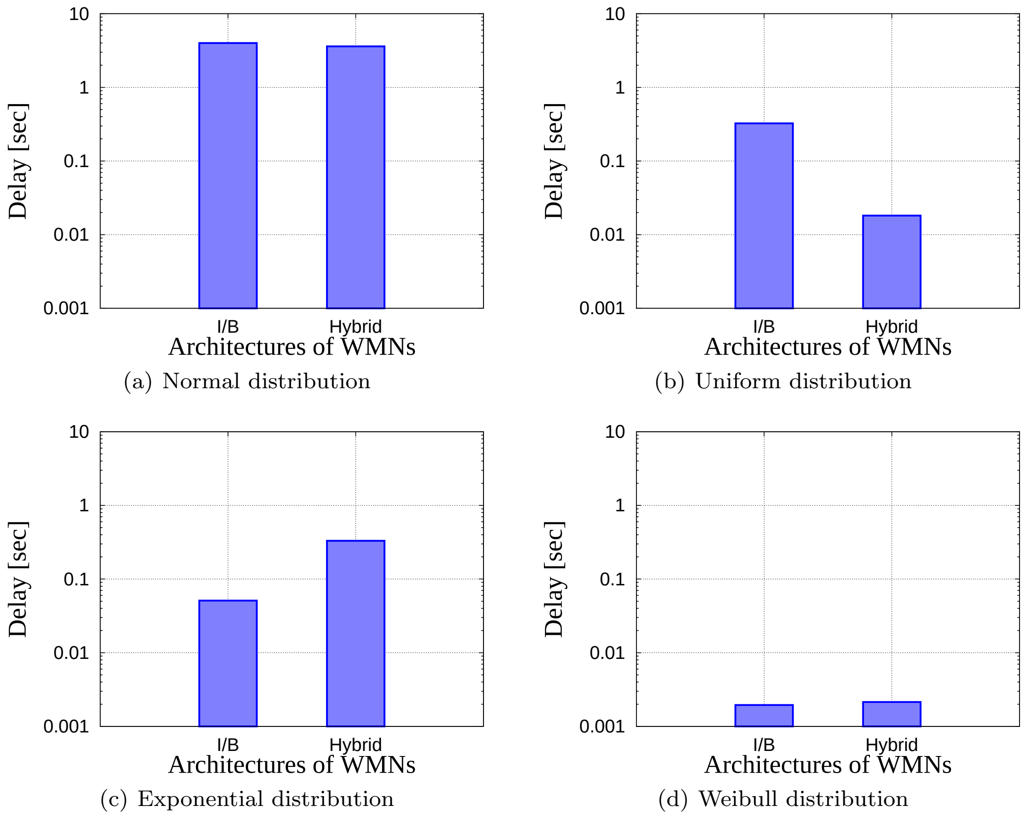
Fig. 9 SGC and NCM vs. number of generations for Weibull Distribution.

– For OLSR protocol and Normal and Uniform distributions, the throughput of Hybrid WMN is higher than I/B WMN architecture. But, for Exponential distribution, the throughput of I/B WMN is higher than Hybrid WMN architecture. For Weibull distribution, the throughput is almost the same for both WMN architectures.
– Considering OLSR protocol, for Normal and Uniform distributions the delay of Hybrid WMN is a lower compared with I/B WMN. For Exponential and Weibull distributions, the delay is almost the same for both distributions. However, the delay of Weibull distribution is lower than other distributions.
– The remaining energy of OLSR protocol for Normal distribution, the remaining energy of Hybrid WMN is higher than I/B WMN. While for Exponential distribution, the remaining energy of I/B WMN is higher than Hybrid WMN. For Uniform and Weibull distributions, the energy decrease is almost the same for both WMN architectures. Also, for Uniform and Weibull distributions, the remaining energy is higher compared with Normal and Exponential distributions.



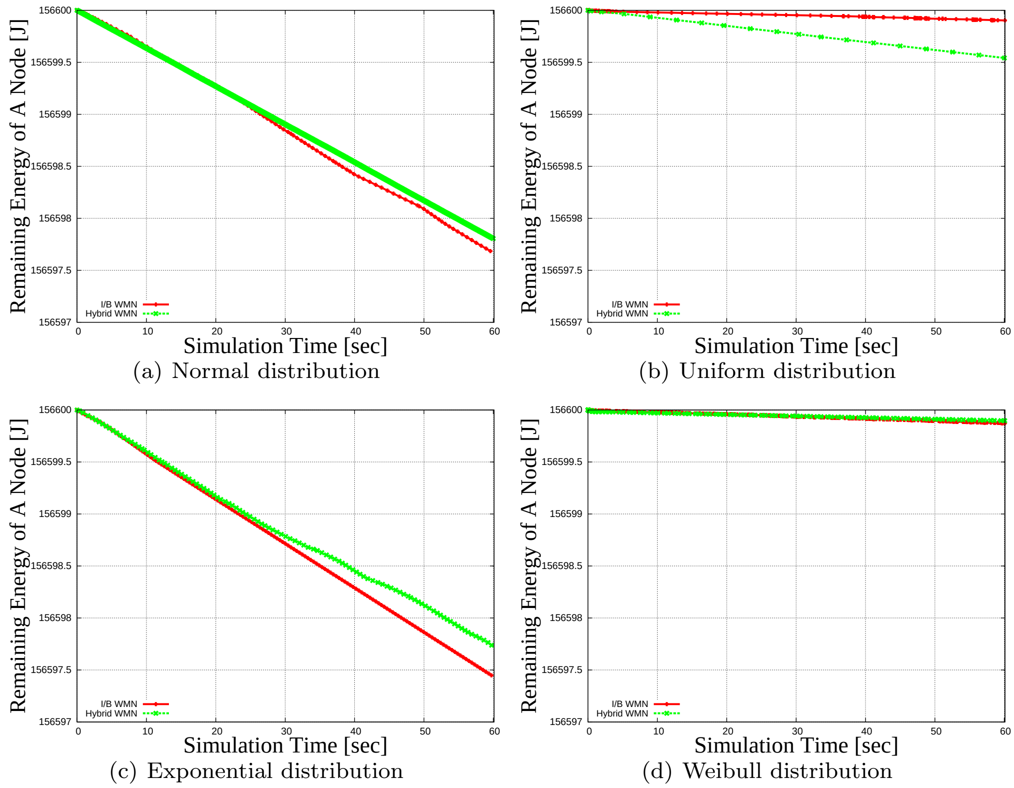
(a) Normal distribution
(b) Uniform distribution
(c) Exponential distribution
(d) Weibull distribution

Fig. 10 Results of average throughput for WMNs using HWMP of different distributions.



(a) Normal distribution
(b) Uniform distribution
(c) Exponential distribution
(d) Weibull distribution

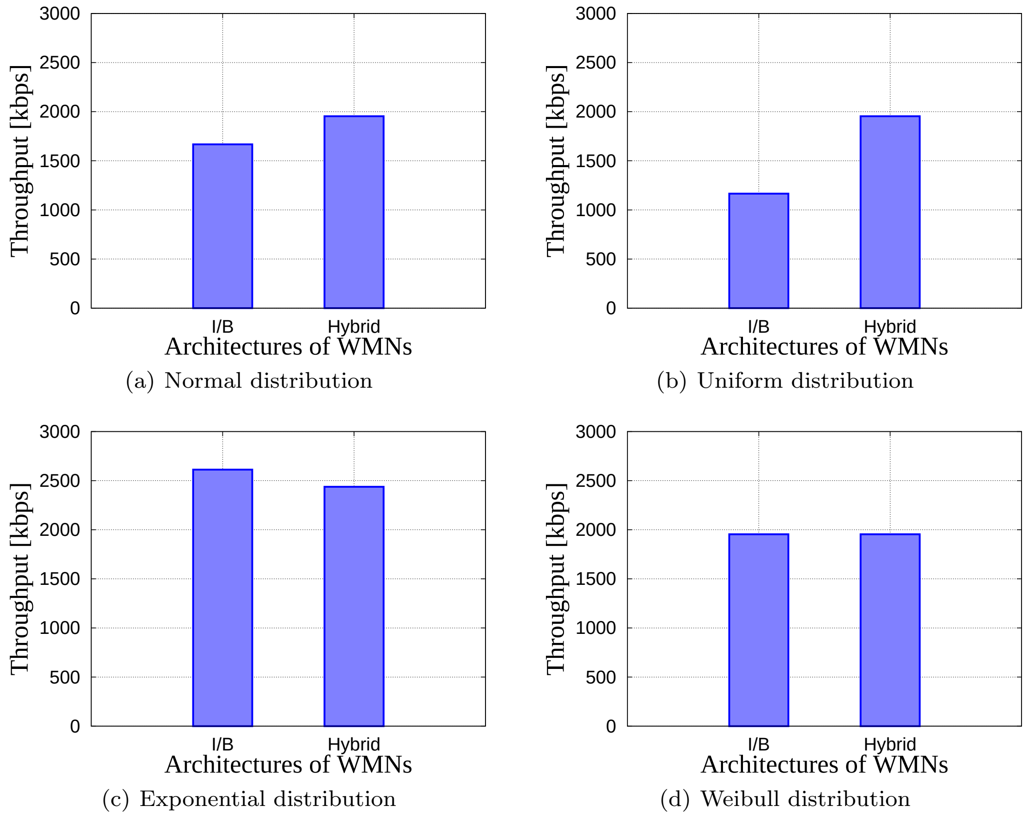
Fig. 11 Results of average delay for WMNs using HWMP of different distributions.



(a) Normal distribution (b) Uniform distribution

(c) Exponential distribution (d) Weibull distribution

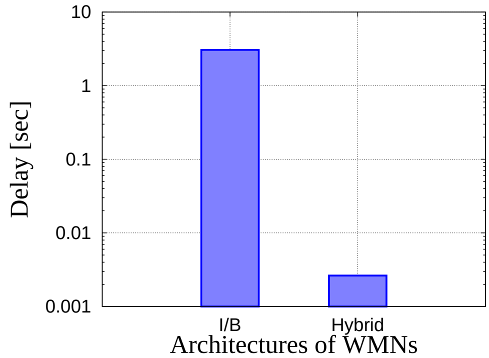
Fig. 12 Results of remaining energies for WMNs using HWMP of different distributions.



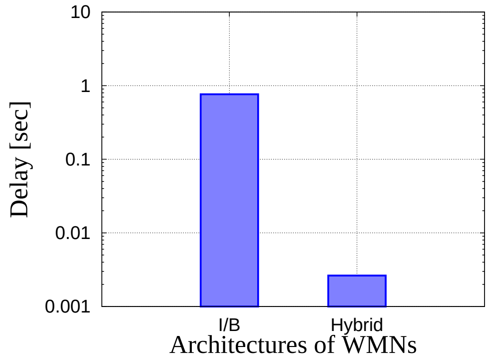
(a) Normal distribution (b) Uniform distribution

(c) Exponential distribution (d) Weibull distribution

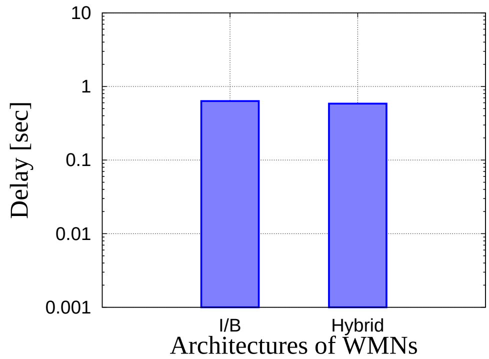
Fig. 13 Results of average throughput for WMNs using OLSR of different distributions.



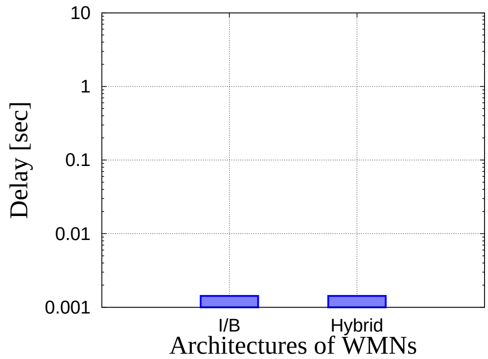
(a) Normal distribution



(b) Uniform distribution

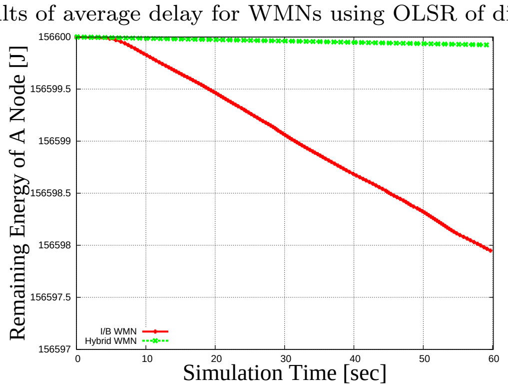


(c) Exponential distribution

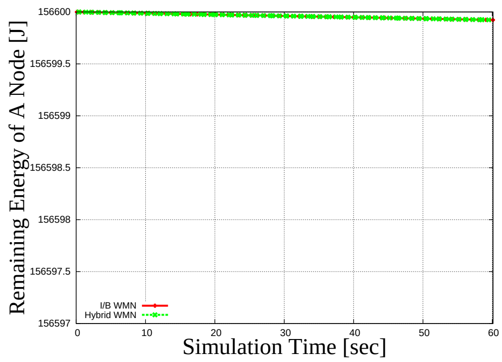


(d) Weibull distribution

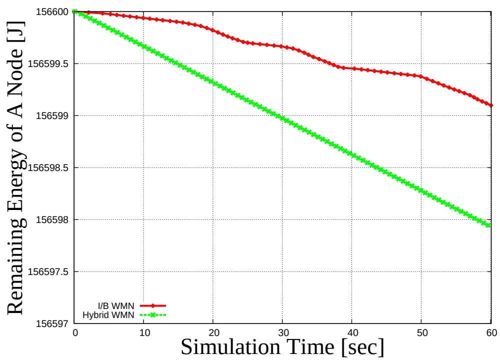
Fig. 14 Results of average delay for WMNs using OLSR of different distributions.



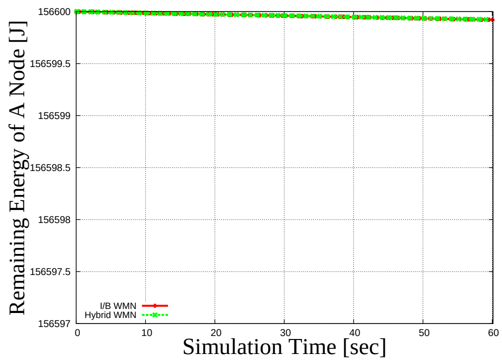
(a) Normal distribution



(b) Uniform distribution



(c) Exponential distribution



(d) Weibull distribution

Fig. 15 Results of remaining energies for WMNs using OLSR of different distributions.

– For OLSR protocol, the throughput of Exponential distribution is better than other distributions. But, the delay and remaining energy is better for Weibull distribution.

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