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COMMUNICATION SUPPORT FOR MOBILE COLLABORATIVE WORK: AN EXPERIMENTAL STUDY

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Advances in mobile computing and wireless communication are easing the evolution from traditional nomadic work to computer-mediated mobile collaborative work. Technology allows efficient and effective interaction among mobile users and it also provides access to shared resources available to them. However, the features and capabilities of the communication infrastructure supporting these activities influence the type of coordination and collaboration employed by mobile collaborative applications in real work scenarios. Developers of these applications are typically unaware of the constraints the communication infrastructure imposes on mobile collaborative systems, because they are not easy to foresee. That leads to a high probability of communication problems in otherwise fully functional mobile collaborative support applications. This paper presents an experimental study with real devices and networks on a realistic physical environment that shows how ad-hoc networks can effectively support mobile collaborative work and the practical limitations. The article analyzes several networking issues and it determines how they influence mobile collaborative work in various interaction scenarios. The paper also presents the lessons learned in the study and it provides recommendations to deal with some networking issues related to real-world ad hoc networks.

Keywords: Mobile collaboration; communication support; mobile ad hoc networks, experimental study.

1. Introduction

Collaborative applications are intended to support the work performed by a group of collaborators who pursue a common goal. Research work in this area has focused on stationary collaboration during the last twenty years; however, advances in mobile computing and wireless communication have made mobile collaboration a real possibility. Healthcare [4, 45], collaborative learning [49, 54] and design [53], emergency management [2, 30], and productive activities [3, 34] are some of the application areas where mobile collaborative solutions can be used to support the activities of nomad workers. The idea behind this new CSCW paradigm is to support collaboration among mobile users, regardless of their physical location [3].

Ellis et al. showed two decades ago that coordination and collaboration depend on communication [12]. Therefore, if we want to enable coordination and collaboration among mobile users, then we have to provide a suitable communication support for them. Today, wireless communication technologies partially match the needs for communication of mobile users. However that communication infrastructure used by mobile collaborative applications is far from simple and therefore careful engineering is required to overcome their potential networking limitations, and thus provide a suitable communication support.

Software designers must take into account the capabilities and limitations of the communication infrastructure when they design a new mobile collaborative application. Knowing these issues will help them to conceive applications able to support the interactions among nomad users in real world scenarios. For example, the interaction and awareness mechanisms [21] to be embedded into the application must be selected by considering the stability and bandwidth of the communication link supporting mobile collaboration. For example awareness mechanisms based on image contents [35] could be inappropriate when the images are transferred through the network and the available bandwidth is narrow. Otherwise, we would be giving the user an interaction or awareness service without the required performance and responsiveness. A poor communication performance typically affects the coordination and collaboration services that are available for the users, and therefore it also impacts on the usability of the application.

Software designers are typically unaware of several communication and coordination characteristics and limitations as they are not easy to preview or infer. Herskovic et al. call this situation the iceberg effect [17], because it encourages designers to focus on the visible part of the product (i.e. the user interface) and forget important parts of the solution that usually are not easy to see (i.e. the communication and coordination mechanisms) but critical. One of the problems caused by the iceberg effect is the uncertainty about the suitability of the communication infrastructure when nomad workers need to use it as a support for collaborative processes in real work scenarios. Therefore it is not possible to guarantee the suitability of the mobile application in terms of the response time perceived by an end user.

In the best case developers rely or perform studies based on network simulators, a software that tries to predict the behavior of a network, usually based on highly simplified scenarios, where nodes move randomly in an open area, relying on idealized models of radio propagation and interference. This type of study provides a glimpse on the suitability of the communication facilities to support a certain mobile activity but they are imprecise as they deliberately miss implementation details relevant for application developers. As the distinction between acceptable and unacceptable communication support in this scenario is so small we claim experimental results with real networks, computers, cards, links, software stacks, rooms that have significant effects are required to understand their capabilities and limitations.

This article presents an experimental study performed at a real setting (e.g. hardware, software, users, networks and physical facilities) with three types of collaboration scenarios (i.e. stationary, partially mobile and mobile). The study also includes several experiments which try to show when and how an ad-hoc network can be used to support mobile collaborative work, and also which are the limitations and considerations to be applied for mobile collaborative applications design. It intends to show designers both the limits of mobile ad-hoc networks to support collaboration and the way to push forward such limits in order to improve the stability and bandwidth of the communication links.

Although empirical experiments provide accurate values, the main challenge is to make the obtained results comparable. Sometimes one or more variables participating in the process need to be simulated, thus reducing their representativeness. In the case of the study presented in this article, the network traffic was pre-established to make the results comparable. Several considerations were taken into account to make this theoretical traffic representative of a real mobile collaboration process. For example, the pre-established traffic was based on an empirical test previously conducted by the authors. Therefore the obtained results probably are more representative than those obtained in simulations. However, studies based on simulations require just a small fraction of the experimentation effort involved in the empirical version of such studies.

The study does not address the mobile collaborative work, but the interactions usually performed by mobile users when conducting such type of activity. Therefore several aspects related to the mobile users' behavior were not considered in this study.

The next section presents the communication requirements to support mobile collaborative work. Section 3 presents and discusses the related work. Section 4 describes the test bed used in this study. Section 5 presents the experimental evaluation and the obtained results. Section 6 shows the lessons learned from experimentation and section 7 lists the recommendations for application designers to deal with ad-hoc networking issues. Finally, section 8 presents the conclusions and future work.

2. Requirements on Ad-hoc Communication for Mobile Collaborative Applications

We define an ad-hoc network as an autonomous and decentralized system formed by a collection of cooperating nodes, which are connected by wireless links. They can dynamically self-organize and communicate among them, in order to make up a network without necessarily using any pre-existing infrastructure. These networks include wireless links with a dynamic topology and a limited communication threshold [20].

Communication infrastructures using these networks to support mobile collaborative work must consider several communication requirements in order to enable the interactions among nomad users. These requirements, which are briefly explained below, affect the usability of the mobile solutions in terms of response time.

(1) *Adequate network performance*. Mobile collaboration requires a stable and efficient network. Whenever two persons decide to interact, the communication link must be able not only to support it, but also to provide sufficient performance for the application to offer a suitable response time to the user. Network performance problems are frequent as users move and the network topology changes, which affects the response time of the solution. The most critical variables to take into account to evaluate the current network performance are latency (i.e. time required to transport the information between two locations), jitter (i.e. the variance of the latency) and throughput (i.e. data transfer rate) [10]. Adequate network performance in wireless networks can be obtained by using efficient routing protocols.

(2) *Reliable links*. Mobile collaboration also requires communication reliability, which is related to the trustworthiness of the communication link to transfer data between two points. The network overload and the agility of the collaboration process will partially depend on this issue. Unreliable networks affect negatively the throughput and therefore end users perceive a bad response time. In other words, the reliability of the network links also affects the usability of the mobile solutions. The network variables that can be considered to diagnose the reliability of the communication link are packet loss and ordering [10]. The links reliability cannot be guaranteed in a mobile network; however the use of routing protocols designed to deal with a dynamic topology make the links reliable.

(3) *Communication coverage*. A node belonging to a mobile ad hoc network (e.g. a nomad worker) must be able to collaborate not just with other nodes that are located at one hop of distance. If we consider indoor areas, such distance can currently be around 20-30 meters; however in open areas it can extend up to 100-150 meters. Although the interaction distance between two nomad users will depend on the type of activity they are performing, a one-hop communication threshold is typically not enough to support collaboration [50]. Therefore additional mechanisms are required to extend it [43]. A well-known solution to overcome this limitation is the appropriate use of routing protocols [42]. In that case, the network variable that can be used to diagnose the communication coverage is the number of hops.

(4) *Interoperability*. Mobile users must be allowed to interact with anyone else on a casual or opportunistic collaboration. As a consequence their collaborative mobile applications should offer interoperability of communication, data and services [29]. Typically this issue can be addressed using standardized communication protocols (e.g. IP over diverse radio link standards, and TCP or UDP transports), data formats (e.g. XML) and service representations (e.g. Web Services). The variable that can be used to diagnose this communication aspect is the adherence to the standards involved in the solution.

Several studies have been published about how some of these issues affect collaborative applications when they run over Internet. A study presented by Gutwin et al. shows that performance/usability of real-time distributed groupware applications depend on network variables such as latency, jitter, packet loss, bandwidth and type of traffic (UDP/TCP) [15]. Network delays due to latency and jitter have serious effects on users' work, causing difficulties in coordination and forecasting [15]. In extreme situations they cause communication break downs; this occurs, e.g., when latency > 300 ms [48] or jitter > 500 ms [11]. It has been also reported that insufficient bandwidth increases latency and packet loss [15].

Several researchers have also stated that usability of mobile applications depends on several variables, e.g. network reliability, throughput and latency [13, 26, 27, 52], which are similar to those presented above for stationary scenarios. We can then assume that communication reliability and performance play a key role on the usability of mobile solutions. However, it is not clear which are the acceptability threshold for mobile end users in terms of those variables. The study presented in this article provides just an insight that helps software designers to improve the values of these two variables in mobile collaboration scenarios. It would be interesting to determine the users' threshold of indignation [44] for mobile collaborative applications, which is not addressed in this study.

Although this study is focused on mobile collaboration supported by ad hoc networks, it is important to note that there are also other ways to provide communication support for mobile collaboration. For example mixing nodes from an ad hoc network and remote nodes accessible through Internet. In that case we have to consider gateway nodes acting as bridge between these two worlds. In [24], the authors show how to select a gateway between all the available ad hoc network nodes.

In this study we are also considering that all nodes are ready to actively participate in the management of the ad hoc network. However in a real scenario, there may be nodes that are not available to help in this activity. In those cases we count on several strategies to encourage active node participation, e.g. pricing strategies [51].

3. Related Work

The implementation of routing protocols has been the most popular strategy used to try to deal with the requirements presented in section 2. Much research has been done in order to improve the communication capabilities of Mobile Ad hoc Networks (MANETs) [23].

Most research has been carried out through simulations due to the high cost and technological difficulty of setting up MANET testbeds, although sometimes such studies do not accurately reproduce behavior in real scenarios.

This section reports studies performed using only real-world implementations of MANETs. Most of them have been done utilizing two types of mesh networks: static and mobile ad hoc networks. The analysis of the communication in both scenarios provides an interesting insight to understand the capabilities and limitations of these networks when they support mobile collaborative work.

3.1. *Studies using Static Ad hoc Networks*

A static ad hoc network is implemented through a multi-hop mesh composed of stationary nodes equipped with radio antennas (e.g. WiFi), where each node can consume and provide communication services [23]. These networks are typically used to provide multi-hop access to distributed resources, and also to support interactions among members of the mesh. Testing on this type of networks helps to estimate the maximum throughput and the minimal latency and jitter that can be obtained in a MANET. It can also help to define a convenient packet size in order to maximize the throughput and minimize the packets loss. The MIT roofnet project [6] is an experimental and independent multi-hop 802.11b mesh network consisting of about 38 nodes located in different houses in Cambridge, Massachusetts, installed and operated by the Massachusetts Institute of Technology (MIT). The network participants are volunteers who accept hosting in their apartments the equipment required to implement a mesh node. The authors make a study of packet loss and performance in the Roofnet using different packet sizes on the delivery ratio of single-hop transmissions. The results show that: a) larger packets have a much lower probability of being delivered than smaller ones and b) links that have a packet loss rate greater than a given threshold (*lossy links* with high throughput), seem to be a good choice in multi-hop paths. This last result occurs because such links provide better overall throughput than high quality links with a low bandwidth. Furthermore, short-distance, high-throughput links are preferable to long distance, low-throughput links in this respect.

Garroppo *et al.* [14] presented an experimental evaluation of two open source routing solutions for wireless networks, which work at layer two of the ISO/OSI stack and they are transparent to the IP layer. The first solution is a reference implementation of the upcoming 802.11s standard, which was named *open80211s* [36]. The second solution is a routing protocol known as *Better Approach To Mobile Ad-hoc Networking (*BATMAN) [5]. The goal of the tests reported by Garroppo *et al.* is to verify whether the protocols use a stable path from C_1 to C_n, and, in case of path changes, check whether they result in reduced transfer rates. Although stability cannot be regarded as an absolute value, in most static deployments, frequent path swapping comes with an unavoidable overhead and possible performance reduction. The test results also show that BATMAN-adv protocol is generally more stable than open80211s, and this last one presents a considerable path swapping. Besides, under static scenarios, BATMAN-adv shows much more reliable performance than open80211s.

3.2. *Studies using Mobile Ad hoc Networks*

The mobility of a MANET node can cause frequent route breaks. Updating routes can be time consuming, thus packets might be lost in bursts for short periods of time since they are sent on non-working routes. Re-routing onto newly established, more suitable paths can furthermore lead to out-of-order packets. In addition, despite that handheld devices have shown significant increases in computational power, recent experiments indicate that high bandwidth consuming communications (e.g. video streams) are still unfeasible in MANET [16].

Several real-world experiments have been carried out in order to understand the impact of nodes mobility. Maltz *et al.* [28] presents an implementation of the Dynamic Source Routing (DSR) protocol, tested in a MANET composed of five mobile nodes installed in cars moving at top speeds of 40 km/h and two stationary nodes. Stationary nodes were installed 700 m apart at opposite ends of the course traveled by the mobile nodes. The authors mention some general lessons learned from these tests, such as: a) packets controlling the routing protocol should be delivered with high priority - e.g., by implementing multi-level priority queues, b) management of human experiment participants is difficult and time consuming, and c) wireless signal propagation is highly variable.

The DSR prototype implementation was then extended to support real-time traffic such as audio and video [18]. In this study, the network consists of one mobile and seven fixed nodes. The mobile node transmitted an audio and a video stream over up to three hops to one of the fixed nodes. The experiment showed that the transmission of real-time traffic over an ad-hoc network could be possible if the routing protocol is adapted to the specific scenario.

The experiments presented in [9] study the impact of three different link-quality metrics (ETX, per-hop RTT, and per-hop packet pair) for ad hoc routing and compared them to minimum hop-count routing. They study these metrics using a DSR-based routing protocol running in a wireless network with 23 nodes. The experiments show that the ETX metric has the best performance when all nodes are static and the hop-count metric outperforms all of the link-quality metrics in a scenario where the sender is mobile, because it reacts more quickly to fast topology changes. On the other hand, an experiment conducted with implementations of Ad-hoc On-demand Distance Vector (AODV) and Destination-Sequenced Distance Vector (DSDV) routing protocols is described in [8]. These protocols were tested in a scenario with four fixed and one mobile node. The fixed nodes were set up in a chain topology, and the mobile node passed this chain from one end to the other. The experiment tries to identify the fastest protocol when reacting to changes in the network topology; therefore it can provide a better throughput between mobile workers. The authors mention that the DSDV implementation did not suffer as much as AODV, because it used a handshake before accepting a link.

Calafate et al. [7] report an experimental evaluation of four MANET routing protocols (DSR [18], OLSR [19], TORA [37] and AODV [39]), which were compared for coded video transported as UDP flows. The results show that packet loss burst due to route changes is a major problem, which should be handled by the routing protocol.

We can summarize by noting that nodes mobility induce challenges in the communication support, because the characteristics of existing links are likely to change, or they might even break. Mobile collaboration typically requires stable communication links and adequate performance; the goal is to extend the distance between collaborators as much as possible without hurting the communication quality. This section has presented several experimental results that provide hints on the communication requirements to perform computer-supported mobile collaborative work.

There are also other interesting aspects to analyze related to the impact of the communication support. For example the impact that it has on the environment [25] and the level of volunteer collaboration [51]. However these aspects are beyond the scope of this work.

Next section describes the test bed used by the authors to try to understand the influence of the networking issues over mobile collaborative work. Then, section 5 shows and discusses the obtained results, and section 6 presents the lessons learned.

4. Test Bed Description

All the tests done in this study used real implementations of ad-hoc networks. However the network traffic was pre-established to ensure the comparability of the results obtained in the several tests. In order to provide realism to the traffic on the MANET, the study followed the recommendations by Kiess and Mauve [23]. Several mobility patterns were used in this study, which were done with real users. Such patterns adhere to a typical stationary, partially mobile, and mobile collaboration process respectively. The pre-established traffic for each test scenario was based on the results of empirical tests conducted by the authors in real collaboration processes, in which the mobility patterns were involved. Moreover the tests included in the study considered an ample range for the offered loads. Therefore there is a high probability the data transfer need of a real collaboration process is within that range. It also helps to improve the representativeness of the tests results.

The tests conducted in each studied setting involved at least 10 repetitions in order to get representative values. Moreover, the observed variables were measured during at least 1 minute. The next sections present the hypotheses and the experimentation scenarios involved in this study. We also describe the routing protocols, hardware and software employed.

4.1. *Work Hypotheses*

The work hypotheses for this study had two sources: (1) preliminary results provided by other researchers, and (2) the experience of the authors as developers of this type of solutions. These hypotheses are the following ones:

Hypothesis 1: The network bandwidth and reliability decrease when increasing number of hops between the sender and receiver nodes. This hypothesis intends to establish a basis of understanding to analyze and make conclusions about the tests included in this study. Validating this hypothesis will help to identify the maximum acceptable distance between two collaborators in order to consider the application as usable (in terms of performance) by end-users.

Hypothesis 2: The network bandwidth and reliability decrease with increasing mobility of the nodes. Considering the results related to the hypothesis 1, this hypothesis intends to demonstrate the mobility of the nodes also affect the throughput between two collaborators. Validating this hypothesis will help us to estimate the degree of mobility the nomad users can have without seriously deteriorating the performance of the mobile collaborative application.

Hypothesis 3: The network bandwidth and reliability decrease due to increasing interference generated by mobile devices from other users. Like hypothesis 2, this one intends to verify that interference produced by mobile devices affect the throughput between collaborators, and also that such interference increases with the number of nodes participating in the MANET. Validating this hypothesis will help us to observe the effect of users' density on the obtained throughput, and the performance as perceived by the end-users.

Hypothesis 4: Routing protocols based on number of hops (such as BATMAN [5]) have better reliability and bandwidth than protocols based on statistics (such as OLSR [41]). This hypothesis intends to demonstrate that routing protocols based on statistics are slower to react than those based on number of hops. Therefore the first ones are able to provide a better throughput to mobile users. As a consequence, collaborative applications which use the first type of protocols have better usability in terms of performance perceived by an end-user.

Hypothesis 5: In ad-hoc networks, UDP-based communication has better performance than TCP-based communication. This hypothesis attempts to show that connection-less communication is able to provide, in ad hoc networks, additional throughput to mobile collaborative solutions. Demonstrating this hypothesis could provide software designers a tool to help them reduce the performance degradation generated by mobility and interference from other mobile users.

4.2. *Experimentation Scenarios*

In order to validate the hypotheses, the study considered three indoor experimentation scenarios: a stationary, a partially mobile and a mobile scenario. We decided to use indoor scenarios because they provide more important communication challenges to support mobile collaboration than open areas. Typical indoor settings have important signal interference due to the presence of computing devices and access points in the area, and also signal degradation because due to walls and doors. The experimentation scenarios represent typical settings in mobile collaboration activities. Such scenarios are briefly described below.

Stationary work scenario: There was no mobility in this scenario (each node was static). Communication can occur between any pair of users independently of the distance between them. A packet filtering was used to force the network topology to work as a chain, which is the worst topology that we can have in the work scenario. Five nodes were located at 11 to 14 meters of distance between them; therefore, a 4-hops ad-hoc network was established. In such setting several tests were conducted (they are explained in section 5.1). Since this scenario allows monitoring and reproducing the network multi-hop behavior, it was used to validate *hypothesis 1*. This scenario is representative of several mobile collaboration instances, e.g. in loosely-coupled work [40], where users are temporarily stationary when they decide to collaborate. An example of these situations has been reported by Moran et al., whom studied the mobile work in hospitals and identified an important number of collaboration meetings (i.e. stationary collaboration scenario) held by the medical staff [31]. Similarly, Ochoa et al. report meetings held by construction inspectors in the field after an inspection round [34]. This setting is also representative of mobile collaboration mediated by access points (i.e. static nodes), which are temporarily deployed in the work area just to increase the coverage of the ad hoc network. In these settings collaborators are also static while performing such activity. The authors have empirically observed that collaborating mobile workers tend to be static during such process. If they need to see the device screen to conduct that process, then they typically stop moving because the focus of attention is now on the screen instead of their steps. It seems to be a natural and involuntary reaction from most collaborating mobile users, which leaves them static during such period.

Partially mobile work scenario: This test scenario uses the same hardware, nodes location and network topology than the first one. However, this new one introduces an extra node which continually moves between both network ending points. The mobile node was implemented using a single person with a laptop, who moves through a path drawn on the floor and with a stable velocity while the other nodes keep static. The test began with the mobile node (i.e. node 6) located close to node 1 (network ending point), and the data transfer is always done between the mobile user and node 5 (the other network ending point). Packet filtering was also used to force the communication between these nodes to always go through two hops. This scenario was used to validate *hypothesis 2*, because it is possible to isolate the effect produced by a single mobile user on the network. Such scenario is representative of *partially unattended collaboration activities* (e.g. data synchronization or notifications triggered by a mobile user), in settings involving access points as intermediaries that support the collaboration process (similar to the last collaboration situation described in the stationary work scenario). Partially unattended collaboration occurs when a nomad worker interacts with one or more mobile devices, but he/she does not with the persons using them. For example, the worker does actions to implement the access, update and distribution of shared files, or to verify the users' participation in an ad hoc work session. Monares et al. show [30] how partially unattended collaboration can be used to support the work of Firefighter Incident Commanders during urban emergencies.

Mobile work scenario: Typically, mobile users working in groups need to exchange information within their group or between groups, for example to keep work sessions participation, implement awareness mechanisms or perform unattended collaboration activities. The experimentation scenario included two groups of four mobile nodes each. The mobile workers used exactly the same laptop model in all experimentation scenarios. The tests were carried out in a laboratory of 146 m2 and the distance between groups was 8-10 meters. The intra-group and inter-group communication was monitored. In the first case, mobile users interact just with the teammates; however in the second case the communication is between members of different groups. The comparison of both cases will allows us to validate *hypothesis 3*. There was no constraint on the number of hops used by the communication process during these tests. Both collaboration instances (i.e. intra-group and inter-group) are present in real work scenarios. For example, Neyem et al. report unattended notifications that promote face-to-face collaboration instances among civil engineers and firefighters (i.e. inter-group interactions), whom support urban search and rescue activities after a disaster [33]. Rodriguez-Covili et al. show how unattended synchronization of a mobile shared workspace used by members of a construction inspection team (i.e. intra-group interactions) ease the inspection process and also the reporting of the results [43].

Let us consider the scenarios that allow us to explore the validation of hypotheses 4 and 5. Since this validation does not require specific settings, they can be evaluated in each of the described testing scenarios.

Neyem et al. establish and justify a set of typical coordination mechanisms that are usually required by mobile collaborative applications in order to support nomad workers activities; e.g. ad hoc collaborative session, session dataspace, ad hoc environment, mobile users and roles [32]. These coordination mechanisms were proposed by CSCW researchers several years ago, but now they are redefined to deal with the work context changes produced by mobile users and unstable communication links. These coordination services are frequently required by mobile collaborative applications to support nomad work in the three presented experimentation scenarios. Therefore, the experimental results of the tests will help designers to realize how to deal with structural design issues related to these applications.

4.3. *Routing Protocols of Mobile Ad-hoc Networks*

The routing protocol usually has important consequences on the network reliability and performance. Thus, we reviewed the most widespread protocols and we selected the following ones:

Better Approach To Mobile Ad-hoc Networking (BATMAN) [5]. This is a proactive protocol using a distance vector approach to determine the best route between sender and receiver. The routing metric used by this protocol is the number of hops used in the communication. The protocol implementation used during the tests was BATMANd for Linux.

Optimized Link State Routing Protocol (OLSR) [41]. This is a proactive protocol using a link state approach to select the optimal route. The routing metric used by this protocol is Expected Transmission Count (ETX) [9]. The protocol implementation used in the test was OLSRd for Linux and Windows.

Although there are several well-known routing protocols, e.g. BATMAN [5], DSDV [8], DSR [18], TORA [37] AODV [39] and OLSR [41], we choose the best one based on number of hops (i.e. BATMAN) and the best one based on statistics (i.e. OLSR). The reason to make such selection was to obtain comparative results between protocols implementing the two most well-known strategies for routing on MANETs. Thus, we can realize the effect of the routing strategy on the network throughput. Moreover, it will help us validate hypothesis 4.

4.4. *Metrics for Link Quality Evaluation*

The metrics used to assess link communication quality during the tests were those relevant for mobile collaborative work (described in section 2) and also those designed to determine the Mobile Ad-hoc Networks (MANETs) protocols performance [9, 23]. The metrics provided by the traffic generator itself were also taken into account [46]. These metrics were divided into three groups, depending on the type of traffic used for measuring them: (1) ICMP traffic metrics using Round-Trip Time (RTT), (2) UDP traffic metrics considering throughput, packet loss and jitter, and (3) TCP traffic metrics including throughput, handshake time, out of order packets and number of re-transmissions.

The UDP/TCP traffic was pre-established and generated using the Iperf tool [46] in order to ensure the repeatability of the experiments. The metrics were measured by conducting a 60 seconds test, on which UDP/TCP packets were transferred between a given source-destination pair. For UDP, packets were generated at different bit rates; consequently, several UDP traffic loads were offered to the network. Unlike with UDP, in the TCP experiments we tested the maximum achievable throughput; therefore, no fixed bit rates were specified.

The RTT was measured by conducting a 60 seconds test, on which ICMP packets were transferred between a source-destination pair, using the regular ping service. Those experiments were carried out for packet sizes of 64 or 1024 bytes.

4.5. *Hardware*

The experiments were carried out using eight laptops model HP NX6310 with an IBM Intel Core 2 T5500 of 1.66 GHz processor and 1 GB of RAM. Each of these computers had an internal Intel PRO/Wireless 3945ABG Network Connection card for IEEE 802.11b/g wireless connectivity. During the experiments, the wireless cards on the laptops were set to channel 1 at the 802.11b/g band, using auto rate, transmission power 1 dBm and RTC/CTS off, following recommendations in [22].

4.6. *Test Bed Supporting Software*

All laptops were equipped with Linux Operating System (Ubuntu 8.04 Linux distribution with the 2.6.24-19-generic kernel) and also MS Windows XP. The traffic generator used in the test was Iperf (version 2.4) and the regular ping service provided by the operating system.

The traffic analyzers were Wireshark, and tcpdump (similar to Wireshark but with a command line interface). Following the Kiess and Mauve recommendations [23], a MAC filter was also used to classify packets on the MAC layer and force a multi-hop behavior avoiding direct communication between two nodes.

A LiveCD was prepared in order to avoid the human intervention as much as possible. This LiveCD adds an extension to the operating system facilitating the test bed implementation, use and data gathering [47].

5. Empirical Results

This section presents the obtained results in the tests performed in the described experimentation scenarios. These results allow mobile groupware designers to see the range of values that can be found, for each key networking issue, in real implementations of ad hoc networks. Therefore, they can evaluate the type of coordination and collaboration mechanisms that can be implemented to support mobile collaboration in such work scenarios. The experimental results also allow understanding the degree of validity of the stated hypotheses.

5.1. *Empirical Results in the Stationary Work Scenario*

During this type of tests the controlled variables were the packets size and the number of hops between the collaborating nodes. The observed variables were the received throughput and the RTT (Round-Trip Time), which help us to predict the bandwidth of the network and indirectly, the performance of the collaborative application in such scenario. These variables were measured at the ending points of the communication path. All tests were performed using an 802.11b network; however, in some cases the tests were also done using 802.11g to verify the results trend. Figure 1 shows the results obtained involving 3 and 4 hops, which is a segment that could be present in several collaboration instances (e.g. hospital work and responses to urban emergencies). This segment represents distances of 30-60 meters between the collaborators in built areas. The segment could be extended to 200-300 meters in open areas.

The variable observed in Figure 1 was RTT, where the series correspond to the sample mean of different test sets. The sample mean of the worst test set (based on relative dispersion of the test measures) is 12.13 ms with a Standard Error of the Mean (SEM) of 0.25 ms. The margin of error for the mean (E) is at most 0.58 ms for a confidence level of 95%. Therefore we thought the observations and conclusions based on this test set are valid.

For each n repetitions of the test sets, we report the sample mean value (X). Then we use standard statistical methods to generate the confidence interval for expected values. The statistical error (i.e. the confidence degree of the accuracy) was calculated using the corresponding confidence interval (CI) at a given confidence level (CL); being the statistical error = 1 – P, where P is the probability to find a value out of the confidence interval [38]. The CI is given by X - E ≤ μ ≤ X + E. The margin of error for the mean is equal to t_c* standard error of the mean, where t_c denotes the value of the t distribution corresponding to an upper-tail area of α/2 and a n–1 degree of freedom. The CL = 100 * (1 − E) %; it means there is a 100 * (1 − E) % of confidence the real mean μ is between X - E and X + E.

The RTT increases with the number of required hops and also with the packet size. The behavior of OLSR and BATMAN protocols were similar, which is not surprising because the work scenario is static.

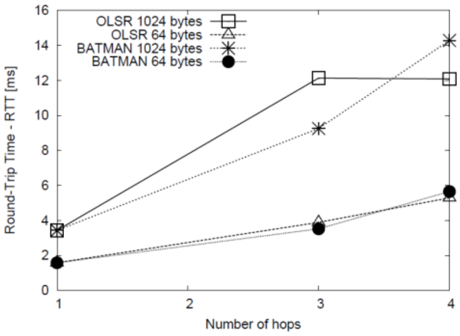

Fig. 1. RTT of the ping service, using different routing protocols and packet sizes

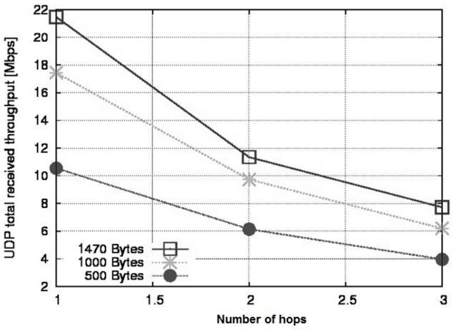

Fig. 2. UDP throughput for 802.11g with different packet sizes and number of hops using BATMAN

Figure 2 shows the results of a test done on the same setting (using BATMAN), which had 2 and 3 hops and the use of an 802.11g network. The series correspond to the sample mean of different test sets. The sample mean of the worst test set is 17.44 Mbps with a SEM of 0.34 Mbps. The margin of error for the mean is at most 0.79 Mbps for a confidence level of 95%. Such test was done just to verify the results trend. Clearly the packets size influence and the number of hops influence are similar to those identified in the first test.

Figure 3 and 4 show additional results in which we can see that the throughput decreases with the number of hops. Moreover, the margin of error shown in such figures is less than in figure 1 and 2.

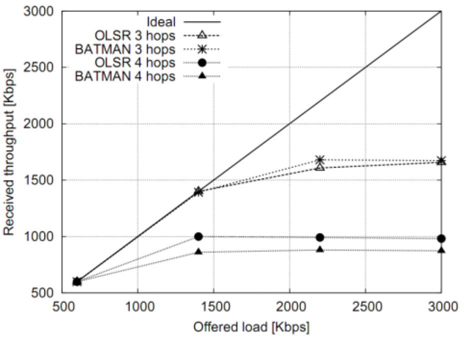

Fig. 3. Throughput on UDP, considering 3 and 4 hops

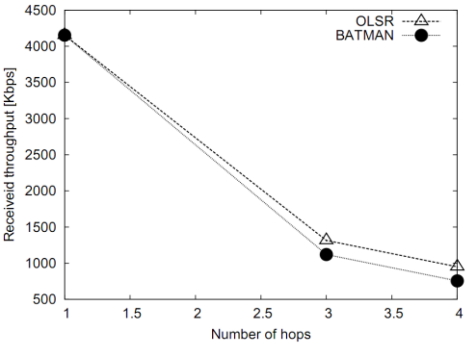

Fig. 4. Throughput on TCP, considering various routing protocols and number of hops

This results trend is independent of the transport protocol we use (i.e. UDP and TCP). In Figure 3 the sample mean of the worst test set is 1658 kbps with a SEM of 23.13 kbps. The margin of error for the mean is at most 52.32 kbps for a confidence level of 95%. The sample mean of the worst test set presented in figure 4 is 4153 kbps with a SEM of 106.9 kbps. The margin of error for the mean is at most 106.87 kbps for a confidence level of 95%.

Once again, for both types of traffic, the behavior of OLSR and BATMAN were similar. In case of tests using TCP, the packet out of order, re-transmission and handshake time (about 0.5 ms) are zero or negligible numbers. Summarizing, the received throughput was almost equal for both routing protocols (Fig. 4); however it decreases with the number of hops and with increasing packets size. Since the influence produced by the number of hops was isolated in this experimentation scenario, we can say that the obtained results are (at least) aligned with hypothesis 1.

5.2. *Empirical Results in the Partially Mobile Work Scenario*

This experimentation scenario included five static users and a mobile one. The obtained results show that BATMAN has a better behavior than OLSR for all considered TCP metrics (Table 1). It can be due to the fact that OLSR uses the ETX metric for the selection of the routes, and that metric utilizes statistical information of the 10 last probes to compute its current value. Since the mobile user location is constantly changing, the computed best route becomes out-dated soon. Therefore, it will generate a significant number of out-of-order packets and require a high number of retransmissions.

Table 1. Routing protocols comparison using TCP

	BATMAN	OLSR
Received Throughput (kbps)	2110	2035
Number of packets out of order	0.05	2.25
Number of re-transmissions	0.00	296.75
Handshake time (ms)	0.00	0.04
RTT (ms)	6.59	7.37

Figure 5 shows the results of the same tests, but using UDP. We can see there that UDP is able to obtain a better throughput than TCP. In such experimentation scenario, BATMAN showed a slightly better UDP throughput than OLSR for medium offered loads. The behavior of the routing protocols shows reverse results for higher loads. Figure 5 allows us to compare throughput obtained by the mobile device when it is on the move and also when it is static. In this case the sample mean of the worst test set is 2525 kbps with a SEM of 25.5 kbps. The margin of error for the mean is at most 55.52 kbps for a confidence level of 95%. The experimental results show the mobility negatively affects the communication throughput. These results then support part of hypothesis 2.

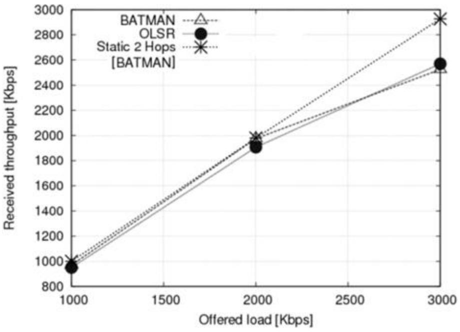

Fig. 5. Throughput using different routing protocols and offered loads

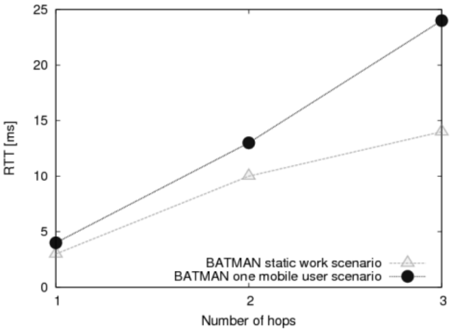

Fig. 6. RTT of the ping service using BATMAN in a static and a partially mobile work scenario

Figure 6 compares the RTT of the communication using BATMAN in the static and the partially mobile scenarios using two and three hops. The sample mean of the worst test set is 24.71 ms with a SEM of 0.25 ms. The margin of error for the mean is at most 0.57 for a confidence level of 95%. The results show the latency increases with the mobility, which reduces network bandwidth (hypothesis 2). However it is not possible yet to get some interesting conclusion about the influence the users' mobility on the communication reliability (second part of hypothesis 2).

5.3. *Empirical Results in the Mobile Work Scenario*

This experimentation scenario had tests with two and three groups of mobile users. Initially the mobile users were arranged in two groups of four nodes each. A path was drawn on the floor and the nomad users walked on it with a constant speed in order to imitate the mobile users' movements. Intra and inter-group communication were evaluated in this scenario.

Figure 7 shows the results of UDP throughput considering intra-group communication. Both routing protocols show here a similar behavior when the data transfer is between group members and the offered load is below 2000 kbps. However, OLSR is able to obtain up to 500 kbps over BATMAN when the offered load is over 2000 kbps. There was no relevant interference among nodes because the communication was performed among group members that were co-located. The communication interference of one group over members of the other group was negligible since both groups were 8-10 meters apart. However, this interference can be clearly identified in inter-groups communication, since one communication path crosses through other currently active paths. This situation is usually present in unattended mobile collaborative activities, e.g., automatic update of the list of work session members or automatic update of the list of currently reachable mobile users.

The network behavior for inter-groups communication differs from the previous interaction scenario (Fig. 8). We have a more important number of mobile nodes to consider when determining the communication path now. Therefore, routing protocols based on number of hops seem to achieve a high throughput. The testing results show in this case that BATMAN performs better than OLSR for loads over 600 Kbps. In those settings BATMAN is able to reach up to 800 Kbps of "extra" received throughput. This situation could be explained by the fact that OLSR uses the ETX link quality metric to determine the best path between sender and receiver. Therefore, OLSR frequently uses 2-hops routes instead of the faster 1-hop route used by BATMAN.

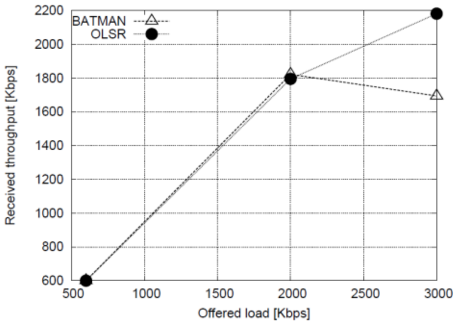

Fig. 7. Intra-group communication involving mobile nodes

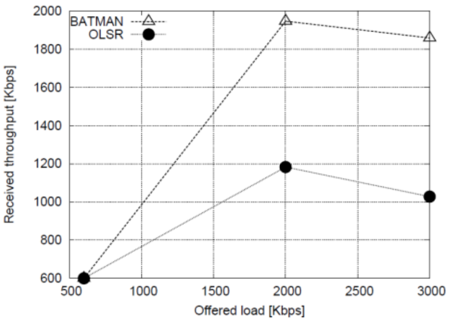

Fig. 8. Inter-group communication involving mobile nodes

Table 2 shows additional results from the inter-groups communication tests. We can see the network throughput decreases with increasing number of transmitting nodes (1 tx: one node transmitting per group, and 2 tx: two nodes transmitting per group). It could be indicating the communication interference increases with the number of transmitting nodes (hypothesis 3). Supporting this assumption we can see the % of packet losses and the jitter increase with the number of transmitting nodes. These results are aligned with hypothesis 3.

Table 2. Routing protocols comparison using UDP

UDP Offered load (Kbps):	2000				3000			
Routing Protocol	BATMAN		OLSR		BATMAN		OLSR	
Number of Transmitting Nodes	Tx1	Tx2	Tx1	Tx2	Tx1	Tx2	Tx1	Tx2
Received Throughput (kbps)	2000	1620	1477	1327	2133	476	2737	369
% loss	0	0	0.53	0.93	0.18	28.7	6.59	63
Jitter (ms)	1.86	16.5	1.62	5.45	136.6	1085	140.2	195.2
Number of datagrams out of order	0	1	0	0	6	1	125	38

These experiments were repeated using TCP now as transport protocol. The results trend was consistent with that obtained for UDP, but the throughput was lower than the previous case. Thus, we can get some preliminary conclusions. The obtained throughput when using UDP seems to be higher than that reached with TCP in most mobile collaboration scenarios. Another preliminary conclusion indicates that OLSR is usually better than BATMAN when the communication is intra-group, but BATMAN has a better performance when communication is inter-group.

If we analyze the network behavior when UDP was used, then it may be noticed the performance is affected (in terms of jitter, % of packet losses and received throughput) by the number of nodes which are transmitting inside each group.

We performed a new set of tests using the same experimentation scenario, but with a different group setting in order to study in depth the influence the interference produces on the communication throughput and reliability (hypothesis 3). We used BATMAN as routing protocol in these tests. The first test kept the original groups setting, i.e., two groups of four mobile users each. In such case, the test was conducted with several offered loads and one node transmitting per group. The test was then repeated with two transmitting nodes by group. The results are presented in the following figures.

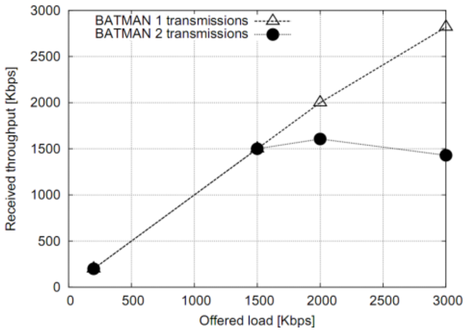

Fig. 9. UDP throughput vs. number of transmitting nodes

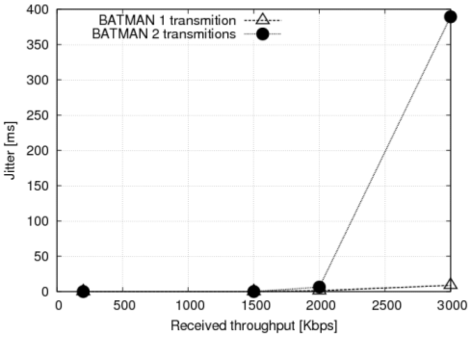

Fig. 10. UDP jitter vs. number of transmitting nodes

Fig. 9 shows the throughput decreases with the number of transmitting nodes, probably because of the interference produced by the two simultaneous interactions on two physically close communication paths. In this case the sample mean of the worst test set is 1606 kbps a SEM of 41.2 kbps. The margin of error for the mean is at most 97.37 for a confidence level of 95%.

Fig. 10 the sample mean of the worst test set is 389 ms with a SEM of 8.8 ms. The margin of error for the mean is at most 28.06 ms for a confidence level of 95%. Moreover, these results show the network jitter increases with the number of transmitting nodes because of the same reason. However, the difference becomes highly relevant just over 2000 kbps of offered load. In Figure 10 the margin of error, after 400 ms of test, was 48 ms. Although there is a considerable variation in the measured values, we think the conclusion about the jitter remains valid.

We can infer from these figures that a communication instance will be affected by the interference produced by others that cross its communication path. Table 3 summarizes the results obtained for the key networking issues during these tests. The last column of Table 3 corresponds to the same test but involving three groups; each one with a transmitting node. We can observe the number of groups does not make any difference. The influence is just based on the number of simultaneous communication instances involving mobile users that are not co-located during the collaboration process.

Table 3. Key networking issues vs. number of transmitting nodes (per group).

	UDP Received Throughput (kbps)		
UDP Offered load (Kbps):	2 groups (2 tx in total)	2 groups (4 tx in total)	3 groups (3 tx in total)
2000	2000	1606	1822
3000	2818	1429	1694

	UDP Jitter (ms)		
UDP Offered load (Kbps):	2 groups (2 tx in total)	2 groups (4 tx in total)	3 groups (3 tx in total)
2000	1.21	6.36	4.56
3000	8.81	389.43	30.37

	UDP % packet loss		
UDP Offered load (Kbps):	2 groups (2 tx in total)	2 groups (4 tx in total)	3 groups (3 tx in total)
2000	0	0.37	0
3000	0.28	24.61	3.49

	UDP # of out of order datagrams		
UDP Offered load (Kbps):	2 groups (2 tx in total)	2 groups (4 tx in total)	3 groups (3 tx in total)
2000	0.5	0.33	0.5
3000	0.67	42.67	3.61

5.4. *Hypotheses Validation*

A brief validity analysis of the hypotheses is presented below based on the results discussed in the previous sections.

Hypothesis 1 *- The network bandwidth and reliability decrease when increasing the number of hops between the sender and receiver nodes*. We isolated the effect produced by the number of hops in the stationary work scenario. The results presented in Figures 3 and 4 show the throughput decreases with the number of hops for both UDP and TCP transport protocols. Therefore, the obtained results support hypothesis 1.

Hypothesis 2 *- The network bandwidth and reliability decrease with the mobility of the nodes.* Considering the results of the tests in the three experimentation scenarios we can infer this hypothesis is true. Figure 5 and 6 show the influence produced by a single mobile node, and the obtained results are aligned with the hypothesis. Let us compare the results obtained in partially mobile (section 5.2) and mobile work scenarios (section 5.3). It seems the mobility of the users negatively affects the network throughput, if we consider the same number of transmitting nodes.

Hypothesis 3 *- The network bandwidth and reliability decrease due to the interference from other mobile users.* It is highly probable hypothesis 3 be true based on the results presented in Tables 2 and 3.

Hypothesis 4 *- Routing protocols based on number of hops (such as BATMAN) have better reliability and bandwidth than protocols based on statistics (such as OLSR).* The tests results indicate this hypothesis is false. However, we were able to identify the influence of these routing protocols in each studied work scenario. In static and partially mobile scenarios both routing protocols have a similar behavior. It is not surprising because the communication routes do not change much, since nomad workers have low mobility. By contrast, the results depend on the physical location of the persons involved in the collaboration process in the case of mobile scenarios. OLSR seems to be slightly better than BATMAN if the users are grouped in a small area because most communication messages are delivered with just one hop. However, in mobile scenarios where collaborators are not co-located, BATMAN seems to be better than OLSR, because this last one uses the ETX metric to determine the best route. Such metric depends on statistical values, therefore it does not react as fast as required when the users are highly mobile.

Hypothesis 5 – *In ad-hoc networks, communication on UDP has better performance than communication on TCP.* For highly mobile work scenarios, the obtained results (Figs. 3 and 4; Tables 1 and 2) are showing the UDP communication degrades slower than TCP communication. Therefore, the throughput with UDP is higher than with TCP. These results are showing this hypothesis could be valid.

6. Lessons Learned

The empirical information obtained from the tests performed in the described scenarios should be useful to mobile collaborative applications designers. This information will be relevant to understand the capabilities and limitations of a collaborative system, when it supports mobile work in a real work scenario. The most relevant lessons follow.

The communication support degrades when:

- *The number of hops required to transport a message increases*. Evidence of it is a reduction in throughput, a greater latency, and large packet losses. It affects the mobile collaborative work when the users are disperse, e.g., on activities taking place in a hospital.
- *The mobility of users increases*. Typically the latency increases and the throughput decreases because the routing protocols are not fast enough to react to the changes in the network topology and composition. It affects the collaboration in scenarios with high mobility; for example in emergency situations, such as big fires or urban search-and-rescue activities.
- *The simultaneous interactions in the same area increase*. The throughput typically decreases and the packet losses increase. Although the throughput in these scenarios is good enough to support collaboration at moderate rates, network demanding applications (e.g. audio/videoconference systems) or mobile collaborative systems used in areas with many simultaneous interactions (e.g., a mobile educational application used by students in the classroom) can be seriously affected.

Routing protocols running at each node are required to enable communication beyond the immediate neighbors, i.e., at more than one hop of network distance. It means that a user can collaborate with persons located in other buildings, just because of using a routing protocol. Otherwise the user is restricted to collaborate with persons that are physically close (around 10-20 meters in built environments).

The behavior of the routing protocols is diverse. Therefore, the designer must select a protocol depending on the users' mobility, and the features of the work physical scenario.

The choice of transport protocols is counter-intuitive. A connection-less transport protocol (e.g. UDP) typically provides a better throughput than a connection oriented one (e.g. TCP). Path redundancy could help increase the communication throughput.

7. Recommendations for dealing with the Ad hoc Networking Issues

This section presents a list of recommendations to deal with the requirements on ad hoc communication that were presented in section 2, based on the tests results and the authors' experience as developers of mobile ad hoc collaborative solutions. Such requirements can be addressed at two levels: (1) in the networking infrastructure that support interactions among the mobile devices, and (2) in the mobile collaborative system supporting collaborative activities among nomad users. The recommendations presented below deal with most communication requirements at these two levels.

7.1. *Dealing with the Communication Requirements in the Network Infrastructure*

Communication requirements can be satisfied by the network infrastructure in several ways. Some of them are the following ones:

Data compression. Compression is applied to the volume of data needed to represent information. It helps to increase the apparent throughput [10] and to reduce the number of packets required to perform an interaction between two mobile workers. Less packets on the network help reduce the packet losses, and therefore, to increase the communication reliability.

Rate control. The goal is to ensure a minimal acceptable level of performance for the communication infrastructure. For this purpose, the network transmission should be decoupled from the system's event model, and the transmission rates should be carefully regulated. Since MANETs have a limited bandwidth, which is shared among all nodes transmitting simultaneously, the regulation of the transmission rate on each node could be a solution to avoid the collapse of the network when it is overloaded. These regulation mechanisms may also help to maintain a quality of service level. The consequence is the response time perceived by mobile users tends to be homogeneous, and thus we avoid having excessively slow or fast nodes.

Multicasting. Multicast, i.e., sending a message to multiple destinations at once, could help eliminate data redundancy freeing network capacity, or allowing additional interactions among mobile users. However, multicast can become another issue when network links are diverse in capacity and for applications requiring reliable group communication.

Standardized Protocols. Clearly the use of standardized protocols contributes to the communication interoperability. However, the interoperability required by mobile collaborative systems also involves the shared data and services they use to collaborate. In such case the recommendation is the same; i.e. using standardized data representations (e.g. XML) and services types (e.g. Web services).

Routing. We can infer from the test results that routing protocols using the ETX metric to determine the best path can offer a best communication performance if the users are co-located or they have low mobility. Collaborative activities involving high users' mobility should be supported by routing protocols based on number of hops, because they quickly react to changes in the network topology, and therefore they offer best communication performance.

7.2. *Dealing with the Communication Requirements at the Application Level*

Regardless of the mechanisms used to deal with the communication requirements at the networking layer, we can also consider other solutions to help improve communication between end users. Such solutions are the following ones:

Randomized (Gossip) indirect propagation mechanisms. Sometimes two collaborators are unreachable because there is no direct link between them. Then, it is possible to deliver a gossip, which is message travelling through the network during a certain time period, looking for the destination user [29]. Typically, these messages (if they are received by the destination) try to promote an encounter. For example, "*URGENT: try to be at … after lunch*". Although this mechanism may not always succeed, it can contribute to improve the reachability of users in disperse work scenarios or in situations in which few persons work together at the same time.

Pushing notifications. If a user has a couple of unsuccessful attempts to interact with somebody, then this user typically may no longer be aware of such person. However, if the system notifies the user when the destination becomes reachable again, then it enables additional collaborative interaction. Notification mechanisms must be autonomous, proactive and non-invasive to reduce the burden on the participants.

Adaptive user interfaces. Applications that dynamically change their interaction paradigm can better accommodate to changing network conditions. Thus, applications can deliver a limited or extended level of service to the end-user depending on the network conditions (e.g. moving from high to low video, to audio only or text communication according to the network conditions). This type of self-adaptation mechanism allows applications to gracefully adapt reducing the impact of the network changes on end-users.

Revealing network problems. Revealing network problems can be implemented as awareness components, which inform users about networking problems. Thus, users can take some action to try to solve or mitigate the problem. For example, when a mobile user becomes isolated, the awareness mechanism can inform him/her about that. Therefore, the user can change his/her location to be able to interact with other users.

8. Conclusions and Further Work

Although there are various studies of ad hoc networks, most of them are just focused on data transfer and technologies analysis [23]. The study reported in this article analyzes the ad hoc networks as support for mobile collaboration processes. Therefore, the experimentation scenarios are focused on situations that are usually present in mobile collaborative work.

This study tries to understand how the communication features in ad hoc networks affect the design of groupware mechanisms, particularly those supporting coordination and collaboration activities. It is important to remark this study does not simulate mobile collaborative work, but it just provides elements to help designers to understand the kind of practical issues to be faced by a mobile user in real deployments, when using a MANET as network communication support. For that reason the mobile users' behavior was not addressed in this study.

Real networks, hardware and users were used in the experimentation process. However the network traffic was pre-established for every studied scenario as a way to ensure the comparability of the obtained results. Although clearly it represents a limitation of the presented study, the traffic values used in the tests were estimated based on empirical tests performed by the authors. Moreover, the offered loads used in the experiments considered an ample range, which increase the representativeness of the test results. The study considered intra-group and inter-group communications, two typical data transmission protocols (i.e. TCP and UDP) and also two representative routing protocols (i.e. OLSR and BATMAN).

Five hypotheses were stated based on the authors' previous experiences and also the preliminary results reported in the literature. These hypotheses help designers to understand the communication capabilities provided by MANETs in stationary, partially mobile and mobile collaborative activities.

The analysis of the empirical results allows us to make a preliminary validation of the stated hypotheses. Although the study considered just two routing protocols, they are the best ones implementing routing strategies based on number of hops (BATMAN) and based on statistics (OLSR). It means that probably the tendency of the results is not going to change if we use other routing protocols for MANETs.

These findings help designers to understand what network support can be required (and obtained) in real work scenarios when two or more mobile users decide to collaborate. They also allow us to identify the limits of the communication performance and reliability in a certain interaction scenario, and the mechanisms that we can use to try pushing such limits.

Designers of mobile collaborative applications can take advantage of this study, in order to benefit themselves from the opportunities for improving the communication support and avoid the obstacles presented by these dynamic networks. The design of contextualized applications is always a challenge, but it is even greater for mobile collaborative systems due to the intrinsic diversity and the dynamic work scenarios [1]. We expect the results of this study can help contextualize this type of solutions.

Next steps in this study will try to extend the number of experimentation scenarios to cover a wide spectrum of mobile collaboration styles. It would be interesting to determine the users' threshold of indignation [44] for mobile collaborative applications, and thus to establish a reference value for communication reliability and throughput for this scenario. Such values will become a target for developers of mobile applications. Finally, the authors want also to include additional hardware diversity in the tests to understand its impact on the collaboration capabilities provided by applications.

Acknowledgments

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