Wireless Mesh Networks performance assessment for confined Areas deployment

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Summary
Complex problems arise in planning network operations, particularly for deployment in an underground environment. Experimentation with Wireless Mesh Networks (WMN) suggests that their capacity can be surprisingly low due to the requirement that nodes forward each others' packets. The achievable capacity depends on the network size (i.e. number of hops), traffic patterns and detailed local radio interactions. This paper examines the capacity variation using an open source software network traffic generator and real experimental data obtained in an underground mine located in Val-d'Or, Québec, Canada. Our results helps in understanding the limitations of the total bandwidth available for WMN in an underground mine area.
The Wireless Access Points are deployed in a complex area such as mine galleries. The performance (maximum throughput) of a WAP (Wireless Access Point) is evaluated; the end to end and peer to peer communication effects on throughput for more than one hop are also analyzed by tuning UDP (User Datagram Protocol) traffic or TCP (Transmission Control Protocol) connection on a wireless Mesh network deployed at 70m below ground level. This environment is typical of an instable propagation environment submitted to multipath effect. This paper shows that a maximum total end to end capacity available in the WNM is roughly 5.8 Mbps and the end to end throughput available to each node is roughly $0(1/2^n)$ with n the total number of hops. Also WMN radio interface's behaviour and specially the number of hops in mine gallery is analyzed for comparison with it behaviour well known and already well studied in free space.
Key words:
Radio interface, Throughput, multi-hop, underground topology, TCP.

1. Introduction

In mining installations, the variability in the geometry associated with the mining activities progression makes the Mesh network configuration an ideal prospect for these installations. Mesh WLAN (Wireless Local Area Network) [2] eliminates wire interconnection (backhaul) needed between access point, thus allowing mobility management and dynamic wireless connectivity.

The Mesh configuration extends the concept of LAN Hotspot, while being self-configurable and self-spread.
This type of network is used in underground environment because it's a global wireless network. Maintenance costs are minimized since there is no cable needed between devices (router Mesh) which formed the network wireless backhaul. This network is flexible and easy to implement because Wireless Mesh device combines simple access point (AP) and router functionality. It currently represents a solution not only for accessing the Broadband Internet but also for more autonomous, flexible and easily deployed future networks. Routing of traffic packets is one of the main differences between ad hoc and Mesh networks. For a Mesh network, all the traffic circulates towards or from the gateways (generally used by the Mesh devices to provide connectivity with the IP world), whereas for ad hoc network, the traffic is between two arbitrary nodes [3]. Each node of the Mesh network can be used as a router or default gateway coupled with an access point. The gateways are the only exit doors to the Internet. The network trends to be dynamically self-organizing and self-configuring, with the nodes in the network automatically establishing and maintaining routes among themselves. Users can be stationary or comparatively mobile [2].
A systematic network deployment protocol requires a detailed performance study of its elements in the operating environment. Also, the performance when those elements are cooperating is of a great importance for later network backhaul expansion. This means that the throughput available to each single node's applications is limited not only by the channel capacity, but also by the forwarding load imposed by distant nodes. This effect could seriously limit the usefulness of the self routing property of this kind of wireless network. Ad hoc and Mesh Networks performances, mainly TCP, UDP, routing, MAC performance in free space propagation domain was addressed these past years [4-8] without tackling the question of using those new and performing wireless for

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broadband application (automation, remote control) in complex mine area.

The analysis of WMN scalability is based on inequality (eq.1) which tells us that WMN performance is affected by radio interfaces performances. It Is noticed that as the expected path length increases, the bandwidth available for each node to originate packets decreases [3] [9], where λ is the available capacity at each node, C is the total network one hop capacity, n is the number of nodes, L is the expected path length and r is a fixed transmission ratio.

$$\lambda \langle \frac{C/n}{L/r} \quad (1)$$

The ratio L/r is the minimum number of hops required to deliver a given packet from its source to its destination.

In this study, WMN radio interface's behavior and specially the number of hops limitation for its efficiency application in mine gallery is analyzed for comparison. This one is done using known performances of WMN' in free space, since underground results are unavailable. Also, performances of UDP and TCP in IEEE 802.11s based Mesh wireless network are evaluated. TCP is prevalent transport layer protocol used in the IP world today. It provides reliable data transfer and congestion control. As a transport layer protocol, it runs above the network and MAC layers. Our analysis focuses on static Wireless Mesh Networks, namely our scenarios, nodes and clients do not move during packet transit times (so-called nomadic conditions). For the total available capacity analysis, throughput performance evaluations are also done by experimentation in order to determine the suitable topology of WMN in a real confined area.

2. Wireless Mesh Network Details

In general, a mesh network consists of:

1) an Intelligent Access Point (IAP or gateway) which coordinates the others Access Points (AP) and manages their configurations.

2) a chain of Mesh routers (simple router or default gateway) coupled with Access points is used as a wireless Backbone. Those routers communicate with each others and function as a relay (an emitter and receiver) to ensure the link with other (neighbour) nodes to which there are connected.

For the specific Nortel WMN used in our experiment [2], two kinds of access points are used. The first one is called AP@NAP (Network Access Point couple with default gateway functionality) and is basically wired to a central gateway via a switch and a NAP-Router (fig.1). The second one is access point called standalone AP which can have a link from the AP@NAP and can therefore establish links with other standalone AP (AP coupled with router functionality). The 7250 gateway and the AP 7220 (standalone AP) which use two modes (radio) are presented in figure 1. The Access link mode (between standalone and a station as Iperf client in the figure 1 for example) uses the norm 802.11b/g and works at the 2.4 GHz ISM frequency band (between 2412 MHz and 2462 MHz) with a maximum data rate of 11 Mbps for 802.11 b and 54 Mbps for 802.11g, while the Transit Link (between access points) establishes a link at a central frequency of 5.8 GHz (between 5740 MHz-5840 MHz). Six channels (148, 152, 156, 164, 168, and 160) using OFDM modulation with a maximum data rate of 54 Mbps is dedicated to transit links. An OSPF (Open short Path First) routing protocol is used by the networks components (APs and gateways) to cooperate.

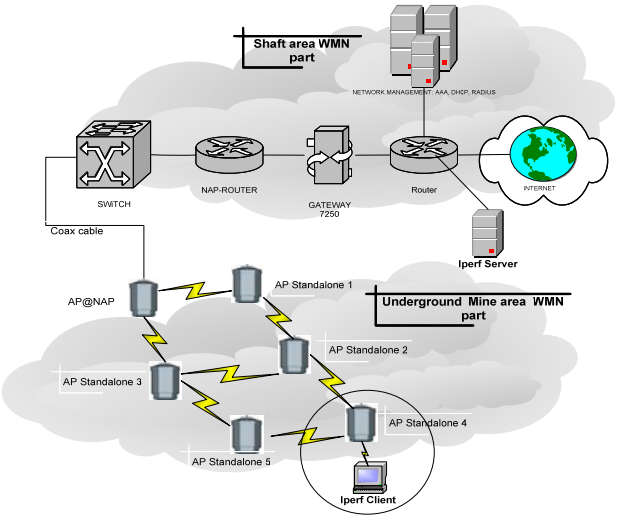

Fig. 1 Components of a mesh wireless network.

The Internet transport layer has two principal protocols: TCP and UDP. Both of them are submitted to evaluation in our experiments. The protocol TCP is a connection protocol, whereas UDP is a connectionless one. It is important to recall that a UDP packet is distinguished from a TCP one only by the addition of a small heading. AP@NAP offers for the user a data rate of 10 Mbps but as the user moves down in hops, this throughput will drop. To clarify network (throughput) behaviour, the access link can give till 10 Mbps (802.11b mode) by itself, but the user will only get throughput based on what is offered by the upstream transit link. The maximum bandwidth provided by an access link is limited by IPSec (Internet Protocol Security) resource consumption on the AP. The total capacity of an AP@NAP can theoretically vary from 14 Mbps to 16 Mbps for large packet UDP traffics (packet size 1500 bytes) function to the time spent by the AP to

share its transit link channel when there are more than one transit channel on its single transit link.
Finally, the Transmission Control Protocol (TCP) is the prevalent reliable transport protocol used in the internet today. The TCP [10-11] has some advantages related to the connection allowing handshaking between sending and receiving transport-layer entities by using anticipation window (TPDU), packet errors checking, retransmission of the lost or erroneous packets, reordering of received packets and flow control. It is used for the application transport sensitive to errors and less sensitive to deadlines (transmission delay). TCP has another important advantage: it can adapt to the network conditions and do congestion control.
As TCP, UDP [11] works by using CRC (cyclic Redundancy Check) mechanism ensuring packet integrity but a packet failing checksum is simply discarded, with no further action taken (as a new sending). Note that with UDP there is no handshaking between sending and receiving transport-layer entities before sending a TPDU (Transport Protocol Data Unit). For this reason, UDP is said to be connectionless.

2.1 WMN node Characteristics

As Nortel Mesh AP combines APs and routing, they have two radio interfaces. There is a radio for the wireless access link and a radio for the wireless transit link. The access link operates at a center frequency of 2.4 GHz (802.11 b), whereas transit link works at a center frequency of 5.8GHz. There are many types of Mesh access point. Depending on the number of radio interfaces, Mesh access point with a radio (interface) and Mesh access point with several radios are available. An example of a Mesh access point with a radio is the MIT Roofnet or Freifunk access point. The main difference between Nortel Mesh access point and MIT Roofnet or Freifunk access point is the fact that in the latter only the transit link are wireless.
In our applications, the output power and frequency range for each radio interface is tuned so that interferences between APs are controlled. Frequency control can also be enabled automatically (dynamically). Routing between the APs can be controlled by selecting the frequency range of the transit link. That way, the network backhaul topology can be well defined.
A Nortel Mesh AP can theoretically support a maximum of three hops when used in free space environment. Source APs can communicate with destination APs by sharing fairly the slot of the destination AP. The time slot interval can be 30 ms, 35 ms or 50 ms. The data rate of the transit link and the access link on the APs fluctuates according to the channel noise. The noise of the wireless transit link is above -80 dBm for example when the data rate is set to 54 Mbps. Between -82dBm and -80 dBm the rate is 48 Mbps [2].
The signal strength therefore depends on the power radiated EIRP (Equivalent isotropically radiated power) output of the AP's radio interface and the data rate of packets (Table 1).

Table 1: WMN's free space interface radio characteristic.

Access Link (simple AP)

Data rate (Mbps)	range (m)
11	125
5.5	200

Transit Link (router)

Data rate (Mbps)	range (m)
54	200
36	320

This paper analyses how far away from the network, clustered APs have access to a minimum of 1Mbps bandwidth. It's with this question that some tests are conducted in underground environment to determine the networks suitable topology using carefully chosen scenarios described later in this paper. Theoretically, in free space, Nortel [2] recommended that the decrease of end to end TCP bandwidth (transport layer) with respect to the number of hops is about 0 ($1/2^n$).

3. Experimental underground environment

Overall, this experimentation determines total available bandwidth and how it breaks down in an underground environment subjected to the combined effects of multipath, roughness and reflection coefficient and finally diffraction coefficient. Propagation in mining environment has been studied at length lately and these studies revealed the complexity related to the chaotic propagation of electromagnetic waves in this environment classified and designated as complex [12-13]. The non-canonical topology of the gallery in mine environment makes it an ideal environment to study the connection reliability between APs not in clear line of sight. As unbelievable as it seems, in underground mine area, there are galleries with loop and some without loop (fig. 3). That loop coupled with the topology of the WMN makes the transfer of packets possible in the case of failure in the operational direction since the Mesh devices (also router) can communicate in both directions (bidirectional communication). The impact of a failure in this type of network can be managed by the addiction of frequency redundancy allocated to each AP in the network for example in galleries without loop.
The underground tunnel sections used for the experimentation are shown in figure 3. The tunnel width is

roughly 3 meters. The lateral surfaces and the ceiling are rough and composed of rocks. Air conditioner (fan devices) and electrical cables are installed along the lateral surface of the tunnel (fig. 2). Metallic nets are fixed on the ceiling to retain fragmented rocks. The wireless access points are fixed on the metallic net.

Fig. 2 Photograph of the underground gallery.

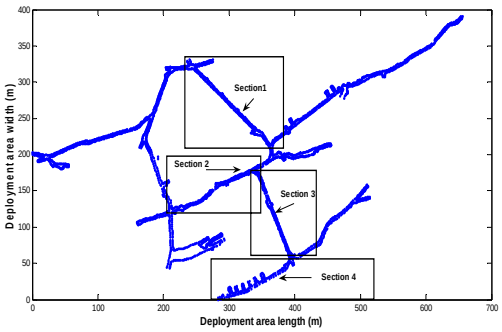

Fig. 3 Mine area and galleries (sections).

4. Experimental Protocol

Figure 1 shows all components of the Wireless Mesh Network. The network is divided in two parts connected by a coax. The first part is located on the shaft on the mine surface and the second part in the underground mine area (fig. 3) at -70 m from the ground level. It can be noticed in figure 1 that the server Iperf is close to the Gateway and is in the same IP address domain. The client can be moved and linked to an appropriate wireless AP function to not only the number of the hops from the gateway but also the scenario chosen for this evaluation. At the access link level, the channel is allowed to AP Mesh to avoid co channel interference. Figure 4 presents received power profile after a long campaign in different galleries shown in figure 3.

Those measurements show the access links received power profile from 802.11 b wireless Card. In figure 4, received power measurements signatures are recorded follow the gallery long. The received power is recorded at uniform distance step from the source emitter following a route located at the gallery center, a route following the right lateral wall and the route following left lateral wall of the gallery. Also figure 4 shows the power received from source APs located at each end of each gallery to analyzed connection quality in case of roaming. This study can help to choose the appropriate antenna gain of each device in a same gallery as the electromagnetic physical parameters can change from an AP's location to another one. It can be clearly observed multipath and multiple reflection effects in the narrow galleries. Base on those recorded power profiles and the WMN Mesh radio interfaces it can be clearly noticed that the real observed receiver sensitivity varies from a gallery section to another. Despite the fact that the measurements are made in a stable propagation channel, the data rate at the AP can be affected by the fast variation of the received power profile. It is the reason why the use of optional antenna is suitable to improve the wireless radio interface performance. The gain of the antenna must be chosen depending on the length of the gallery section to avoid interference. The AP must be also placed to suitable distance to ensure that immediate pair nodes are in the range of each other. Finally those distances ensure not only a minimum percentage of cell area overlapping which varies between 45% and 50% to facilitate roaming but also a theoretical high data rate between an access point (source node) and its immediate neighbour. The radio interface behaviour analysis reveals that the overlap minimum area between immediate APs is an efficient parameter to characterize the link quality in a confined area. It is of course the parameter which couples efficiently access link with transit link. Every access point is in Line Of Sight (LOS) with its neighbour, Fig. 6. The efficient AP range in the different galleries varies from 20 to 50m if the noise threshold is set to -80 dBm, Fig. 4. Since a same bidirectional connection quality is not always guaranteed, it is recommended for source and destination node to be closed as much as possible the gallery topology allows it. Only one AP@NAP (default gateway coupled with access point) is used in the network during this experimentation. The UDP and TCP performance of the WMN is analyzed using different scenarios summed up in table 2. Every node (Mesh device) has identical receiving sensitivity and transmission power. The evoked scenario (table 2) shows the effect of the length of the chain of transmission via the number of active Access Points in the chain.

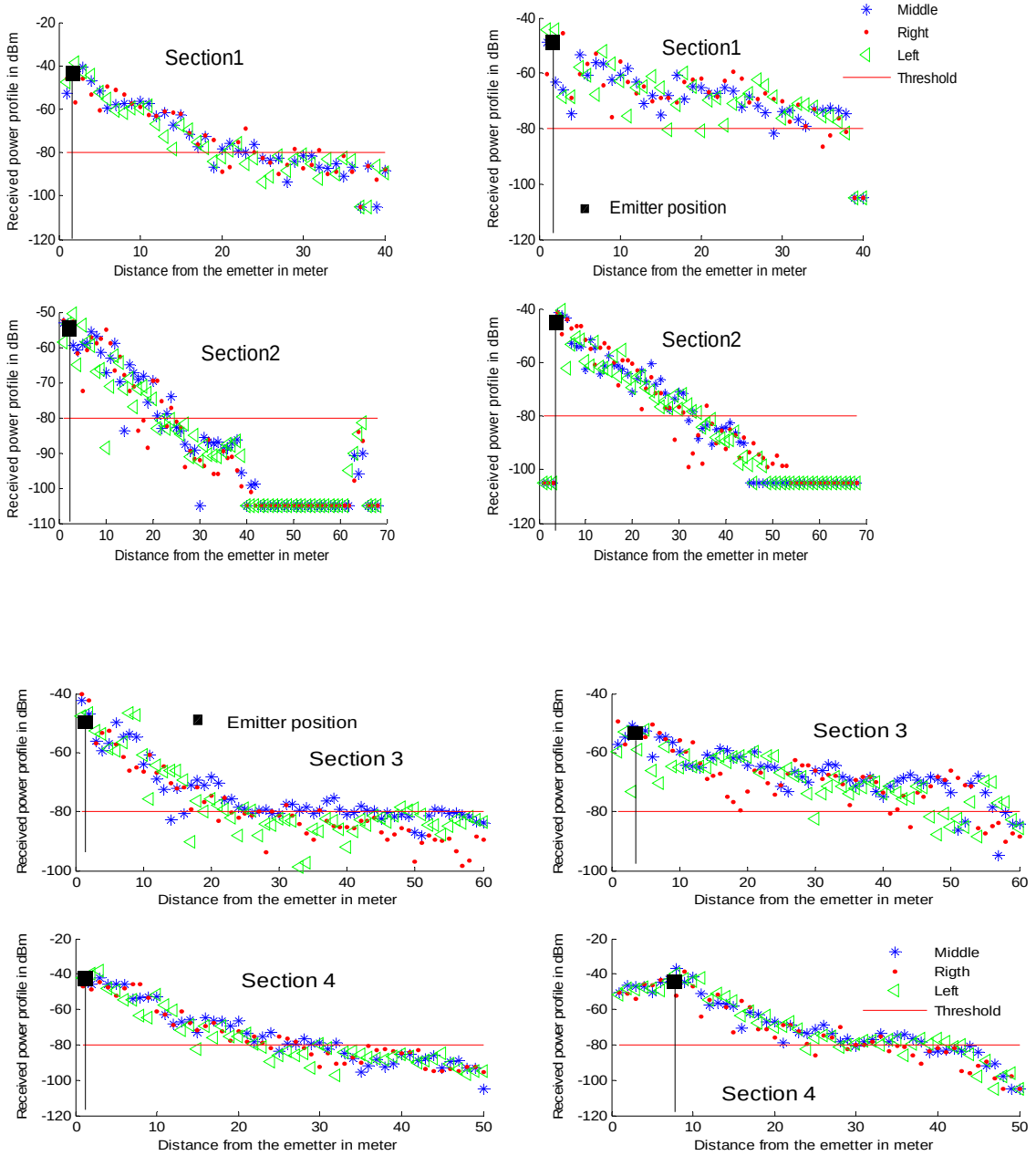

Fig. 4 Narrow band received power characteristic over 802.11b access link in different underground mine galleries.

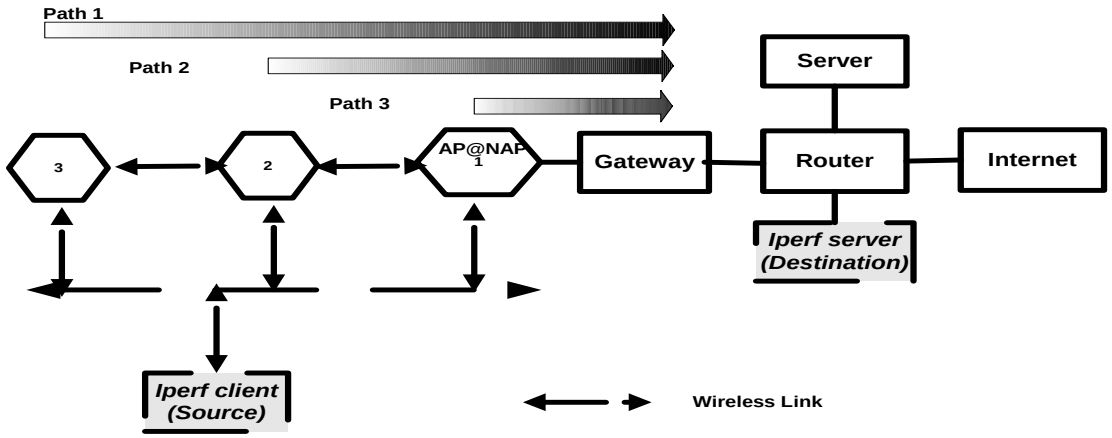

Fig. 5 Test bed used to evaluate total bandwidth according to Iperf client position.

Table 2: Possible APs' states according to scenarios

Scenarios	State of AP@NAP	State of AP2	State of AP3	Client connected to
1	True	False	False	AP@NAP
2	True	True	False	AP@NAP
3	True	True	True	AP@NAP
4	True	True	False	AP2
5	True	True	True	AP2
6	True	True	True	AP3

True: AP operating

False: AP none operating

The test bed is presented, (fig. 5). Concerning the test bed, the Iperf server's location is static, each measurement lasts 60 s and is repeated at least 10 times [14]. Without losing the goal of this study, the chain network (Wireless Backhaul) is made of maximum of three APs. In general, in free space environment, the WMN is deployed so that each access point in the network has at its disposal 1Mbps bandwidth. Therefore, to achieve our goal, it is important to determine how far away from the network, APs no longer have access to a minimum of 1Mbps bandwidth. So from one scenario to another one the Iperf client moves from an AP to another one. The paths follow by the traffic is illustrated in figure 5 according to the Iperf client position. Also, notice that only the AP, to which the client Iperf is connected, is loaded by traffic. Depending on the scenario, some APs in the chain are let active (True) or non active (false) as it is mentioned on table 2. If this state is true, it means that it can establish a route toward the gateway by possibly crossing neighbours. For example during the first scenario in table 2, the Iperf client is linked to the AP@NAP to evaluate the available total bandwidth in the WMN. The Iperf client sends traffic to the Iperf server. Since the total bandwidth is evaluated, in scenario 2, without moving the Iperf client, this time AP2 is activated. For information no traffic is loaded to AP 2 (Scenario 2) and it is recorded a new total bandwidth. In the scenario 3, AP3 is just added in the network. No traffic is loaded to AP3 and the total bandwidth available on the AP@NAP is recorded.

During above scenarios, the WMN capacity performance is evaluated and the results obtained will be discussed in the next paragraph.

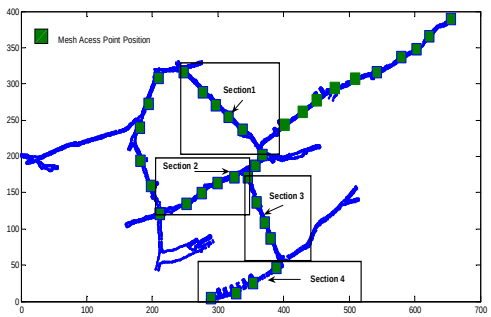

Fig. 6 Real positions of the Access Points in the real Mine area (the axes are in meter unity).

There is a distance which varies from 20m to 41m between direct neighbours Mesh Access Point (fig. 4). This separation distance variation is due to the changing topology of the complex area in the same manner that the range of the AP varies in function of the AP's location and the gallery geometry (fig. 4). As it is mentioned early in this paragraph, strait gallery profits of long distance separation.

5. Results

In order to evaluate the communication performance of the WMN, several experiments were performed and a number of measurements were taken under varying conditions. The parameters of interest were:

- Communication throughput: The average useful data rate in bit per second (kbps) obtained during the interval of measurement (60 s).
- Jitter: The smoothed mean of differences between consecutive transit times. The server computes the relative transit time as the difference between the time that the Iperf server receives a packet and the time the packet is sent by the client.
- Packet loss: The percentage of packet loss during the interval of measurement (60 s).

Three factors are also important in wireless network deployment: length of the exchanged packets, available throughput of the used links, and buffer size of the active devices of the network. Their values can vary from a test with another and will be indicated if necessary at the time of analyzing the results. For the following measurements the size of the packets sent by the Iperf traffic generator is set to 1470 bytes. The buffer size is 8 kbytes (default value) about six times the packets length to avoid testing the length of the queues on the way of the packets sent which can maybe have an influence on the rate of packets lost.

1- UDP Performances: As UDP performances are important for real time application, its behaviour has been studied in the underground mine corridor. The UDP throughput without packets loss is always more than 95% of the maximum available maximum throughput in the network [14]. Also its variation is almost zero (fig. 7). The maximum available bandwidth is found by iterative research method (step by step) until the throttling of the Wireless Mesh Network is reached. The total maximum available bandwidth is 5.8 Mbps when allowing a percentage of loss of datagram inferior to 10%.

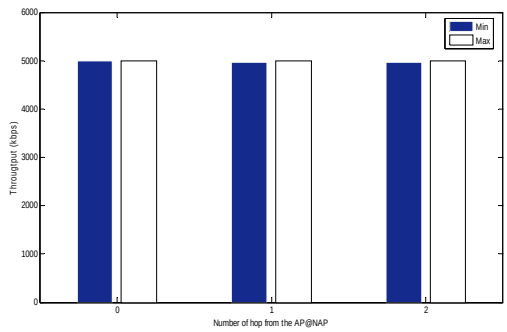

Fig. 7 UDP Throughput with Bandwidth fixed to 5 Mbps. (Scenario 3).

The UDP test allows us to measure the jitter. The jitter resulting from the packets sent (1470 bytes) during 60 s varies according to the number of hops. The maximum and minimum jitter observed during 10 simulations is given on fig. 8. The maximum UDP jitter variation is about 2 ms between immediate neighbour access points when the number of hops on the path from the AP@NAP increases (fig. 8). Figure 8 shows the severe variations between maximum and minimum jitter at the same AP when the number of hops increases. This variation can be caused by the environment because underground mine is an environment which deals with delays due to multipath effects, multi reflections effects and diffractions despite the small distance between immediate APs. Also the size of the buffer of the APs can have a significant effect on the jitter. As direct effect, it can deteriorate the quality of the signal of the received packets, and cause losses of packets in UDP or retransmissions in TCP. The achievable bandwidth is fixed to 5 Mbps to avoid reaching the peak of overflow congestion when adding APs on the WMN.

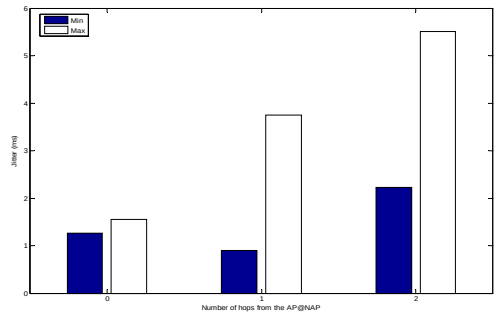

Fig. 8 UDP Jitter (Scenario1)

2- TCP Performances: Contrary to UDP performance observed, TCP performance varies. The scenario shows the effect of routing and cooperation between access

points and how the available bandwidth is used with TCP connection.

Opposite to UDP performance observed, end to end TCP performance (throughput) decreases function to the number of the hops, (fig. 9).

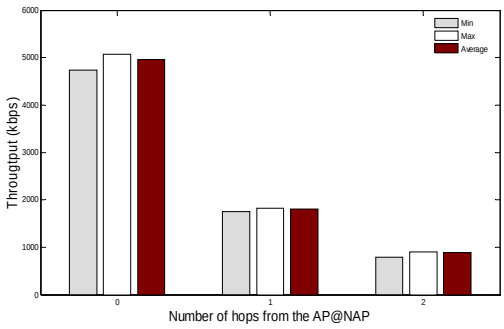

Fig. 9 TCP Throughput.

6. Discussion of Results

The interface radio characteristics vary function to the Mesh devices location. It is difficult to consider that a constant path loss factor to model the received power profile in the confined environment. But it has been shown and this paper confirms that the received power can be statistically modeled by a lognormal distribution [13]. The range of the transit link (802.11 b) of each AP is a maximum of 50 m in the complex indoor area instead of 125 m in free space at a data rate of 11 Mbps when the power threshold is fixed to -80 dBm.

The AP@NAP is the active default gateway in the network. Its bandwidth is systematically and almost equally share when there is more than one redundant AP Mesh (Standalone AP) in stand-by mode directly alongwith the active gateway (AP@NAP). By default its bandwidth is systematically divided into three equal parts.

Under each AP Mesh (Standalone AP), the throughput is systematically almost shared between its redundant Mesh APs.

1- Basically AP access link throughput will also decrease when the number of hops increases. The total available bandwidth obtained from the test is shown in figure 10A. It is evaluated to 5.8 Mbps. Figure 5 shows the different tests done under the AP@NAP for example to put in relief the loss of bandwidth (breakdown of bandwidth) due to redundant AP in the network. Active redundant APs' effects results are shown under the AP@NAP in figure 10B and after one hop from the AP@NAP. It is notice in all of case loss of bandwidth. From this result and taking into account that the performance of the throughput obtained when the Iperf client is linked to the AP@NAP, it can be concluded that the native TCP protocol using multiple hops wireless transit links over 802.11a protocol, can suffer of congestion due to redundant active Mesh APs routing information in the network . The terminology redundant AP is used for all Mesh AP which is not AP@NAP and which supports at least one other Mesh AP if a tree topology is considered. The degree of decrease of the total available throughput is relatively more important (Fig. 10B) and limits the total network's capacity when the network increases. So TCP total throughput performance varies not only function to the number of hops from the AP@NAP (gateway) but also the total number of active Access Points in the wireless network backbone. Figure 10D is derived from figure 10B. The total bandwidth is divided by the maximum of relay that can support a Nortel AP Mesh. This maximum of relay is limited to 3 for Nortel Mesh APs. So the maximum of total bandwidth available will be equally share by redundant AP operating on disjoint canal and linked to AP@NAP (active default gateway). Figure 10E shows the decrease of the bandwidth in the WMN' AP in function to their position (number of hops from the gateway) in the clustered APs network. Referring to the topology of the network and assuming that the available bandwidth is equally shared between AP Mesh subtended to any Mesh AP in the WMN, only one topology is suitable for a deployment of WMN in complex environment by taking in to account results shown in figure 10E. All derived topology from this topology and well matched to the mine topology can be used. Indeed, figure 10E shows theoretically that the decrease of end to end bandwidth with respect to the number of hops is about $0(1/2^n)$. This figure also illustrates that after 2 hops from the AP@NAP the bandwidth at the disposal of an AP Mesh is less than 1Mbps. The topology must match to results (constraints) illustrated in figure 10E couple with figure10A. Indeed, figure 10A projects that AP@NAP can support a maximum total bandwidth of about 6Mbps and the following APs under AP@NAP can support a total maximum bandwidth of 2Mbps. That topology are illustrate in figure 11. The topology shows the breakdown of the available maximum bandwidth in the WMN: The topology in figure 11 presents only 2 hops and allows a clustering of 10 APs Mesh.

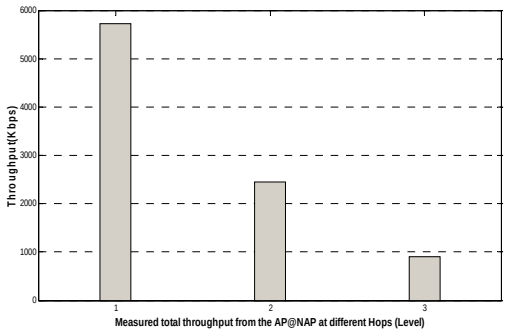

Fig. 10A: Measured total bandwidth available on the Mesh AP chain network after 1, 2 and 3 hops from the Network gateway respectively.

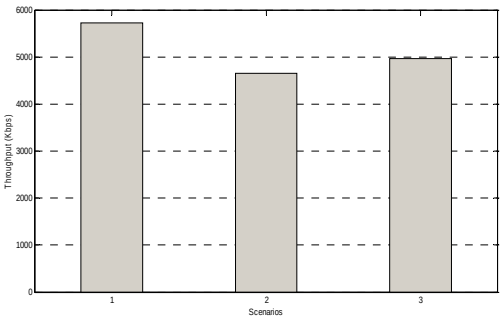

Fig. 10B: Measured total bandwidth shared by a single AP@NAP for scenarios 1, 2 and 3 respectively.

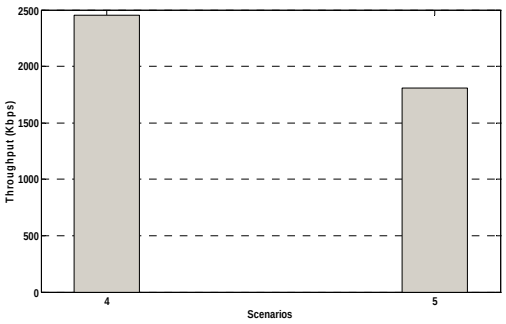

Fig. 10C: Measured total bandwidth shared by any single redundant AP under the AP@NAP (after one hop).

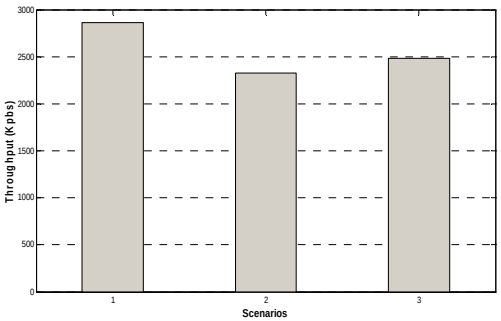

Fig. 10D: Measured total bandwidth shared by single redundant AP under a single AP@NAP

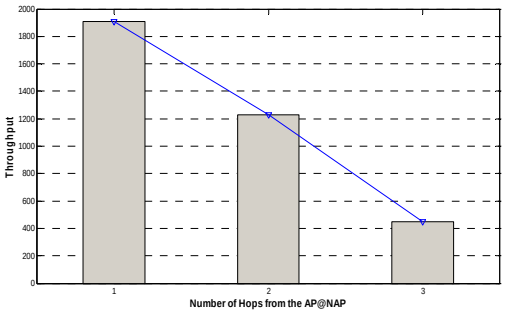

Fig. 10E: Measured total bandwidth available at each single redundant AP under the AP@NAP after respectively 0,1 and 2 hops from the network AP@NAP

Fig. 10: Experimental TCP performance

The topology designed assumes that no access link wireless connection is established with the AP@NAP. Our gaol is reached as it is the only topology that allows a disposal of 1Mbps at the Mesh APs far from the AP@NAP. This topology is very important to better refined cluster in case of gateways placements under quality of service constraints [15].

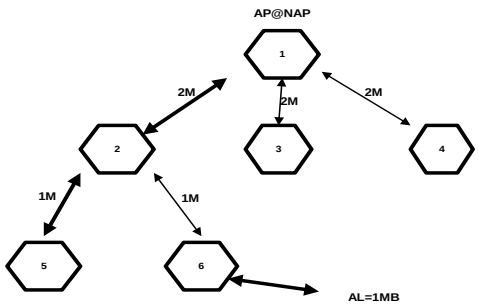

Fig. 11 Topologies suitable for complex area.

2- The effect of the routing protocol cannot be neglected in this analysis despite the fact that the routing table does not change during the whole experimentation and OSPF Hello messages size is very short. The total throughput decrease (fig. 10B) observed at the level of the transport layer, when AP is added on the chain can be explained by many reasons. This total bandwidth available decrease is about 20% under the AP@NAP (fig. 10B) and 30% after one hop from the AP@NAP (fig. 10C), [16]. It can be also induced by interference between simultaneous neighbouring transmission in addition to fading and environmental noise.

3- It has been also found that the maximum total end to end capacity available at the transport layer is roughly 5.8 Mbps and the end to end throughput available on a single AP Mesh is roughly $0(1/2^n)$ (Fig. 10E) with n the total number of hops from the AP@NAP in the underground gallery. Also, the maximum number of hops when you move further away from the AP@NAP before the bandwidth falls below 1Mbps at the standalone AP is 2. For comparison, this number of hops reached in free space is 3.

4- This result is likely to be useful both in understanding Mesh Network performance and in the deployment of real Wireless Mesh Network in underground area. The maximum total capacity reached by the WMN is about 57% of the expected 10 Mbps. This value measured on the AP@NAP when there is no other active redundant Mesh AP under the AP@NAP, can be used as the threshold of the total capacity available on the network in this area with a precision of 80%.

7. Conclusion

This paper has dealt with WMN performance evaluation for underground mine applications for revolution of communication and automation in this confined area. A certain number of fundamentals conclusions have been reached by a rigorous analysis of the results, namely:

1- the WMN is well matched for real time applications in mine area because the UDP throughput never changes when the number of hops from the AP@NAP increases but important packets losses may occur when total bandwidth available needed for application is more than 5.8 Mbps. This total maximum bandwidth must be limited to 2 Mbps under each AP@NAP in the WMN.

2- For TCP performance, it has been realized that an efficient match of the total throughput capacity, scale it up with network size and guarantee that a minimum of 1Mbps bandwidth must be available between source and destination node as the network grows in underground mine. The number of hop is reduced to 2 in the complex area in stead of 3 in free space [2] before the bandwidth falls below 1Mbps at the standalone AP.

3- For the capacity flow balance, it can be recommended that, in complex area, low or variable data rates should be used in order to avoid running out of capacity.

4- Due to the fact that the mine galleries used for this study are narrow, it is not always possible to get profit of a large relay (path diversity) which is the main characteristic of wireless Mesh Network. But it is possible to get profit of the loop introduced by the mine gallery topology (ramp). Also recovery of link failure is possible by changing the routing direction.

5- As an advantage WMN technology can reduce mine investigation cost because it is possible to remove access points and deploy them when the mine topology varies. A good allocation of channel which matches with the underground mine topology must be done to reduce the effect of interference. Also, future investigation on the TCP congestion- window value is important to determine the suitable TCP protocol in order to improve the TCP performance in underground mine area and reduce delay to find the ideal congestion window faster. A particular parameter setting for TCP protocol may be a way to improve the global Network throughput capacity in this area as the best TCP protocol would do.

6- Finally a real traffic in underground mine area will be proposed to study the effect of congestion in the WMN.

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